PROJECT PE-2

OVERCOMING SOIL DEGRADATION THROUGH PRODUCTIVITY ENHANCEMENT

ANNUAL REPORT 2001

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CIAT
Centro Internacional de Agricultura Tropical
International Center for Tropical Agriculture

Cover design:

The Soils Fair is a key activity of the Local Indicators of Soil Quality methodological guide where farmers and scientists communicate through a commonly developed language and simple demonstrations on how to measure soil quality.
Recuperation of degraded soils involves organic matter additions by abundant root systems of pasture (*Brachiaria dictyoneura*) and fallow (*Sesbania sesban*) species.

PE-2: Overcoming soil degradation through productivity enhancement

Annual Report 2001

2001
UNIDAD DE INFORMACION Y DOCUMENTACION

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Acknowledgement

The members of the soils research team wish to acknowledge the efforts of Dr. Richard J. Thomas in promoting soils research at CIAT as Manager of Soils Research Project and in the CGIAR through his leadership of the Soil Water and Nutrient Management Systemwide Program convened by CIAT. Richard has led and championed soils research with wide range of partners resulting in a sound body of excellent science. He has a clear vision of a balanced program of strategic and applied research that produces useful tools - developed from sound science - that help our clients to improve their livelihoods. The fruitful work of the soils research team and partners under his leadership on "Sustainable Land Management of Acid Soil Savannas" has been recently selected as the winner of the 2001 CGIAR's Excellence in Science Award in the Outstanding Partnership Award category. This award re-affirms his belief of the role of the CGIAR in being centers of excellence and a recognition of the need to reach outside the CGIAR to improve the efficiency of research. Not only the staff of the Soils Research Project of CIAT, but also all beneficiaries of CIAT's research outputs must be indebted to Richard's inspired leadership.

The Soils Research Team.

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PROJECT OVERVIEW

Objective: To identify strategic principles, concepts and methods for protecting and improving soil quality through the efficient and sustainable use of soil, water and nutrient resources in crop-livestock systems.

Outputs: Crop/forage components characterized for compatibility in systems and resource use efficiency in acid soils; methodologies and indicators for assessing soils quality; incorporating local knowledge; strategic principles for managing crop residues and green manures, soil biota, and soil erosion; process-oriented simulation models calibrated and validated to overcome site specificity; strategies for confronting soil degradation disseminated to NARS and NGOs (Table 1A).

Gains: Guidelines for selecting productive and resource use efficient crop/forage components and combinations; guidelines for managing nutrients, crop residues and green manures, and controlling erosion and improving soil structure; a diagnostic kit of soil quality indicators to assist farmers as well as extension and NGO personnel in assessing soil health and making resource management decisions; a decision support system for resource conservation and productivity enhancement; strengthened NARS capacity in strategic research on soil, water and nutrient management.

Milestones:

2000 Nutrient cycles and budgets and soil organic matter accumulation in crop rotation and pasture systems quantified; management guidelines for minimizing erosion and increasing productivity defined for hillsides; strategies for managing soil fauna identified; plant attributes identified for greater nutrient acquisition and use efficiency.

2001 Indicators of soil fertility, biological health, and physical quality identified for hillside and savanna agroecosystems; demonstrated benefits of crop rotations and pasture systems on soil quality and productivity; guidelines for maintaining soil structure produced.

2002 List of soil quality indicators available to NAS to monitor land degradation. Decision making tools available for managing soil erosion, nutrient depletion, and maintenance of an arable layer. Erosion and nutrient depletion risk assessment maps available. Correlations established between local soil quality indicators and scientific measurements.

Users: Principally crop and livestock producers and agriculture extensionists (advisors) in acid soil agroecosystems of LAC. Relevant also to farmers on similar soils in tropical Africa and Asia.

Collaborators: NARS/NGO's: CORPOICA; EMBRAPA; CIPASLA; CETEC; CIPAV

Universities: Nacional, del Llano (Colombia), UNA (Nicaragua), UCA (Nicaragua), ENA (Honduras), E.A.P. Zamorano (Honduras), Paris, Rouen (France), Hohenheim, Freiburg, Gottingen (Germany), SLU (Sweden), AUN (Norway), Cornell, Michigan State, Montana State, Ohio State (USA), ETH (Switzerland.).
International Research Institutes: IFDC (USA); IRD, CIRAD (France); CATIE (Costa Rica), CIP (Ecuador), FAO-Lempira Sur (Honduras), IIAG-CSIC Galicia (Spain).

CG system linkages: Enhancement & breeding - 15%; Crop Production Systems - 50%; Biodiversity - 15%; Stengthening NARS- 20%; Co-convenor Systemwide Program on soil-water-nutrient management (SWNM) and lead institute for the Integrated Soil Management (MIS) consortium.

CIAT Project linkages: Diversity in systems of rhizobia and mycorrhizae populations (SB-1), acid soil adapted components received and adaptive attributes identified for compatibility in systems (IP-1 to IP-5), simultaneous evaluation of multipurpose legume to improve soil and feed quality (IP-5), combination of Integrated Soil Fertility Management and Integrated Pest Management research approaches (IP-1), strategies to mitigate soil degradation (PE-3 to PE-5), to make soil conserving systems profitable (SN-1) and to strengthen NARS via participation (SN-2).

Financing plan: 60% unrestricted core, 40% restricted core .

Table 1A. Project work breakdown structure

Project title: Overcoming soil degradation through productivity enhancement

Purpose
To identify strategic principles, concepts and methods for protecting and improving soil quality through the efficient and sustainable use of soil, water and nutrient resources in crop-livestock systems

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Output 1 Soil, water and nutrient management constraints assessed and plant components characterized for improved production and resource conservation	***Output 2*** Strategies developed to protect and improve soil quality	**Output 3** Improved decision making for combating soil degradation and greater agricultural productivity	**Output 4** Institutional capacity for SWNM enhanced through the dissemination of concepts, methods, tools and training
1.1 Determine and characterize edaphic and climatic constraints. 1.2 Survey native plants and their potential use as biofertilizers. 1.3 Survey land users for soil and crop management knowledge 1.4 Characterize plant components for production potential, nutrient use efficiency (phosphorus and nitrogen) and improvement of soil physical conditions. 1.5 Determine rooting strategies of crop, forage and improved fallow components 1.6 Test compatibility of plant components in different systems (including farmer participation)	2.1 Develop a concept of, and strategies for, the establishment and maintenance of an "arable layer" for sustainable production. 2.2 Develop strategies for nutrient acquisition and replenishment via efficient nutrient cycling and integrated nutrient management. 2.3 Develop appropriate and diverse strategies for controlling soil erosion. 2.4 Develop strategies to maximize C sequestration in soils and minimize emissions of green house gases. 2.5 Characterize soil biodiversity and develop strategies to manage beneficial soil biological processes.	3.1 Identify dynamic soil properties and test their suitability as soil quality indicators 3.2 Develop and test a soil quality monitoring system (including indigenous knowledge) for use by farmers and extensionists in hillsides and savannas. 3.3 Compile data bases to feed into simulation models and decision support systems 3.4 Develop decision support tools for improved soil, water and crop management. 3.5 Develop and test a decision support system for organic materials. 3.6 Develop soil degradation risk assessment maps.	4.1 Organize and coordinate field days and workshops 4.2 Prepare guidelines/pamphlets on soil, water and nutrient Management concepts 4.3 Promote and participate in specialized training courses, prepare training materials 4.4 Publish research results in refereed journals and other publications 4.5 Supervise postdoctoral research, graduate and undergraduate theses 4.6 Foster research linkages with institutions in the region and advanced research organizations

Table 1B. Project: PE-2 - Logframe 2001

Narrative Summary	Measurable Indicators	Means of Verification	Important Assumptions
Goal Overcoming soil degradation through productivity enhancement and resource conservation	• Yields in farmers fields increased. • Land degradation halted/reduced. • Yields per unit area and input increased. • Land use changed	• Farmers surveys. • Regional/national production statistics. • Land use surveys (satellite imagery, rapid rrural appraisal) .	• Land survey data available • Farmers adopt new technologies Socioeconomic conditions are favorable for achieving impact

Purpose
 	
Strategic principles, concepts and methods for protecting and improving soil quality through the efficient and sustainable use of soil, water and nutrient resources in crop-livestock systems, developed and disseminated to clients.
	• Technologies for soil improvement/ management developed.
	• Limiting soil-plant-water processes identified.
	  • Compatible plant components identified for low fertile soils in crop-livestock systems.
	  • Guidelines, manuals and training materials for soil management produced.
		• Scientific publications
		• Soil and crop management guidelines published
		• Decision support systems developed
		• Annual reports
			• Economic analysis of options available
			• Effective linkages within CIAT and partners in the region
			• Socio-economic inputs available from other projects (e.g., PE-3, BP-1)
			• Field sites accessible

Outputs 1. Soil, water and nutrient management constraints assessed and plant components characterized for improved production and resource conservation.	• Soil and water management constraints identified with farmer and NARS participation. • Questionnaire produced and farmers interviewed in at least two agroecosystems. • Plant components identified and matched to edaphic/climatic constraints.	• Annual Report • Reviews published • Document of synthesized results • Detailed tables published in Annual Report.	• Literature available • Farmers continue to participate. • Projects SN-2, PE-3 and PE-5 actively participate. • Collaboration of Project PE-4 and NARS. • At least one assistant is assigned to the activity in Honduras/Nicaragua • SN-3 (IPRA) plans work with EB (BID poverty project).
2. Strategies developed to protect and improve soil quality.	• Recommendations of soil and crop management practices for efficient nutrient use and erosion control in systems. • Soil properties, management practices and plant components that affect N capture and fluxes identified. • Strategy identified for minimizing global warming potential in the savannas • Strategy identified for establishing and maintaining beneficial soil macrofauna populations in savannas.	• Project reports/ publications. • Management guidelines published • Document of synthesized results	• Sufficient operational funds available for chemical analyses. • Continuity of long-term experiments. • Modeling expertise available from partners e.g. Michigan State Univ. USA, IFPRI,CSIRO • Soil biology expertise from ORSTOM/Univ. of Paris available.

Narrative Summary	Measurable Indicators	Means of Verification	Important Assumptions
3. Improved decision making for combating soil degradation and greater agricultural productivity.	• *List of Soil Quality indicators prepared* and available to monitor degradation in reference sites. • Tools designed for estimating soil erosion and training manual written. • Decision-making tool for soil and water management produced. • Map of risk assessment of soil degradation (erosion, soil nutrients) for hillsides and savannas produced. • Decision making tools for use of organic materials produced. • Decision tree to create/maintain an arable layer produced. • Correlations established between local soil quality indicators and objective measurements. • Improved crop and soil models developed and validated	• Annual Reports/ publications. • Training manual for use with tools • Kit available to farmers and NARS. • Maps published. • Pamphlet published detailing decision tree.	• Collaboration from partners. • Information from questionnaires synthesized comparisons made with available PE-3 results. • Collaboration with PE-3 on soil erosion in CA. • Collaboration with SN-2, PE-4, PE-3, TSBF and SWNM Program. • Collaboration with MW (UNEP) on land quality indicators at reference sites. • Collaboration with PE-4.
4. Institutional capacity for SWNM enhanced through the dissemination of concepts, methods, tools and training.	• At least 9 undergraduate, 3 Master's and 2 Ph.D. theses submitted. • Workshop held on soil physics. • Workshop on C sequestration held. • At least three projects with partners submitted to donors. • ELABS initiated • At least 10 field days and four training workshops held on local soil quality indicators	• Theses available in library. • Reprints available. • ELAFIS workshop report • Workshop report on C sequestration. • Project documents	• Continuing interest/participation of NARS and ARO partners. • Continued support for collaborative activities e.g. systemwide SWNM program.

EXECUTIVE SUMMARY

The objective of the Soils Project (PE-2) continues to be the identification of strategic principles, concepts and methods for protecting and improving soil quality through the efficient and sustainable use of soil, water and nutrient resources in crop-livestock systems. To achieve this objective, we emphasize assessment of soil, water and nutrient management constraints; characterization of plant components for improved production and resource characterization; development of concepts and strategies to improve soil quality and health; development of decision support systems for combating soil degradation and greater agricultural productivity; and dissemination of concepts methods, tools and training to enhance institutional capacity for soil, water and nutrient management.

This year the responsibility of Project Management was transferred from Dr. R.J.Thomas to Dr. E. Barrios.

This year we have increased our efforts in Central American Hillsides in close collaboration with PE-3, IP-5 and PE-4 projects of CIAT. We have also faced problems of restricted access to our field sites in Colombia. We have addressed this problem, in part, with an approach to decentralize our research effort by out-posting three research staff to Nicaragua. Out-posted staff include one shared (PE-2, IP-5, PE-3) post-doctoral fellow as well as two research assistants carrying out their PhD and MSc theses in collaboration with IRD and CATIE respectively. We have also increased our team efforts to synthesize the work on the long-term experiments in the Colombian Llanos. This will result in a publication with partners on land use options and soil management recommendations for the Altillanura region of the Llanos of Colombia.

We also made special efforts to increase integration with other CIAT projects – PE-3 (hillsides), IP-5 (forages) and PE-4 (land management) – combining soils and production systems research at the plot, farm and landscape scales, developing better soil and crop management options and decision support tools for savanna and hillside farmers. This integration has been catalyzed by additional shared activities and positions.

Increased efforts in Africa are expected as we progressively move towards more integrated activities with the Tropical Soil Biology and Fertility Programme based in Nairobi, Kenya. This strategic alliance will also complement new joint activities with IP-1 (beans) on the application of molecular tools to study soil microbial biodiversity in our efforts to combine Integrated Soil Fertility Management (ISFM) and Integrated Pest Management (IPM) research approaches.

Main highlights of research progress in 2001

Output 1. Soil, water and nutrient management constraints assessed and plant components characterized for improved production and resource conservation

- Showed that the supply of both N and P limit corn yields at Central America reference sites.
- Showed that: (i) excessive application of chicken manure as an organic fertilizer on Andean volcanic ash soils leads to soil crusting and sealing by physical/chemical dispersion mechanisms and the interaction of physical and chemical characteristics; and ii) improper land use and fertilization practices can markedly reduce cassava root yields.
- Developed a method to predict precipitation (including intermittent drought) for seven consecutive days for soils of different texture.

- Surveyed land users in Colombia and Honduras for local knowledge about soils and their management and identified native plants as important indicators of soil quality related to modifiable soil properties.
- Showed that deep-rooted tropical pastures can enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocropping.
- Developed methodology to determine root distribution and abundance for stony soils predominant at Nicaraguan reference site.
- Showed that rooting depth and grain yield of maize could be markedly improved by direct drilling rather than chisel + direct drilling on plots planted from phase I of Culticore.
- Green manure evaluation sites established in 8 communities at the Nicaragua reference site. Communitity field days carried out and key informants identified. Participatory learning process initiated.

Output 2: Strategies developed to protect and improve soil quality

- Showed that the maize and green manure cropping systems were better than the grass alone pasture system at separating the effect of increased number of disc harrow passes on soil physical and chemical characteristics.
- Showed that organic P is involved in short term P dynamics in soils with low or no P fertilization.
- Showed that earthworm surface casts represent a significant source of easily available P to plant roots.
- Observed diet preference by *M. carimaguensis* for seeds from the soil seed bank and found considerable loss of viability of seeds in earthworm casts.
- Showed that biogenic physical structures produced by soil macrofauna on the soil surface can be related to their ecological function in the soil.

Output 3: Improved decision making for combating soil degradation and greater agricultural productivity

- Showed that oxalate extracted P or the combined pools of resin + bicarbonate-P of the Hedley fractionation scheme may be better suited to determine soil P availability in oxisols that receive strategic application of lower amounts of fertilizer P.
- Showed that differences in plant quality attributes could be more important than sample preparation in determining the extent and rate of decomposition of plant material in the soil and rumen.
- Developed a methodological guide, through a participatory approach, to identify and classify local indicators of soil quality related to permanent and modifiable soil properties. This guide is being used in Latin America/Caribbean (Colombia, Honduras, Nicaragua, Peru, Venezuela, Dominican Republic) and Africa (Uganda, Tanzania).
- Showed that distribution and abundance of soil macrofauna appears to be related to local land classification units.
- Created a database for past and present field experiments in savannas and hillsides agroecosystems to facilitate further analysis and use by PE-2 and other CIAT projects.
- Developed soil maps for the municipality of Puerto Lopez, Colombia, using a geo-referenced soil data bank (GEOSOIL), to facilitate land-use planning and site-specific soil management recommendations.

Output 4. Institutional capacity for SWNM enhanced through the determination of concepts, methods, tools and training

- 9 field days organized, one training course held in Africa, and a workshop held in Colombia.
- 36 students are associated with the project (10 Ph.D. theses).
- Active collaboration is maintained with 87 partner institutions ranging from NARS, NGO's, Universities and other IARC's.
- The project has access to funds from 7 special projects
- 28 articles for refereed journals have been published or are in press, 90% of which are co-authored with other institutional partners.

Progress towards achieving output milestones of the project logframe 2001

Output 1: Soil, water and nutrient management constraints assessed and system components characterized for improved production and resource conservation

- **Soil and water management constraints identified with farmer and NARS participation**

Soils at our Central America reference sites in Honduras and Nicaragua appeared to be both N and P limited thus responding best to the combined application of N and P. One Post-Doctoral Fellow will start studies in Nicaragua on "farm resource and nutrient flows" in the Wibuse watershed at the San Dionisio Reference Site in Nicaragua.

In Cauca region of Colombia, we have made progress in identification of some biophysical mechanisms that are related to crust formation. We found that excessive application of chicken manure as an organic fertilizer on Andean volcanic ash soils leads to soil crusting and sealing due to physical dispersion, chemical dispersion, and the interaction of soil physical and chemical characteristics. We also demonstrated that improper land use and fertilization practices can markedly diminish cassava root yields.

For the Llanos of Colombia, we have succeeded in applying a method to predict precipitation (including intermittent droughts) for seven consecutive days for soils of different texture for the Altillanura region of the Orinoco river basin based on the behavior of rainfall data of Carimagua and La Libertad. This methodology can be used in other tropical regions and will permit a better planning of agricultural land use and farm operations.

- ***Questionnaire produced and farmers interviewed in at least two agroecosystems***

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 sustainable management of tropical soils. Case studies show that there is a consistent rational basis to the use of local indicators of soil quality. Biological indicators (native flora and soil fauna) were shown to be important local indicators of soil quality related to soil management. 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 to cope with environmental change. It is 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.

- ***Plant components identified and matched to edaphic/climatic conditions***

Field studies conducted at Carimagua and Matazul (Savannas) contributed to define lime and nutrient requirements for acid soil tolerant varieties of rice, maize, cowpea and soybeans in rotational production systems on heavy-textured Oxisols. Field and glasshouse studies on crop and forage components indicated that forage legumes are more efficient in acquiring P per unit root length. Comparative studies of a forage grass (*Brachiaria dictyoneura* CIAT 6133) and a legume (*Arachis pintoi* CIAT 17434) demonstrated that the legume could acquire P from relatively less available P forms from oxisols of Colombia.

Field research carried out at Carimagua showed that both native savanna and introduced pastures develop deep root systems compared to field crops such as maize. Studies on root distribution of maize showed that most of the roots are in top 20 cm of soil depth. Application of higher amounts of lime did not improve subsoil-rooting ability of maize but contributed to greater nutrient acquisition. Cultivation with disc harrow (8 passes) markedly improved maize growth and nutrient acquisition. We made progress in demonstrating the importance of deep-rooted tropical pastures to enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocropping. The concepts and strategies developed from this work are relevant to different areas of the Llanos for improving soil quality and agricultural productivity.

Field studies in Cauca (Hillsides) on root and shoot attributes of crop and forage components has identified elephant grass as an effective fodder grass for sloping lands which can minimize soil loss and also could acquire greater amounts of N, P and K from low fertility acid soil due to its abundant fine root production. Studies on rooting strategies of naturalized and introduced pastures indicated that naturalized pasture is adapted to low soil fertility conditions due to its ability to produce finer root system. Inter-cropping of Cassava with cover legumes reduced soil loss and improved nutrient acquisition by cassava. The impact of improved fallow species on subsequent maize cropping is being evaluated.

Output 2: Strategies developed to protect and improve soil quality

- ***Recommendations of soil and crop management practices for efficient nutrient use and erosion control in systems***

Agricultural land-use systems replacing native savanna on oxisols affect the partitioning of P among inorganic and organic P fractions. Indicators of organic P mineralization suggest that organic P is more important for delivering available P in improved grass-legume pastures than in continuously cropped soils. In cultivated soils, much higher P fertilizer doses significantly increase available inorganic P contents with lesser impact on organic P pool sizes. Studies indicated that the amount and turnover of P that is held in the soil microbial biomass could increase when native savanna is replaced by improved pasture while it could diminish when soils are cultivated and cropped continuously.

The important activity of the earthworm species *Martiodrilus carimaguensis* in natural and introduced pastures involving incorporation of P from organic sources into soil P pools, increasing labile P pools, and improving P cycling was demonstrated in short-term studies conducted in the Llanos. The ecological significance of earthworms in P cycling in the native savanna and the introduced pasture was related to superior quality of litter from improved pasture. Enhancement of biological activity in pastures was reflected by larger population sizes of *M. carimaguensis* as well as higher microbial biomass P.

Therefore, strategic application of lower amounts of P fertilizer to crops and planting of grass-legume pastures are recommended to promote P cycling and efficient use of P inputs in low P oxisols of tropical savannas.

Studies on the impact of improved fallows in Cauca (Hillsides) indicated that *Tithonia diversifolia* improves soil P availability in P-fixing soils of tropical hillsides.

- ***Soil properties, management practices and plant components that affect N capture and fluxes identified***

We found that use of disc harrow could improve N uptake by maize and green manure crops but not grass alone pasture system. This year, our efforts to evaluate the impact of no-till systems on plots of Culticore phase I, resulted in demonstrating that direct drilling or chisel + direct drilling treatments are better suited to plots that were under crop-pasture rotation than under monocropping or cereal-legume rotation. We also found that the rooting depth and grain yield of maize could be improved markedly by direct drilling rather than chisel + direct drilling on plots planted from phase I of Culticore. Data on the impact of no-till systems on N capture and fluxes are being analyzed.

- ***Strategy identified for minimizing global warming potential in the savannas***

Three papers from the two Ph.D. theses reported last year have been submitted for publication.

- ***Strategy identified for establishing and maintaining beneficial soil macrofauna populations in savannas***

We have achieved substantial progress toward this milestone and it is summarized in a book entitled "Nature's Plow: Soil Macroinvertebrate Communities in the Neotropical Savannas of Colombia". This book includes 24 refereed research publications. It is already published in English and the Spanish edition is in press. This year we observed diet preference by *M. carimaguensis* for seeds from the soil seed bank and found considerable loss of viability of seeds in earthworm casts. We also showed that biogenic physical structures produced by soil macrofauna could be related to their ecological function in the soil. These structures can modulate the availability or accessibility of one or more resources used by other soil organisms.

Output 3: Improved decision making for combating soil degradation and greater agricultural productivity

- ***List of soil quality indicators prepared and available to monitor degradation in reference sites***

Field studies were conducted to quantify the residual effectiveness of P fertilizer inputs in cereal-grain legume rotations (Maize-soybean or rice-cowpea) in terms of both crop growth response and labile P pool sizes in an oxisol in the Llanos of Colombia. The results showed that soluble P applications to oxisols of Colombia remain available for periods of time which are much longer than expected for "high P-fixing"soils, such as the oxisols of Brazilian Cerrados. These studies also showed that Bray-II could be a useful method to estimate P availability in Colombian savanna Oxisols. Recent work indicated that microorganisms can take up, within a few days, high quantities of phosphate from the soil solution; and an increase in microbially bound phosphorus could be an indicator of improved soil fertility for a low P Colombian Oxisol. Lists of soil quality indicators have been published and are being incorporated into guides for use by stakeholders with PE-3.

- ***Tools designed for estimating soil erosion and training manual written***

A student thesis on the use of a newly designed mini-rainfall simulator was completed this year. A training manual (on the application of the universal soil loss equation) is being prepared for soils of the Andean region based on research carried out in Cauca (Mondomo and S. Quilichao), Colombia.

- ***Decision-making tool for soil and water management produced***

A decision support tool for soil use and management (based on soil slope, texture and depth) has been developed for use in the Colombian Llanos. The NuMaSS (nutrient management decision support system) was successfully tested with data from the long-term experiments in the Llanos. Application of this decision support tool indicated that in the Llanos of Colombia upland rice production is considerably more profitable than either maize or cowpea given the yields obtained and the costs of fertilizer and the price of grain. An alternative strategy to cropping low P Oxisols was developed that involves strategic application of lower amounts of P fertilizer to crops and planting of grass-legume pastures to promote P cycling and efficient use of P inputs.

- ***Map of risk assessment of soil degradation (erosion, soil nutrients) for hillsides and savannas produced.***

This year we made progress in using a georeferenced soil data bank (GEOSOIL) to develop maps based on specific properties of soils. These maps are useful for planning of land use and for developing site-specific recommendations for soil management for the municipality of Puerto Lopez in the Altillanura of Colombia.

- ***Decision making tools for use of organic materials produced.***

The decision tool prepared by a collaborating institute (TSBF in Africa) was tested in 2000 and details reported in project SW-2.

- ***Decision tree to create/maintain an arable layer produced***

A brochure on the strategies to develop an arable layer is in preparation.

- ***Correlations established between local soil quality indicators and objective measurements.***

Efforts on this milestone have resulted in a guide for soil quality indicators and a training module that brings technical and local knowledge of soil quality together. One publication is *in press* in **Geoderma** special issue on ethnopedology. A second training course was held in Africa and the Methodological Guide 'Local Indicators of Soil Quality. East Africa Edition' was published (with PE-3, SW-2).

- ***Improved crop and soil models developed and validated***

Data from long-term experiments in the Colombian Llanos on plant and soil phosphorus have been used by modellers working with the CERES, NuMaSS, PDSS2 and APSIM models.

Output 4: Institutional capacity for SWNM enhanced through the dissemination of concepts, methods, tools and training

- ***At least 9 undergraduate, three Master's and 2 Ph.D. theses submitted***

Three Ph.D. theses were successfully defended at University of Norway, ETH, Switzerland, and University of Paris I, respectively. Two M.Sc. theses were successfully defended at Universidad Nacional de Colombia and obtaining the 'meritorious' qualification. Six undergraduate theses were completed and one of them was recognized as 'meritorious' by the University of the Llanos. This year one of our Laboratory Technicians (Jesús H. Galvis) was chosen for the award of 'outstanding student' by the University of Santiago de Cali for his academic excellence.

- ***Workshop held on soil physics.***

A workshop was held in 1999 and was attended by 50 researchers and technicians from Latin America.

- ***Workshop on C sequestration held.***

A workshop was held in Brazil in October 2000 and the final project is pending.

- ***At least three projects with partners submitted to donors.***

Three new projects (BMZ-GTZ, EC, PRONATTA) received funding in 2001 and one concept note was submitted to BMZ.

- ***ELABS initiated***

Lack of funding has prevented advances in this area.

- ***At least 10 field days and four training workshops held on local soil quality indicators***

9 field days and one training workshop on soil quality indicators were held. Restrictions on staff travel and lack of personnel for training continues to hinder the progress in this area.

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Output 1. Soil, water and nutrient management constraints assessed and plant components characterized for improved production and resource conservation

Activity 1.1. Determine and characterize edaphic and climatic constraints

1.1.1 Assessing nutrient constraints for the intensification of agricultural production in hillsides of Central America

Highlight:

- Showed that the supply of both N and P limit corn yields at Central American reference sites

Purpose:

To determine whether N, P and K are limiting maize growth at the SOL sites of Honduras and Nicaragua.
To relate the limitation in N, P and K to topsoil properties.
To identify entry points for soil fertility research in the reference sites of Honduras and Nicaragua.

Rationale:

Hillside farmers are an important source of domestic food supply in many developing countries. Over 60% of the region's maize is grown on hillside plots, and a large proportion of all beans. Crop yields, however, are significantly lower than in lowlands. This reflects a combination of socioeconomic and biophysical constraints. Most of these hills have large predominantly poor and rural populations with limited access to capital and technology. On the other hand, many hillside soils are fragile - shallow, nutrient deficient and prone to soil and water losses. They require careful husbandry and active soil-building efforts to maintain or increase yields.

Increased agricultural productivity and profitability, together with the development or rehabilitation of the "natural capital", of poor hillside communities could contribute significantly to poverty alleviation.

The purpose of this work was to quantify the degree of response of corn to fertilization as an initial step to identify nutrient constraints and develop sound management strategies to improve soil fertility.

Materials and methods:

Study site: The present study was conducted in the SOL sites of Honduras (Luquigue) and Nicaragua (Wibuse). Luquigue is located at 15° 2' N and 87° 15' W and Wibuse at 12° 45' N and 85° 51' W.
Climate and soil characteristics: The average annual precipitation in the area of influence of the SOL-Luquigue is 1572 mm and in the area of influence of Wibuse is 1200 mm. The altitude of the two sites are 720 and 625 m.a.s.l respectively . However, their position in the landscape is different. The Luquigue site is in the lower part of the Tascalapa watershed and Wibuse in the higher part of the Rio Calico watershed. Soils in both sites are slightly acid with moderate contents of SOM and nutrients (Table 1). Soils in the Luquigue site have a loamy clay texture and are derived from sedimentary materials from the Cretaceous. The Wibuse site has a clayey texture soils derived from volcanic ashes from the Tertiary.

Experimental protocol: A limiting nutrient trial was set up in the two sites following the protocol developed by Buresh (1999). It consisted of an arrangement of N, P and K as follows: 1) control; 2) + 100 kg/ha N; 3) +100 kg/ha P; 4) +100 kg/ha N+100 kg/ha P; and 5) +100 kg/ha N+100 kg/ha P + 100 kg/ha K. Treatments were distributed in the field using a Complete Randomized Block Design with four reps. Nitrogen and potassium rates were applied as split applications in the row 20 and 40 days after corn planting. All P was applied at planting.

Table 1. Initial chemical properties found in the 0-15 cm topsoil of the sites selected for the experiment in the SOL in Luquigue, Honduras and Wibuse, Nicaragua.

Nutrient	SOL-Luquigue	SOL- Wibuse
PH	6.4	5.8
SOM (%)	5.0	5.8
N total (%)	0.2	0.3
P (ppm)	9.0	11
K (ppm)	61	12
Ca (ppm)	1960	5140
Mg (ppm)	695	1580
Fe (ppm)	80	23
Mn (ppm)	18	15
Cu (ppm)	1.8	2.2
Zn (ppm)	0.9	0.4
Mg/K	37	8.4

SOM = soil organic matter

Corn variety used in the Luquigue site was HB 104 and NB-6 in the SOL-Wibuse.
Plant parameters evaluated during the experiment were: 1) plant height and nutrient content at flowering time; 2) number and weight of cobs per plant and; 3) grain yield.

Results and Discussion:
There was a marked effect of fertilization on crop development at both sites. Plants were taller with the +N+P or N+P+K treatments as compared to the single applications of N or P (data not shown). Plants receiving only N showed symptoms of chlorosis with young leaves probably related to Mg deficiency.

Grain yields at SOL-Luquigue increased by two fold with either +N+P or +N+P+K application (Figure 1). The single application of P increased by 40% grain yields as compared to the control treatment while the N alone treatment reduced them by the same magnitude. These results shows the clear need for the combined application of N+P in order to improve corn productivity at this site.

Responses to fertilizer application in the SOL- Wibuse site were similar to those found in the Luquigue site. However, differences were not statistically significant due to high spatial variability in the experiment.

In spite of the relatively high contents of total N and moderate availability of P in the soils of the two sites corn responded markedly to N and P fertilizer applications. This result suggests that most of the inorganic fractions have been depleted during the process of land use intensification due to little use of inputs.

During the present year, the work has been expanded to a network of farm fields located at different positions in the watershed in order to confirm fertilizer responses at different altitudes, parent materials and land use history. Results will be reported next year.

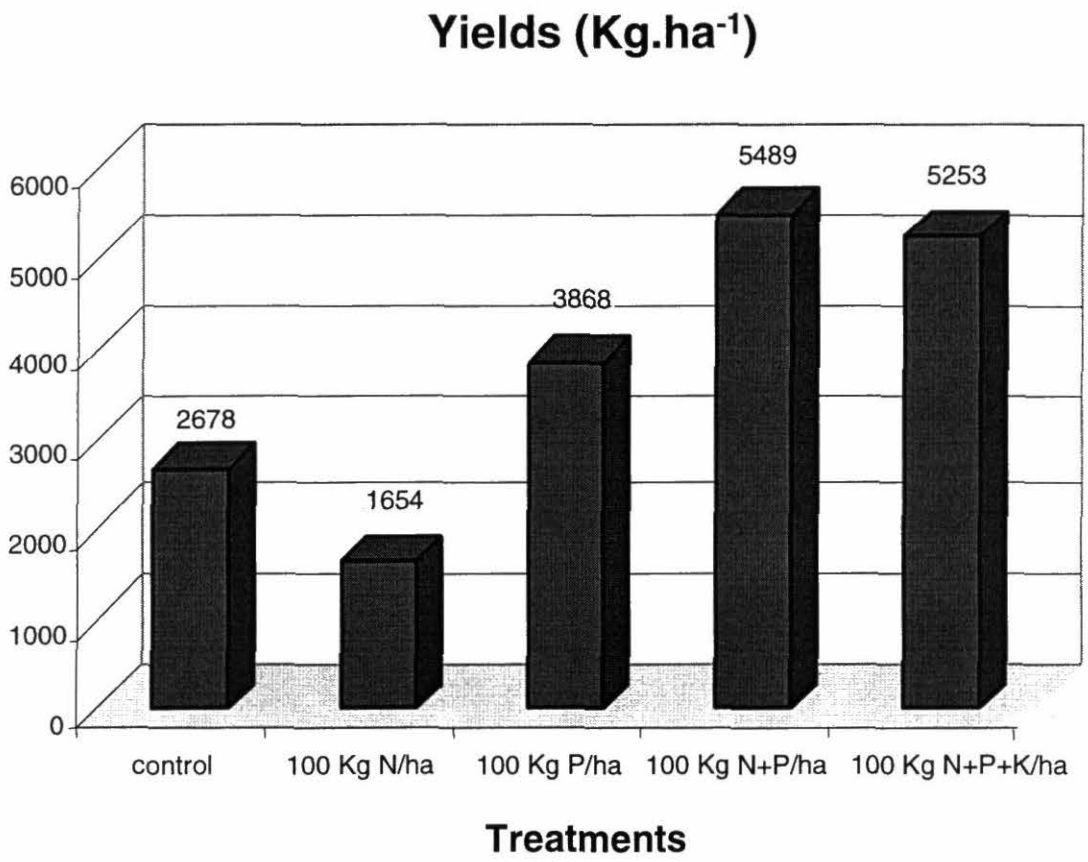

Figure 1. Maize response to N, P and K fertilizer applications at the SOL Luquigue site.

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Contributors:

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1.1.2 Characterization of the phenomenon of soil crusting and sealing in the Andean Hillsides of Colombia through evaluation of physical and chemical characteristics

Highlights:

- Showed that: (i) excessive application of chicken manure as an organic fertilizer on Andean volcanic ash soils leads to soil crusting and sealing by physical/chemical dispersion mechanisms and the interaction of physical and chemical characteristics; and (ii) improper land use and fertilization practices can markedly reduce cassava root yields.

Purpose:

To characterize the phenomenon of crusting and soil surface sealing on Andean volcanic ash soils, and to develop land use and soil management recommendations for endangered areas.

Rationale:

Land resources throughout the world are being increasingly destroyed. Specifically, an increase in soil destruction is mainly due to soil degradation through water and wind erosion, with additional physical and chemical deterioration. Tropical and subtropical hillside areas and steep slopes are most affected, even more than soils in the temperate zone, because of intensive climate and poor soils. These soils face extreme risk of becoming completely depleted.

The Andes of South America is an area vulnerable to soil erosion. The local political situation coupled with socioeconomic constraints encourages unsustainable land use and fertilizer management. These practices can significantly change soil properties. This change of physical and chemical stability decreases soil fertility and productivity to the point that farming is severely affected. Especially rural farmers who produce their food on steep slopes are most affected by this phenomenon, which results in their loss of income and livelihood.

Soils, partly influenced by volcanic ashes in the Andean region have good physical properties with regard to root penetration and soil structure. But improper land use and fertilizer management can lead to complete change in soil structure, building up soil crusting and sealing and finally increasing erosion and surface runoff through significantly reduced water infiltration. While the reasons for soil crusting and sealing on volcanic ash soils are not fully understood, promising results strengthen the hypothesis that an interaction between physical and chemical characteristics leads to this type of soil degradation. A better understanding of the processes influencing soil surface degradation will contribute to a more comprehensive view of soil erosion and its primary factors. This will help to make future recommendations for sustainable land use in this region.

The overall aim of this work is to investigate and characterize the phenomenon of soil crusting and sealing on volcanically influenced soils of the Andean region. This work is supported by special project funds from the DAAD/Germany and the Eiselen Foundation/Germany as well as 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 were established on an amorphous, isohyperthermic, oxic Dystropept (Inceptisol). 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, maximum intensity of rain up to 27.5 mm in 5 minutes and a mean annual temperature of 23.8°C.

The measurements on soil crusting were carried out on 27 Standard Erosion Experimental Plots (Wischmeyer Plots) that were originally designed by the soil conservation team from the University of

Hohenheim as completely randomized block in three repetitions. These plots have been used since 1986. Treatment history of the last eight years is presented in Table 2.

To the best of our knowledge, the research area represents the only integrated erosion demonstration and elaboration site in Latin America. The main advantage of this site is being monitored for the extent of soil erosion processes for the past 16 years. Thus any changes in soil structure resulting from this long period of cultivation, conservation and depletion can be easily investigated. Cassava (CIAT 383) was used as the main crop in different treatments to evaluate the impact of land use and fertilization.

Treatments: The treatments imposed since December 2000 are described in Table 3. Plots were limed before planting cassava with 500kg/ha dolomitic lime and chemical fertilized plots received 300 kg/ha mineral fertilizer (10N, 30P, 10K). Chicken manure from local poultry farms has been used. It had the following nutrient composition (% : N 1.8, P 2.38, K 2.87, Ca 10.58, Mg 0.64; ppm: Fe 2538, Mn 422).
Physical parameters: Ongoing research that began in 1999 is continued in 2001. Measurements included resistance to penetration, shear strength, rate of water infiltration, aggregate distribution and stability, texture, turbidimetrie, and percolation resistance. A Pocket Penetrometer (Model DIK-5560) was used for penetrometer measurements. Soil crusting and changes in soil surface hardening could be tested directly in the field. To analyze the shear strength a Hand Vane Tester (Model EL26-3345) was used in the field.

Chemical parameters: In addition to physical analysis, special emphasis was placed on analyzing the chemical properties of the soil. Preliminary tests showed a high correlation between electrical conductivity (EC) and soil hardening. Thus sub samples of each plot were analyzed for water soluble levels of K, Ca, Mg and Na by wet extraction. In addition to water soluble nutrients, exchangeable levels of K, Ca, Mg, Mn, Al and Fe were also measured. Finally the wet extract was used for EC measurements. Special attention was paid to EC because of high correlations between EC and several nutrients, penetration resistance and shear strength.

Infiltration: Rate of water infiltration was measured in April 2001 using a minisimulator. A fixed soil area (32.5 cm x 40 cm) was subjected to rain by a defined rain intensity class of 95 mm/h (deviation 5%) and surface run-off was measured. Infiltration was calculated through the difference between amount of rain and runoff.

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

Table 2. History of treatments in Santander de Quilichao.

Treatment	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 oF4(V)	Maize oF4(V)	Cassava oF4(V)	Cowpea oF4(V)	Maize oF4(V)	Cassava oF4(V)	Cassava oF4(V)
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

Table 3. Treatments of 27 Experimental Plots in Santander de Quilichao in 2001.

Treatment	Plots			*Cultivation in-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, min. 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
(8) Cassava rotation (*Brachiaria decumbens* + *Centrosema macrocarpum* in 2001)	8	14	18	Rototiller, min. fertilizer
(9) Cassava intensive tillage	28	29	30	Intensive Rototiller, min. fertilizer

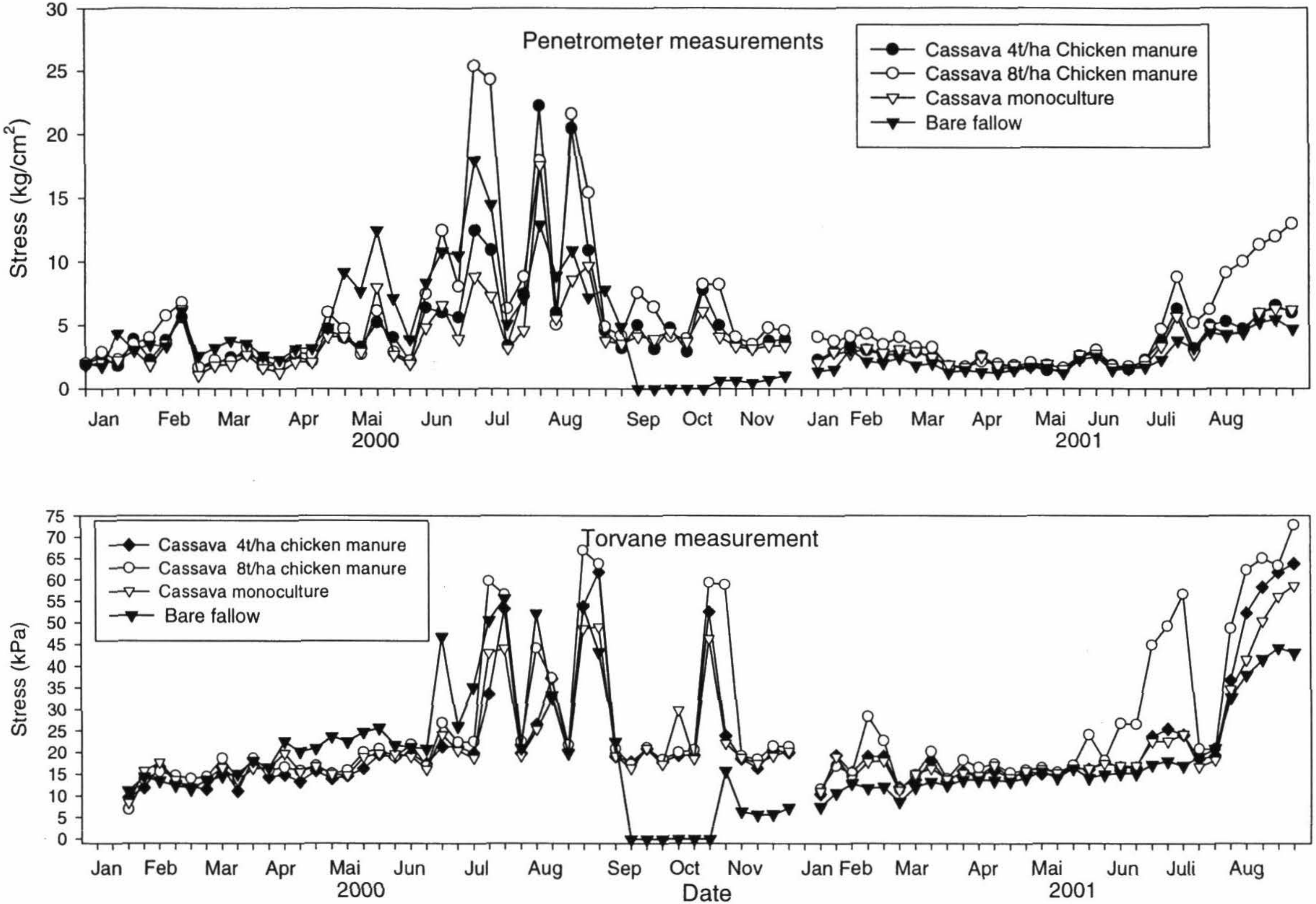
Results and Discussion:

Penetrometer and Torvane measurements: Throughout the entire measurement period (19 months) the Cassava minimum tillage treatment had the highest penetration resistance and shear strength. Untilled soil allows stable aggregates to build up, changing the penetration resistance over time. As already described in the PE-2 Annual Report (2000), soil hardening in Cassava minimum tillage treatment had no influence on water infiltration. In Cassava rotation plots, no strong hardening process could be observed in 2000 when Cassava had been cultivated. In 2001, Cassava was replaced by *Brachiaria decumbens* and *Centrosema macrocarpum*. This replacement lead to higher penetration resistance and shear strength, due to soil compaction.

Results of Penetrometer and Torvane measurements on soil structural changes influenced by chicken manuring are presented in Figures 2 and 3. Two general differences were noticed for the time period after seedbed preparation, one with relatively wet soil conditions (Jan-Jun 2000) and another with very dry period (July-Oct 2000). These seasonal changes had a major influence on both penetration resistance and shear strength. In wet soil conditions no marked hardening process could be noticed. In dry season an increase of soil hardening was observed. Treatments with chicken manure notably turned into hardsetting soils, whereas Cassava 8t/ha chicken manure exceeded to Cassava 4t/ha chicken manure. Cassava monoculture and Bare fallow, which were not fertilized, showed lower penetration values and shear strength. A previously observed change into a single grain structure in these treatments became more obvious. At the beginning of September 2000, Bare plots had to be tilled to maintain a uniform Bare fallow status.

In 2001 similar results were observed. As soon as the soil dried in the main dry period (Jul-Oct) chicken manure plots turned from soft to hard.

Chemical Analysis: Results of chemical analysis are presented in Tables 4 and 5. Within the exchangeable nutrients the significantly highest concentrations of K were found in Cassava minimum tillage treatment, followed by chicken manure 8t/ha and 4t/ha. Significantly lowest concentrations of K values were observed in Bare fallow, Cassava monoculture and Cassava rotation. Similar results were observed with exchangeable Ca, Mg and Mn whereas Cassava 8/t/ha chicken manure had very low Ca concentrations and Cassava rotation had relatively higher Ca content. Minimum tillage treatment had significantly lower exchangeable Al and Fe while Bare fallow had the significantly greater Al content. Cassava rotation and Bare fallow showed greater levels of Fe content.



Figures 2 and 3. Effects of chicken manure on penetration resistance and shear strength, Santander de Quilichao, 1/2000-8/2001

Table 4. Effect of different treatments on exchangeable K, Ca, Mg. Al, Fe and Mn, Santander de Quilichao, Feb 2001

Soil depth (cm)	Treatments	Exchangeable Nutrients					
		K	Ca	Mg	Al	Fe	Mn
		------------ cmol kg^{-1} ------------			------------ mg kg^{-1} ------------		
0-5	Bare fallow	0.08 a	0.09 a	0.03 a	1.48 c	17.24 b	1.27 a
0-5	Cassava 4t/ha chicken manure	0.29 c	2.17 d	0.69 c	0.09 a	10.56 a	8.59 c
0-5	Cassava monoculture	0.16 b	1.04 b	0.38 b	0.55 b	13.00 a	5.33 b
0-5	Cassava minimum tillage	0.42 d	3.29 e	0.92 d	0.07 a	9.53 a	8.89 c
0-5	Cassava 8 t/ha chicken manure	0.35 cd	1.30 bc	0.45 b	0.54 b	12.79 a	6.75 b
0-5	Cassava rotation	0.17 b	1.63 c	0.37 b	0.46 b	17.46 b	6.47 b

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

Water soluble K levels were greater with Cassava minimum tillage followed by 8 t/ha chicken manure, 4 t/ha chicken manure, Cassava Rotation, Cassava Monoculture and Bare fallow (Table 5). Similar results were obtained for Ca, Mg and Na. Only Cassava rotation had Ca and Na values as high as Cassava 8 t/ha Chicken manure. Significantly greater EC values (0.36 mS) were observed with Cassava minimum tillage followed by Cassava 8 t/ha, Cassava rotation and Cassava 4 t/ha. Lower values of EC were observed with Cassava monoculture and Bare fallow (0.11 mS).

Table 5. Effect of different treatments on water soluble K, Ca, Mg, Na and electrical conductivity, Santander de Quilichao, Feb 20001.

Soil depth (cm)	Treatment	Water soluble nutrients				Electric conductivity EC
		K	Ca	Mg	Na	
		------------------ mg kg^{-1} ------------------				------- mS ------
0-5	Bare fallow	1.82 a	3.31 a	0.89 a	4.86 a	0.11 a
0-5	Cassava 4 t/ha chicken manure	4.45 b	12.10 bc	4.07 c	5.46 ab	0.21 b
0-5	Cassava monoculture	2.28 a	7.16 ab	2.24 ab	5.32 ab	0.14 a
0-5	Cassava minimum tillage	8.13 c	26.51 e	7.76 e	7.68 d	0.36 c
0-5	Cassava 8 t/ha chicken manure	7.05 c	13.04 bc	4.14 d	6.22 bc	0.24 b
0-5	Cassava rotation	2.92 ab	16.47 d	3.48 b	6.48 c	0.23 b

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

A closer relationship was observed between electric conductivity (EC) and some of the above mentioned nutrients. Results of these relationships are presented in Figure 4. The highest correlation was found between EC and water soluble Ca and Mg. Correlations between EC and soluble K and Na were lower. In addition, positive correlations between EC and exchangeable Ca, K, Mg and Mn were found. Exchangeable Al and Fe had no correlation with EC.

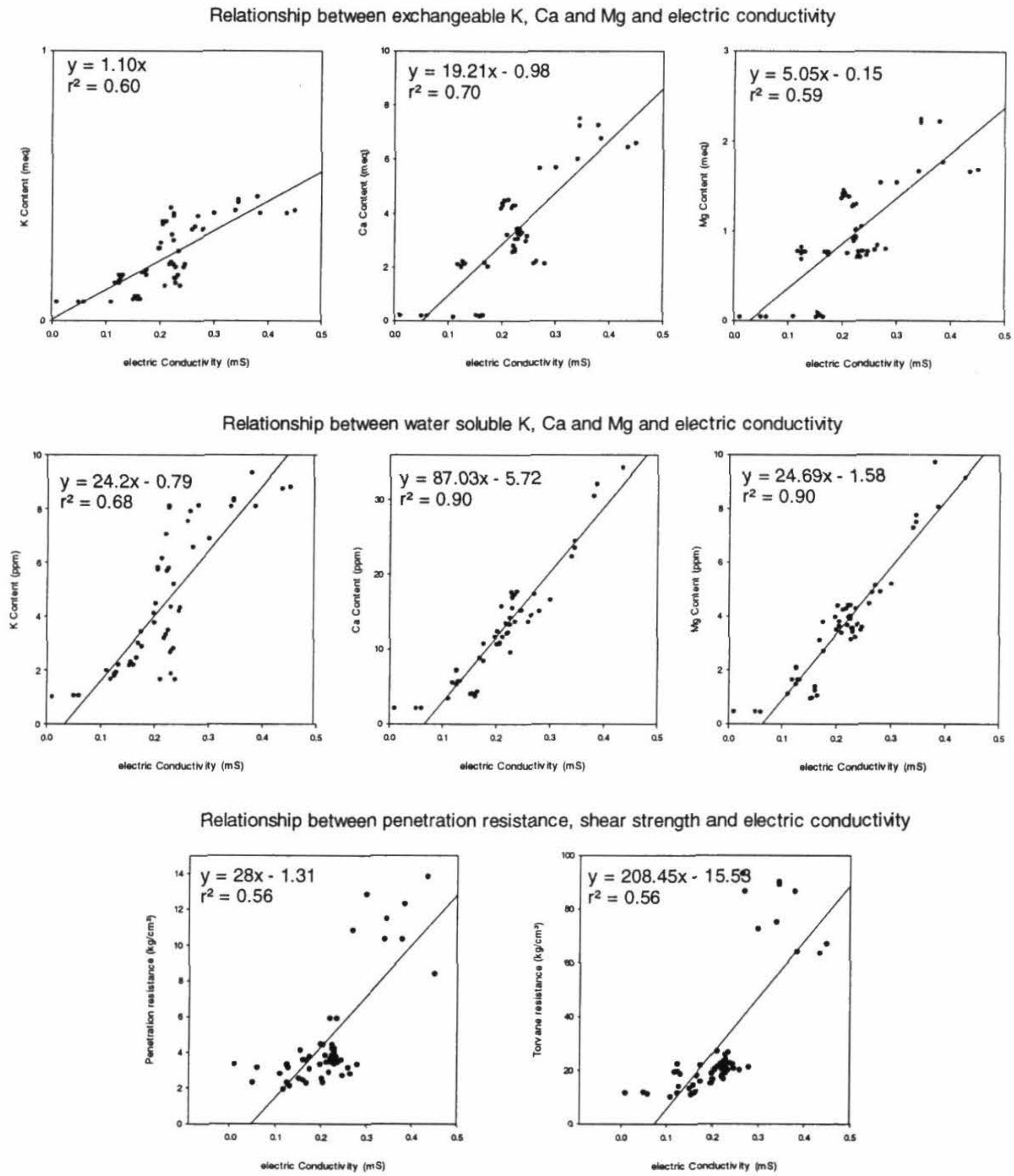


Figure 4. Relationship between electrical conductivity and other soil characteristics (exchangeable K, Ca, Mg, soluble K, Ca, Mg, penetration resistance and shear strength), Santander de Quilichao, Feb 2001.

Correlation between EC and the above mentioned stability factors, penetration resistance and shear strength were of great interest. It was revealed that correlations between EC and these two factors were identical. One remarkable fact is that the Cassava minimum tillage treatment accumulated nutrients, causing a high EC to occur. However, conventionally tilled treatments had lower EC values. The Monoculture and the Bare fallow treatments had the lowest EC values as well as the lowest hardening process at the soil surface.

The dissolving capacity of positively charged chicken manure, such as in Cassava 8 t/ha chicken manure plots, has a strong influence on volcanic ash soils with high clay content. If the soil comes into contact with the fertilizer, nutrients like Na and K tend to dissolve stable soil aggregates by peptization, finally causing clay dispersion. After high amounts of rain, the soil solution is either washed out horizontally by surface run-off, or washed in vertically creating the so called soil sealing. After drying, the crusting process can be observed.

Therefore, the key reasons for soil crusting on volcanic ash soils as found in Santander de Quilichao are the wet and dry seasons and their interaction with organic manuring. The effects on the dissolving and hardening processes are shown in Figures 2 and 3.

For Cassava planted in December, root growth is significantly limited because of these processes, as seen in chicken manure plots and especially the Cassava 8 t/ha plot. High correlations between K, Ca, Mg, Na and electrical conductivity, as well as correlations between penetration resistances, shear strength and electrical conductivity, make it obvious that both chemical and physical constraints are the reasons for the crusting process.

In general, Cassava minimum tillage techniques allow nutrients to be accumulated over time. These nutrients are mainly derived from mineral fertilization and additional mulch. A hardening process does occur (as mentioned above) but the minimum tillage treatment maintains the soil's structural stability, as is evident from infiltration measurements. Cassava minimum tillage and Cassava rotation had greater exchangeable and water soluble Ca contents. Ca contributes to a stable surface structure, as is evident with high values of penetration resistance, but had no influence on water infiltration process. The Cassava monoculture treatment did not have any of these stability agents. A real crusting process was not evident with this treatment. The weak soil structure prevents this treatment from developing a good draining pore system. Infiltration was very low compared to other treatments, resulting in soil erosion in Cassava monoculture as well as in Bare fallow.

Infiltration: Results on infiltration measurements are presented in Figure 5 and Table 6. Generally, high water infiltration in all treatments was observed. This was expected due to good physical structure of these soils. The goal of this research was to find out whether change in land use over time has an influence on water infiltration. Cassava rotation and Cassava minimum tillage had the highest rates of water infiltration for all treatments. As already described before (PE-2 Annual Report, 2000), improved stability of soil aggregates is the reason for this phenomenon. Although Cassava minimum tillage had the greatest penetration resistance, shear strength and water infiltration rate were not influenced by compaction. Continuous fallow crop rotation had a positive influence on water infiltration. The root system of pasture grass contributes to a highly effective soil pore system that results in high water infiltration capacity.

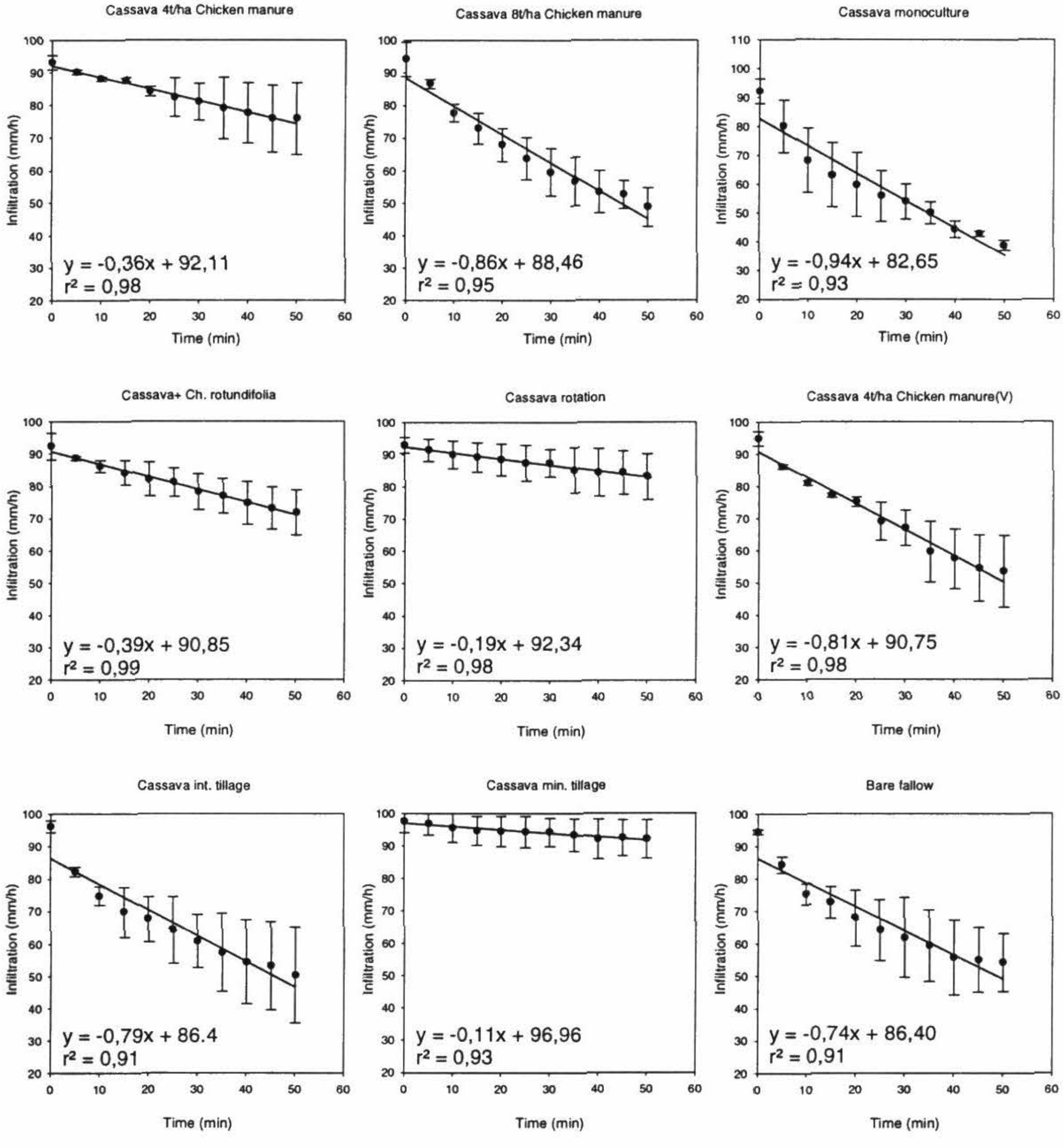


Figure 5. Dynamics of water infiltration measured by minirainsimulation in different land use systems, Santander de Quilichao, April 2001.

Table 6. Influence of different treatments on water infiltration measured by a minisimulator, Santander de Quilichao, April 2001.

No.	Treatment	Water Infiltration (mm/h)	Run-off (mm/h)	Rain Intensity (mm/h)
1	Bare fallow	54.3 a	40.2 b	94.5
2	Cassava 4 t/ha chicken manure	75.9 b	17.3 a	93.2
3	Cassava monoculture	38.9 a	53.2 b	92.1
4	Cassava minimum tillage	92.0 c	5.6 a	97.6
5	Cassava 8t/ha chicken manure	48.8 a	45.5 b	94.3
6	Cassava 4 t/ha chicken manure (Vetiver)	53.6 a	41,3 b	94.8
7	Cassava + *Chamaechrista rotundifolia*	71.7 b	20.7 a	92.4
8	*B. decumbens* + *C. macrocarpum*	83.1 bc	9.9 a	93.0
9	Cassava intensive tillage	50.4 a	45.8 b	96.2

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

The lowest infiltration was observed with Cassava monoculture, Cassava intensive tillage, Cassava 8 t/ha chicken manure, and Bare fallow. The main reasons for this are the impact of raindrops (splash impact) and poor aggregation, as well as reduced permeability due to chemical dispersion. A stable aggregate system, either through long-term aggregation or root biomass, contributes to high rates of water infiltration rates. If aggregate breakdown occurs, as observed in Cassava monoculture or Cassava intensive tillage, infiltration could be strongly reduced.

Harvest: Results of cassava harvest data are presented in Table 7 and Figure 6. Overall the best root yields were found in Cassava 4t/ha chicken manure and Cassava rotation. Reasons for 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 lower yields were found with Cassava monoculture and Cassava intensive tillage treatments.

Table 7. 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).

The single grain structure and low water infiltration capacity contributed to low root yield. The intensive tillage treatment caused a breakdown of the soil aggregates, reduction in soil pore system and less water intake, thereby leading to reduced yields. In both treatments, roots were very small and economically worthless. Cassava 8 t/ha chicken manure treatment 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 of soil that was loosened before planting. Therefore yields in both treatments were lower than in Cassava rotation and Cassava 4 t/ha chicken manure.

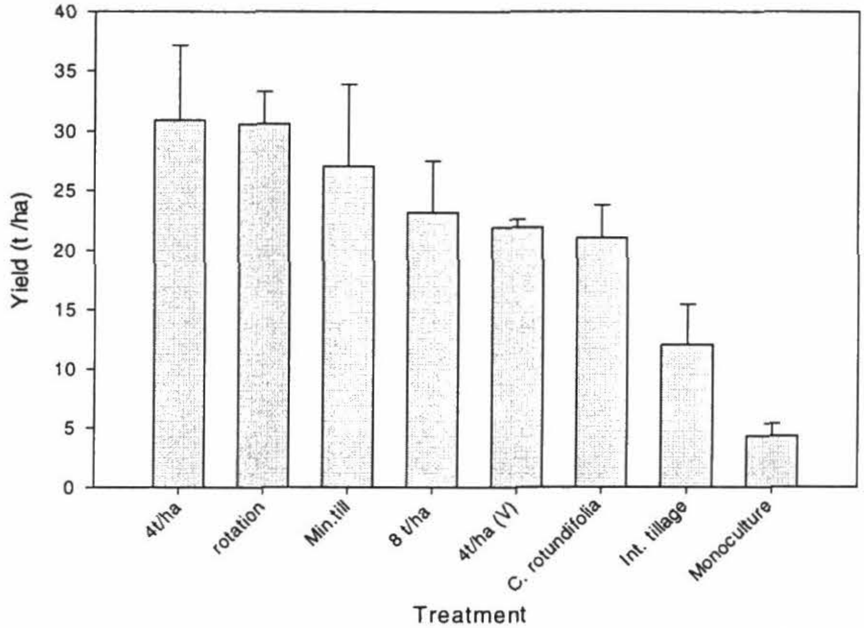


Figure 6. Effect of different treatments on cassava root yield, Santander de Quilichao, Dec 2001.

Impact:

Some general conclusions can be made, although field research is not yet completed. Excessive organic manuring, of up to 12 t/ha chicken manure in the Cauca, leads to a deterioration of soil stability. Soils fertilized with organic chicken manures have more crusting symptoms than other soils. There is a seasonal change in soil crusting and sealing. In the wet season especially, fertilized plots dissolve stable soil aggregates. A hardening process can be observed during dry season. Soil hardening does not necessarily reduce the infiltration capacity of a treatment, as the status of aggregation and stability factors like root growth have to be taken into account. This can be observed with Cassava minimum tillage and Cassava rotation. Therefore, the factors that lead to positive results with regard to soil fertility, soil water status, plant growth, and yield need to be determined, as does the extent to which compaction has a negative impact on root development. High correlations observed between electrical conductivity and several soil parameters indicates that further research work is needed to determine the influence of cations on soil crusting and sealing, and their physical and chemical interactions during dry and wet seasons. Effects of clay dispersion due to Na and K also need to be analyzed in order to strengthen the hypothesis that both nutrients are the key factors contributing to dispersion of soil particles and crusting in chicken manure treatments. We need to find out to what extent and at what intensity chicken manuring can be promoted without damaging the soil surface structure because it must be taken into account that organic fertilizers are cheap and useful for the stakeholders. The main challenge for sustainable land use of Andean hillsides should therefore be to find out the appropriate level of manure application together with proper recommendations of soil management.

Contributors:

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1.1.3 Developing methods to predict spatial and temporal variation in rainfall distribution for the Llanos of Colombia

Highlight:

- Developed a method to predict precipitation (including intermittent drought) for seven consecutive days for soils of different texture.

Purpose:

To develop methods to predict precipitation within seven consecutive days for soils of different texture for the Altillanura region based on climate data records kept at two meteorological stations, Carimagua and La Libertad.

Rationale:

In developing countries most crops are cultivated under rainfed conditions. However, for a better planning of rainfed agriculture, knowledge on probabilities of rainfall in relation to water requirements for crop production is essential for proper use of this important natural resource.

Traditionally in Colombia, the meteorological information is processed through statistical analyses such as the mean, which could mask the extent of variability particularly for rainfall. Since rainfall is a major determinant of crop productivity, it is essential to know the extent of its spatial and temporal variation for the benefit of improved crop performance under rainfed conditions. Therefore, it is important to develop tools to predict rainfall distribution for different soil types of Altillanura using improved statistical models. This will help to develop improved soil and water management strategies for the region.

Materials and Methods:

The study area is located in the Eastern plains of Colombia (Orinoquia river basin). Climate data records that were kept at two meteorological stations: Carimagua (4° 36' L.N, 71° 10' L.W) (1975 to 1997) and La Libertad (4°04' L.N, 73° 29' L.W) (1974-1998) of the Eastern Plains of Colombia were used for the study. The soils in the well-drained region correspond to Oxisols and Ultisols with clay, clay-loam, sandy-loam and sandy soil texture. These soils are acid, infertile with high Al saturation and low organic matter content.

Climate databases of Carimagua and La Libertad research stations were used with the following objectives:

- Analyze the climatic information available at daily, weekly and monthly intervals to predict rainfall probabilities.
- Estimate the probabilities of occurrence of wet and dry days in both locations.
- Estimate soil water balances of the zone of influence of both research stations.

The following statistical distribution methods were used:

- Normal distribution: for yearly and monthly rainfall.
- Binomial distribution: for daily distribution.
- Gamma distribution: for weekly and monthly distributions.

In order to calculate the probabilities of consecutive dry or wet days, the methodology of Feyerhem and Bark was followed, with some modifications to fit it to statistical concepts.

The following equations were used:

$P(D_t)$: number of year the (t)th day was dry (D) divided by the number of years of record.

$P(W_t)$: $1 - P(D_t)$

$P(D_t/D_{t-1})$: number of years that the (t)th and (t-1)st days were dry divided by the number of years that the (t-1)st was dry.

$P(W_t/D_{t-1})$: $1 - P(D_t/D_{t-1})$

$P(W_t/W_{t-1})$: number of years that the (t)th and (t-1)st days were wet (D) divided by the number of years that the (t-1)st was wet.

$P(D_t/W_{t-1})$: $1 - P(W_t/W_{t-1})$

The sum of the probabilities for all possible sequences equals unity. Table 8 shows an example of the dry and wet daily probabilities for the month of July in Carimagua:

Results and Discussion:

The rainfall behavior for the two locations (Carimagua and La Libertad) is unimodal. The dry season occurs from November to March and the wet season is from April to October. The model of gamma distribution used for the description of the rainfall data in both localities showed unimodal behavior as expected. For improved crop performance, it is important to be able to predict the intermittent droughts that could occur at critical stages of crop development. This would require the ability to predict spatial and temporal variability in rainfall distribution within a week or less. Using the gamma distribution method, we found that the probabilities of rainfall have their maximum during the month of July with a value of 0.9 (90%) for Carimagua and of May for La Libertad with 0.9, and its minimum with 0.0 in January for both locations. This information is very useful to develop recommendations for planting and soil and water management for different crops that can be cultivated in the Altillanura region of the Orinoco river basin.

July	D	W	D/D	W/D	D/W	W/W
1	0.2	0.8	0.0	1.0	0.2	0.78
2	0.1	0.9	0.0	1.0	0.1	0.89
3	0.3	0.7	0.0	1.0	0.3	0.67
4	0.1	0.9	0.3	0.7	0.1	0.94
5	0.2	0.8	0.0	1.0	0.3	0.75
6	0.2	0.8	0.4	0.6	0.2	0.83
7	0.2	0.8	0.4	0.6	0.2	0.83
8	0.2	0.8	0.6	0.4	0.1	0.89
9	0.2	0.8	0.2	0.8	0.2	0.83
10	0.3	0.7	0.5	0.5	0.2	0.79
11	0.2	0.8	0.3	0.7	0.2	0.78
12	0.2	0.8	0.0	1.0	0.2	0.78
13	0.3	0.7	0.3	0.8	0.3	0.74
14	0.3	0.7	0.0	1.0	0.4	0.65
15	0.3	0.7	0.5	0.5	0.2	0.82
16	0.1	0.9	0.2	0.8	0.1	0.88
17	0.2	0.8	0.3	0.7	0.2	0.8
18	0.3	0.7	0.2	0.8	0.3	0.67
19	0.3	0.7	0.3	0.7	0.3	0.75
20	0.1	0.9	0.3	0.7	0.1	0.94
21	0.2	0.8	0.3	0.7	0.2	0.85
22	0.3	0.7	0.5	0.5	0.3	0.68
23	0.1	0.9	0.3	0.8	0.1	0.87
24	0.3	0.7	0.3	0.7	0.4	0.65
25	0.3	0.7	0.5	0.5	0.1	0.87
26	0.3	0.7	0.3	0.7	0.3	0.71
27	0.4	0.6	0.5	0.5	0.4	0.65
28	0.3	0.7	0.4	0.6	0.1	0.86
29	0.3	0.7	0.0	1.0	0.4	0.65
30	0.1	0.9	0.5	0.5	0.0	1
31	0.2	0.8	0.3	0.7	0.2	0.85

Table 8. Rainfall probabilities for dry (D) or wet (W) days for the month of July in Carimagua. D/D = probability of a dry day following a dry day; W/D = probability of a dry day following a wet day. D/W = probability of a wet day following a dry day. W/W = probability of a wet day following a wet day.

Impact:
The methodology developed from this study could be applicable to other climatic areas where rainfed agriculture is practiced. The knowledge of sequence of dry or wet days is very useful for defining farm operations such as time of land preparation and dates of sowing and harvesting for different crops.

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Activity 1.2 Survey native plants and their potential use as biofertilizers

Activities initiated in Nicaragua as part of new collaboration with Universidad Centro Americana (UCA) will be reported next year.

Activity 1.3 Survey land users for soil and crop management knowledge

1.3.1 Implications of local soil knowledge for integrated soil fertility management

Highlight:
- Surveyed land users in Colombia and Honduras for local knowledge about soils and their management and identified native plants as important indicators of soil quality related to modifiable soil properties.

Purpose:
To determine the complementary nature of local and scientific knowledge to develop an overall strategy for sustainable soil management.

Rationale:
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. It is the result of an intuitive integration of local agroecosystem responses to climate and land use change through time. Transfer of information from generation to generation undergoes successive refinement leading to a system of understanding of natural resources and relevant ecological processes.

There is increasing consensus about the need for enhanced understanding of local knowledge in planning and implementing development activities. The slow rate of assimilation of new technology and new cropping systems has been often attributed to local inertia rather than the failure to take into account the local experience and needs. The 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.

The complementary role that indigenous knowledge plays to scientific knowledge in agriculture has been increasingly acknowledged. 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 to 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 sustainably.

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.

This work examined two case studies on local soil knowledge and management and the implications of these results on future research on integrated soil fertility management (ISFM). ISFM refers to the broad definition of soil fertility that includes the chemical, physical and biological factors affecting the productive potential of the soil. While ISFM involves managing the widest variety of possible sources of fertility and rely as much as possible on local knowledge and decission making, it also uses research-based understanding and analysis of the underlying soil processes.

Results from case studies to elicit local information using key-informants are reported for small farmers from the Cabuyal river watershed in Cauca, Colombia. A participatory approach was used with six farmer communities 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 for consensus building that facilitates ISFM in the landscape is discussed.

Materials and Methods:

Case studies

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. 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. 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), 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 erosion and loss and thus the usually darker top-soil has given way to the red sub-soil where cultivation is now taking place in many agricultural plots.

Results and Discussion:

Native plants constitute another means by which Andean hillside farmers classify the soils in their farms. In Table 9 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 aquilinum*) 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. 9 Most important plant species used as local indicators of soil quality by Cabuyal watershed hillside farmers, Colombia

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 aquilinum*	Pteridiaceae	H	Poor
Paja garrapatera	*Andropogon bicornis*	Poaceae	H	
Paja blanca	*Andropogon leuchostachys*	Poaceae	H	
Helechillo	*Dichranopteris flexosa*	Pteridaceae	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 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. 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) and activity 3.2.1 in this report. 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 into 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 plennary sessions and organized into indicators of permanent (Table 10) and modifiable (Table 11) 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 alternative 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 poor 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. The importance of soil texture is perceived by local farmers as affecting 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). Fire as an agricultural management tool has been probably used by the earliest farmers as a way to recover nutrients in the native vegetation biomass for the crops, to control pests and to dispose of perceived "excess" plant biomass in the fields. Despite the realization of the harm done by annual fires to 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 suggests this participatory approach as a way to promote collective action at a landscape scale.

Table 10. Integration of local and technical indicators of soil quality related to permanent soil properties in contrast sets identified and ranked according to their importance by Honduran hillside farmers from different villages.

	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/know-ledge 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)			

*Ranking values are inversely related to degree of importance (i.e. 1 = highest importance).

Table 11. Integration of local and technical indicators of soil quality related to modifiable soil properties in contrast sets identified and ranked according to their importance by Honduran hillside farmers from different villages.

	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)	
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)	

* Ranking values are inversely related to degree of importance (i.e. 1 = highest importance).

It is important to note that the type of native vegetation present in a soil is a local indicator of soil quality (Table 12) that not only cuts across the communities studied in Honduras but also across the previous case studies reported here. This observation suggests that there may be an underlying fundamental ecological principle behind farmer observations in the two locations. It is proposed here that one such ecological principle is that of natural succession. Natural and agricultural ecosystems respond similarly to degradative or regenerative processes through natural succession. 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. 12 Most important plant species used as local indicators of soil quality by Tascalapa watershed hillside farmers, Honduras.

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*	Phytolacaceae	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.

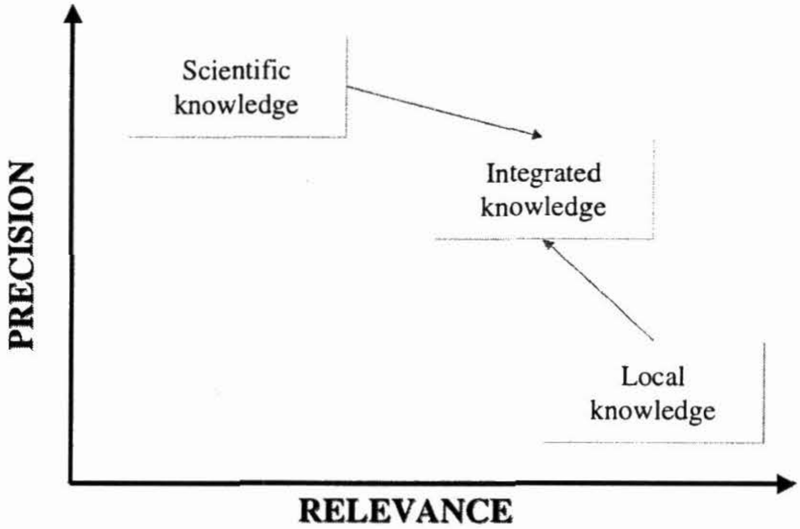

Figure 7 Integration of local and scientific knowledge systems

Implications for ISFM 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). Figure 7 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.

Impacts:

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 effective to elicit local information about soils and their management. Participatory approaches involving group dynamics and consensus building, however, are likely to be key to integrated soil fertility management beyond the farm-plot scale to the landscape scale through the required collective action process.

Native plants 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 like available phosphorus 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.

Contributors:

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1.4 Characterize plant components for production potential, nutrient use efficiency (phosphorus and nitrogen) and improvement of soil physical conditions

1.4.1 Use of deep rooted tropical pasture components to improve soil physical conditions

Highlight:

- Showed that deep-rooted tropical pastures can enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocropping.

Purpose:
To determine the usefulness of deep rooted tropical pasture components to improve soil physical conditions.

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

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

It has been demonstrated that soil physical conditions are usually best under permanent grassland (or forest) and as soil is cultivated, these conditions deteriorate at a rate dependent of climate, soil texture and management. We have found significant negative effects of continued cropping on the physical properties of soils in the Llanos. Studies from the Casanare region of the Llanos showed that total porosity and macroporosity decrease markedly after 5-7 years of monocropping.

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

Materials and Methods:
Location: The experiments were carried out at Matazul farm (4° 9′ 4.9″ N, 72° 38′ 23″ W and 260 m.a.s.l.) located in the Eastern Plains (Llanos) near Puerto Lopez, Colombia. Prior to treatment application, the area was under a native savanna pasture consisting of native grasses. The soil has low fertility and the

availability of P in the soil is low because of the soil's high P fixation capacity. The soil is classified as Isohyperthermic Kaolinitic Typic Haplustox in the USDA soil classification system.

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

a) Aggregate size distribution and aggregate stability aspects were studied in an experiment where disturbed and undisturbed introduced pasture systems were compared with rice monocropping on two sites of contrasting soil texture (Matazul: clay loam; Primavera: sandy loam). Native savanna (undisturbed) system was used as a control. Disturbed pasture received two harrow passes for every two years to reduce surface sealing and compaction.
b) Infiltration rates were measured in an experiment aimed to improve top soil conditions (cultural profile) using different intensities (1, 2 or 3) of chisel passes (vertical tillage) or different agropastoral treatments (pasture alone, pasture+legume and legumes alone) that were planted after 2 passes of chisel.
c) Measurements on volume and chemical composition of gravitational water were studied in an experiment aimed to understand the processes of soil degradation due to either monocropping of rice or introduced pasture (*Brachiaria dictyoneura* cv. Llanero). Different number of harrow passes (2, 4, 8) were applied every year for a period of two years for each treatment.
d) Root biomass and root volume of *Brachiaria decumbens* were determined in two contrasting textural soils: sandy-loam and clay-loam, under two pasture conditions: productive and degraded (less productive), to compare root growth under these two conditions.

Evaluated Parameters:

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

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

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

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

Root distribution: Root sampling was carried out using trench profile method. Three sampling points were randomly located within each treatment of degraded or productive pasture of *Brachiaria decumbens*. A trench of 60 cm wide, 50 cm deep and 60 cm long was dug to determine root penetration and root distribution. Root samples were excavated from the wall of each trench, from each treatment. The nail-boards were made of a 2 cm thick plywood board (50 cm wide and 40 cm long). Twelve cm long nails were inserted at 10 cm intervals (10 x 10 cm) through the back of the board and protruded into the frame 10 cm. Root samples were collected by pressing the nail-boards into the trench wall and slicing the enclosed soil monolith from the trench wall with a steel blade. The samples were soaked in water for at least 2 h after which the soil was removed from the roots with a fine spray of water. The root samples were photographed. Root volume was determined with a measuring jar filled with water by registering the increase in volume. Root biomass (dry weight) was recorded after oven drying for 2 days at 65°C.

Results and Discussion:

Aggregate size distribution and stability: Effect of different management systems. The aggregate size distribution under different management systems is shown in Table 12. At Matazul Farm, the percentage of aggregates >6 mm, 6–4 mm and 4–2 mm decreased in intervened systems compared with the native savanna, while those between 2–1 mm, 1–0.125 mm and <0.125 mm increased. This was noted particularly under monocropped rice. At La Primavera Farm, monocropping with rice resuted in a lower percentage of 4–2 mm and higher percentage of 2–1 mm and 1.0–0.125 mm aggregates. In contrast, the undisturbed pasture had a positive effect on soil aggregation, with the highest (non-significant) percentage of aggregates larger than 2 mm.

To better characterize the influence of soil management on aggregate size, the medium diameter (D_{50}) was calculated. In the case of Matazul, the equivalent D_{50} diameter for native savanna was 1.90 mm whereas for rice monocrop it was 0.4 mm. Disturbed and undisturbed pastures had values of 0.85 and 1.35 mm, respectively. The situation differed somewhat at La Primavera: native savanna exhibited a D_{50} value of 1.50 mm while the undisturbed *Brachiaria* pasture gave a D_{50} value of 1.80 mm, showing the influence of the pasture on soil aggregation.

The results on aggregate stability are presented in Table 13. Aggregate stability values at Matazul Farm were greater for native savanna than for intervened systems. The percentage of stable aggregates larger than 2 mm was significantly greater in relation to other treatments. At La Primavera Farm, undisturbed pasture and native savanna both had a higher percentage of aggregates larger than 2 mm diameter.

Infiltration rate: Infiltration rates, determined under different management system treatments in an experiment aimed to create an arable layer, are shown in Table 14. In relation to native savanna the treatments that included introduced pastures showed higher and more stable rates. Particularly higher rates of infiltration were found under *A. gayanus* pasture.

Gravitational water: The amount of gravitational water draining at different soil depths as a function of soil management system is shown in Table 15. Little water was collected in the top layers of soil of savanna while greater amounts were collected at 15 cm soil depth. The treatment sown to upland rice with 8 harrow passes, did not allow the movement of free water through the soil. With 16 harrow passes more water was able to enter into the soil especially in the top two layers. Under introduced pasture, the amount of free water entering and moving through the soil profile was extremely high (480 cm^3 with pasture vs 0 cm^3 with monocropped rice for 8 harrow passes and 490 cm^3 with pasture vs 100 cm^3 with monocropped rice for 16 harrow passes) at 3 cm of soil depth (Table 15).

The chemical composition of the water collected at different soil depths under upland rice and pastures is shown in Table 16. Higher amounts of nutrients, especially at the first two depths were found under rice.

Root distribution: Examination of soil monoliths collected through profile wall technique showed marked differences in root penetration and root distribution between a degraded pasture and a productive pasture of *Brachiaria decumbens* (Figure 8). Differences in root biomass and root volume at different soil depths, as influenced by soil texture (clay-loam and sandy-loam) are shown in Table 17. Clearly the productive pasture shows a better and abundant root systems than the degraded one.

Table 12. Aggregate size distribution (%) as influenced by soil management system in savanna soils of Colombia.

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

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

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

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

Table 13. Percentage of stable aggregates under different management systems on a Colombian savanna Oxisol.

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

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

Table 14. Rate of water infiltration (cm. h^{-1}) as influenced by different treatments in the experiment on building an arable layer (Matazul Farm).

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

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

Table 15. Gravitational water collected (ml) at different soil depths for different systems of soil management (Matazul Farm).

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

Table 16. Elemental composition of gravitational water collected at different depths and management systems (Matazul Farm).

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

Table 17. Root biomass (g) and root volume (cm^3) of *Brachiaria decumbens* at different soil depths as influenced by level of pasture productivity (degraded or productive) on two soil types.

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

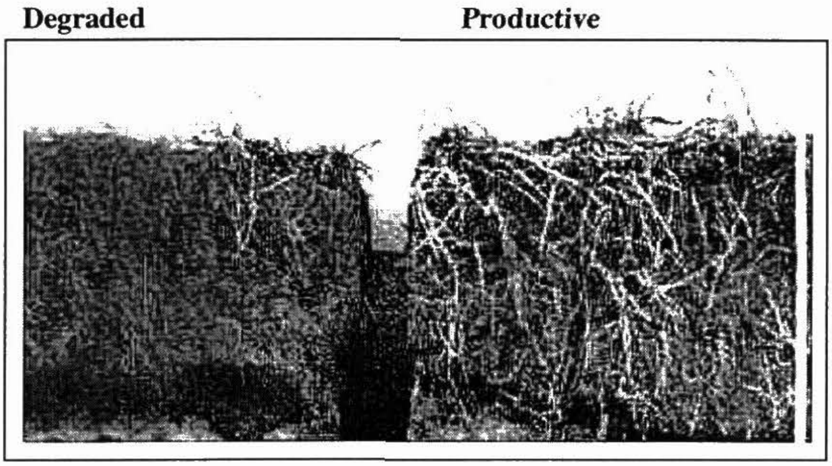

Figure 8. Root distribution under degraded and productive *Brachiaria decumbens* pasture.

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

Four aspects of the research deserve attention: a) The methodology used was appropriate as it was possible to collect drainage water and differentiate between treatments, b) there is a very high variability in the way the water moves into the soil (preferential flow), c) the amount of nutrients that move from one depth to other is a function of the amount of water draining, and d) the capacity of the pastures to allow a better water and nutrient distribution should be used to improve soils.

Impact:
This study shows that introduced pasture components can enhance soil quality by improving the size distribution of stable aggregates, infiltration rates and rainfall acceptance capacity when compared with soils under monocropping. Use of introduced pastures with deep rooting abilities can result in increased soil organic matter and associated improvements in soil physical and chemical properties.

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Activity 1.5. Determine rooting strategies of crop, forage and improved fallow components

1.5.1 Developing methods to determine root distribution and abundance of two improved fallow species in stony Nicaraguan soils

Highlight:

- Developed methodology to determine root distribution and abundance for stony soils predominant at Nicaraguan reference site.

Purpose:

To determine the root distribution and abundance of *Sesbania sesban* and *Tephrosia* spp. growing in two different soil conditions

Rationale:

Improved fallow systems provide a faster regeneration of soil fertility than the natural regeneration by the native flora. The improvement of fallows is an addecuate technological entry point because it is of low risk for the farmer, is of relatively low cost and can have the incentive of generating additional products besides soil fertility improvement (i.e. fuelwood). A very important component of soil fertility regeneration is related to the capacity of improved fallow species to add considerable amounts of organic inputs aboveground through litterfall and prunnings as well belowground through root development and turnover during and after the fallow period. Thus, root turnover can increase the organic matter levels in the soil, even when the above ground biomass is removed. Therefore, understanding their role in soil fertility regeneration is essential.

The capacity of few improved fallow tree/shrub species tested in SOL-Wibuse (San Dionisio, Nicaragua) to develop well in stony soils was attributed to their rooting strategies by local farmers. This study aimed at identifying rooting patterns of the two best adapted improved fallow species in our adaptation trials: *Sesbania sesban* and *Tephrosia* spp. We used a modified versión of the methodology described in Anderson and Ingram (1993) as shown below.

Materials and Methods:

Treatments description: Root studies were conducted in an adaptation trial for potential fallow species at the SOL-Wibuse in San Dionisio, Nicaragua. In this trial, 5 legume species (Table 18) were planted in two different sites: site 1 has few stones and light slope, while site 2 has more stones and higher slopes.

Table 18. Species tested in adaptation trial experiments in Nicaragua (SI = soil improvement, F = Fodder, W = Wood, FW = Firewood, Fo = Food, LF = Live fence, M= Medicinal use, I = Insecticide)

	Reported uses							
Specie	SI	F	W	FW	Fo	LF	M	I
Flemingia macrophyla	X	X		X		X		
Tephrosia candida	X						X	X
Tephrosia vogelii	X						X	X
Sesbania sesban	X	X		X	X		X	
Rhynchosia schombergii	X	X						

Only the two best adapted species to both sites were selected for this study: *Sesbania sesban* and *Tephrosia* spp. The trees were planted in June of 2000 at 1.5 m spacing in a staggered arragement in adaptation plots. Root studies were conducted 1 year after planting (June – July of 2001).

Root mapping: The root map has the purpose to allow the estimation of the total root density throughout the soil profile, and was carried out as follows: A pit (0.75 m width, 3-4 m length and 0.7 m minimum depth) was initially prepared on one side of each plot, 50 cm apart from the most outward line of trees. Carefully, the pit wall closer to the trees was cleaned and straightened with shovels, blades and knives. Stones were removed from the wall when they were not very deep; otherwise, they were left intact. Weed roots were removed to prevent their inclusion in the map. Tree roots exposure was facilitated by applying water with a sprayer and brushing the soil wall with a plastic brush. Next, the profile wall was covered with a translucid PVC sheet, where horizontal and vertical lines had been drawn to generate a grid pattern (10 x 10 cm), to record rotos, stones, and different soil horizons (Figure 9). Each root was marked with a dot, trying to simulate the thickness of the roots. The roots were only recorded if they (or their projections) intercepted the PVC sheet.

After mapping in the field, maps were transferred to grid paper at scale (10:1). Root abundance (number of dots by area) could be estimated as a function of distance of the trees. The number of dots (roots) by horizons indicates the root abundance as affected by soil depth.

Map calibration: To obtain quantitative results it is necessary to calibrate the maps. Therefore, for each 10 cm soil depth a small block of soil (10 cm length x 20 cm width x 2.54 cm depth) was taken from the pit wall mapped, packed in a polyethylene bag and brought to the laboratory.

Next, soil from each block was washed with water over a set of two mesh sieves (0.3 mm + 0.2 mm) and a plastic bucket to carefully collect the roots present. Extracted roots were placed over a glass plate containing water, cleaned (to remove debris) and stored. Only living roots from the sampled trees were kept. Following sorting and washing, water was removed and roots were randomly oriented on the plate, and the one grided acetate (1 x 1 cm) was placed over the plate.

Counts of root intersections (N) with the vertical (V) and horizontal (H) lines of the grid (acetate) were recorded and added ($N = V + H$). Root length (L) is obtained by the formula: $L = \pi N D / 4$, where D is the grid size in mm. (10 mm) (Figure 11).

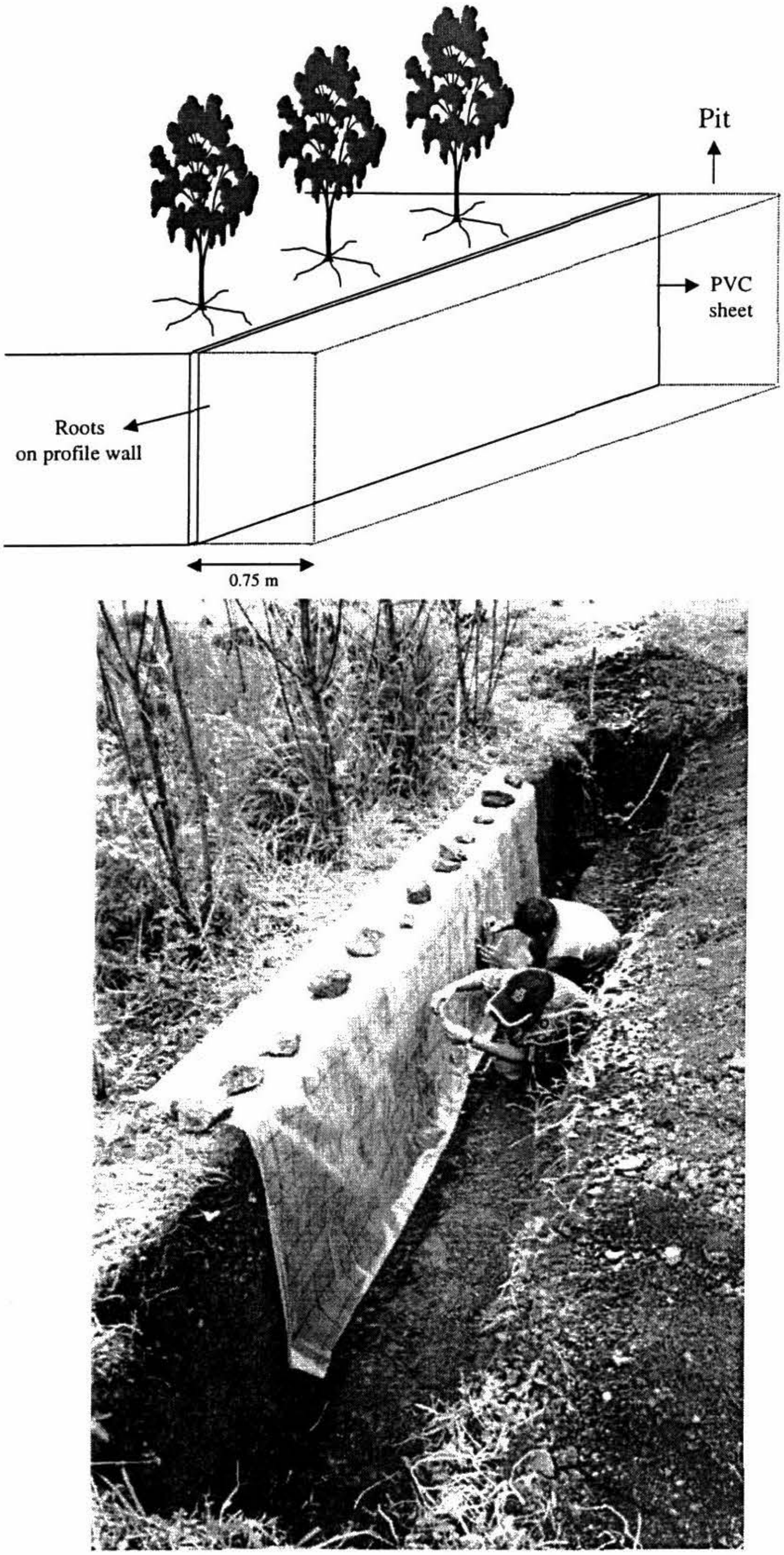

Figure 9. Root mapping: details about preparation of pits and location of PVC sheets on pit wall.

For *Sesbania*, in zone 1, two trees were selected for mapping (3 m length map), while three trees were sampled in zone 2 (4.5 m length map) (Figure 10). However, and because a higher mortality of *Tephrosia* spp., only one tree of this species was selected for zone 1 (1.5 m length map) and two trees for zone 2.

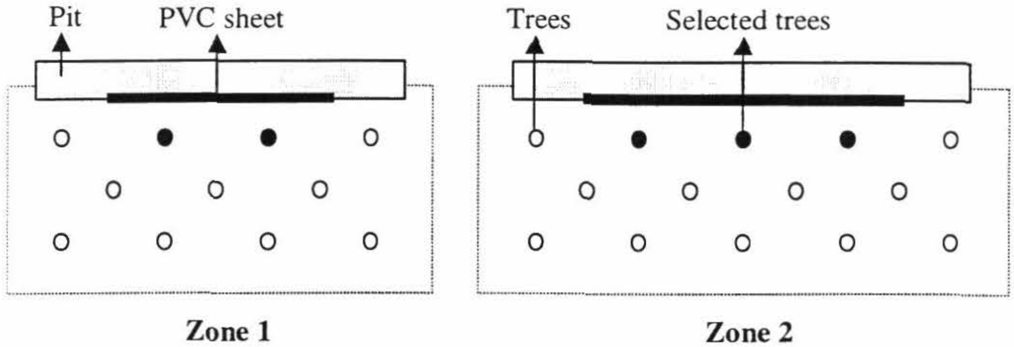

Figure 10. Selected trees for sampling in both zone 1 and zone 2 (example for *Sesbania*).

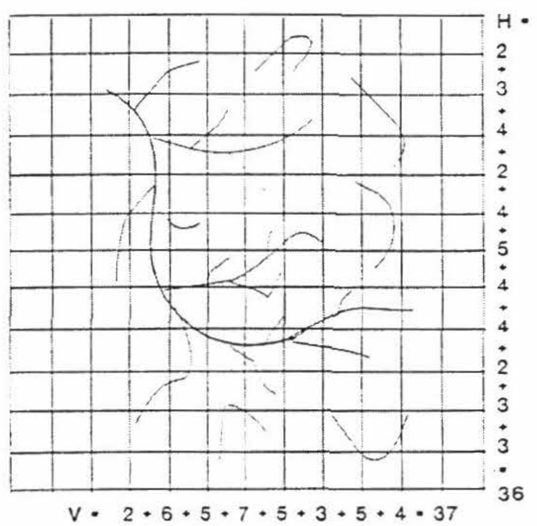

Figure 11. Linear interception method used to determine the root length.

Root pattern graphics: Root pattern graphics have the purpose to capture graphically the root distribution observed in the carefully prepared wall of the soil pit. This activity followed the root mapping, and the methodology used is described as follows:

In the same pit wall used for root mapping, soil was carefully removed from the pit wall all the way to the base of the trees under study (50 cm inside the pit), taking care that root systems of selected trees are not damaged (Figure 12). This work was performed manually with small pointed woody stakes and blades.

During this process, water was frequently applied with a sprayer over the roots to prevent their desiccation. Additionally, each tree was tied with cords to soil to avoid that strong winds could knock it down.

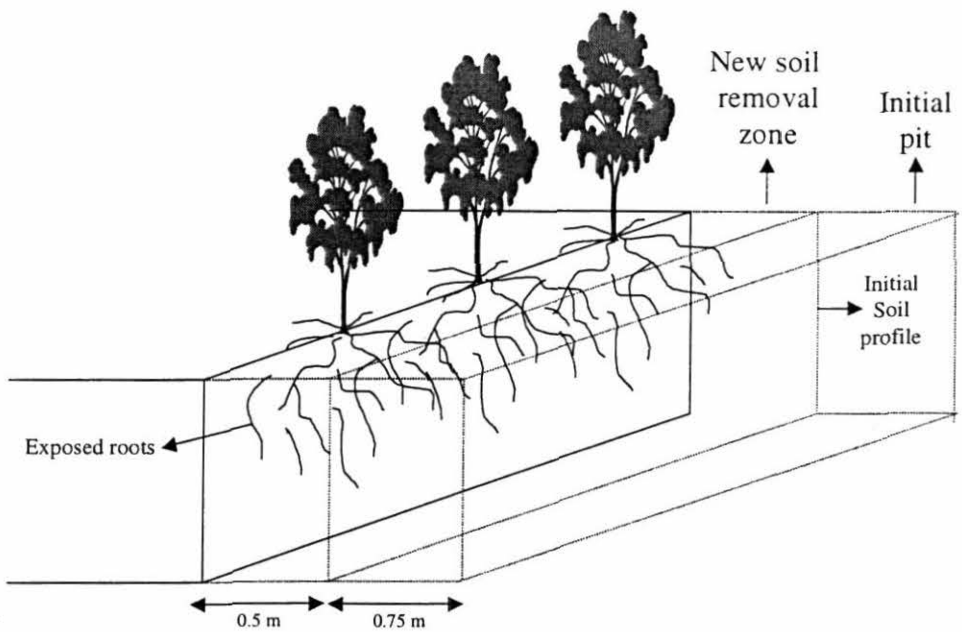

Figure 12. Soil removal to expose the root system of trees.

Next, a grid over the new wall was constructed (in the base of the trees) to help in drawing of root maps. The methodology used is shown in Figure 13.

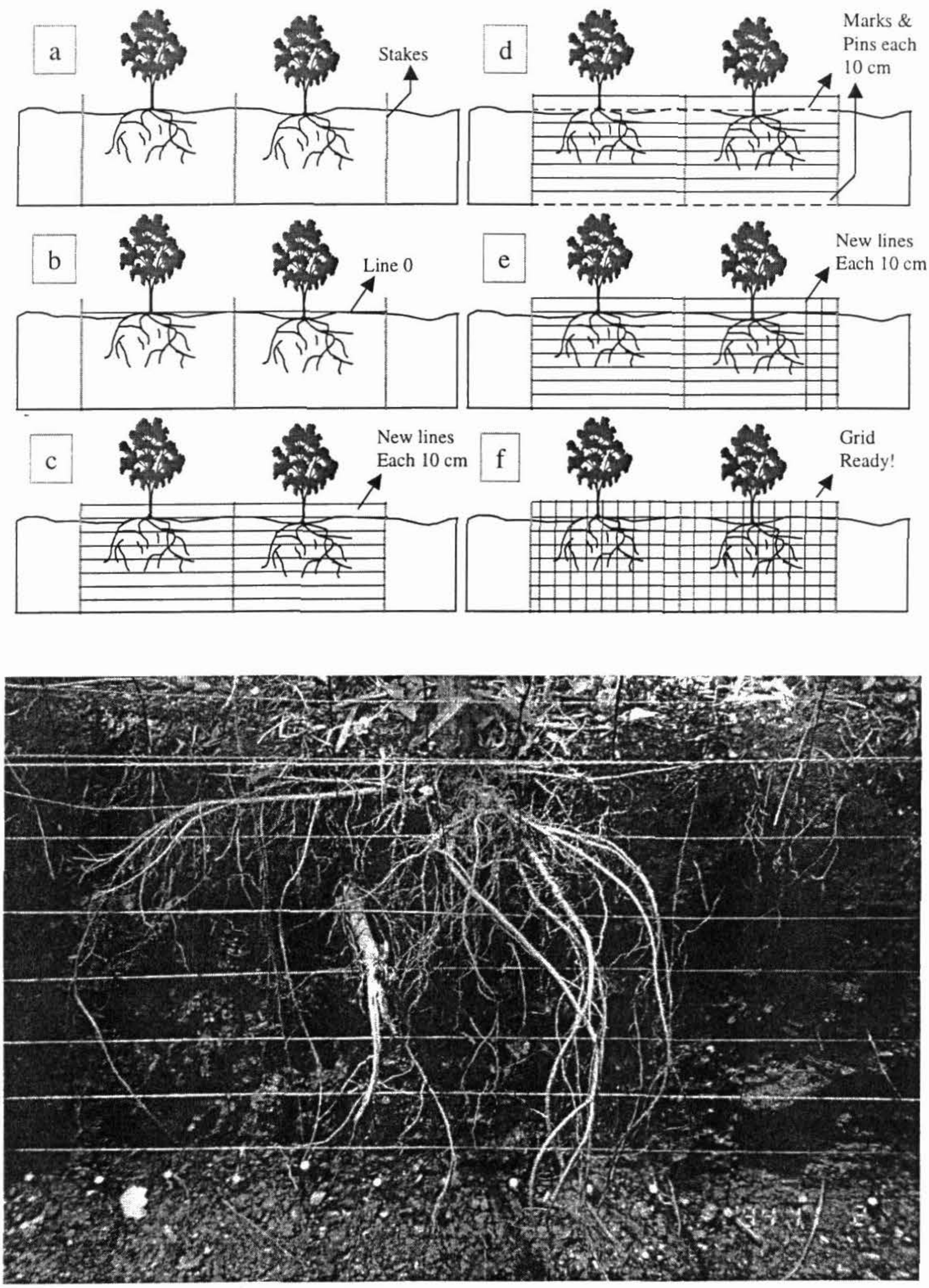

Figure 13. Making the grid (steps) to help the drawing of root graphs.

After making the grid, the roots were drawn in a grid paper at scale of 10:1. In the graph, stones present were also drawn.

Results and discusión:

Root mapping: In Figure 14, root maps of *S. sesban* (SES) and *Tephrosia* spp. (TEP) (zone 1) are shown. Some initial qualitative observations can be made: *Sesbania* presented higher number of dots (roots) than *Tephrosia.* Additionally, we can observe that sites differed in the abundance (> *Sesbania*) and size of stones (> *Tephrosia*) present as well as in the depth of soil horizons present.

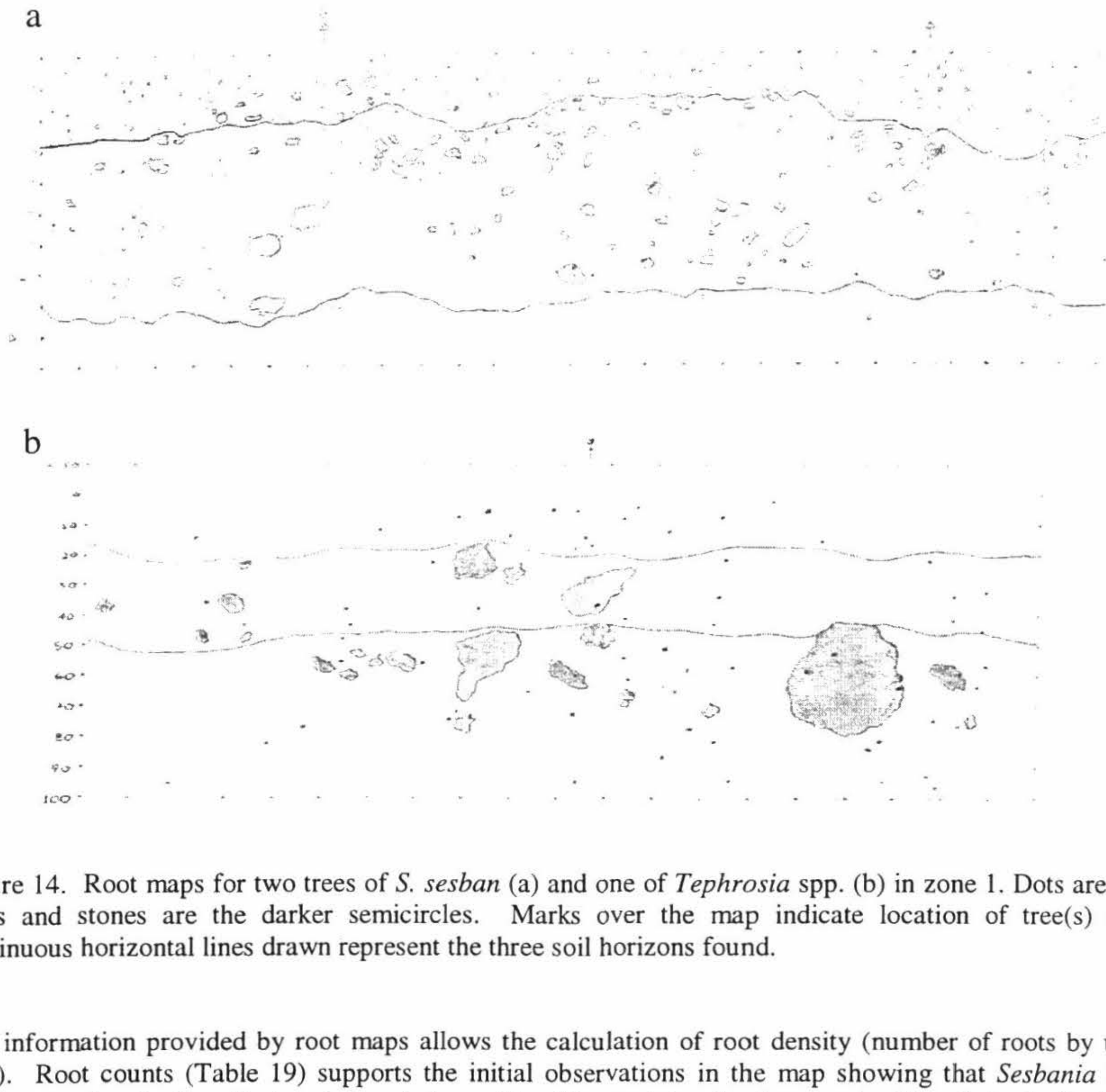

Figure 14. Root maps for two trees of *S. sesban* (a) and one of *Tephrosia* spp. (b) in zone 1. Dots are the roots and stones are the darker semicircles. Marks over the map indicate location of tree(s) and continuous horizontal lines drawn represent the three soil horizons found.

The information provided by root maps allows the calculation of root density (number of roots by unit area). Root counts (Table 19) supports the initial observations in the map showing that *Sesbania* had higher root density than *Tephrosia* in whole profile. The root density decreased with soil depth, for both treatments, being generally higher in the first 20 cm.

Likewise, we can observe that tree root density decreased with distance from the tree base, being higher in the first 35 cm (Table 20), with *S. sesban* maintaining higher root counts than *Tephrosia* spp.

Table 19. Variation of tree root density (number of roots *per* cm^2) of *Sesbania sesban* (SES) and *Tephrosia* spp. (TEP) with depth.

Treatment	Depth (cm) 0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
SES*	0.45	0.47	0.31	0.19	0.06	0.12	0.08	0.09	0.04	0.00
TEP	0.07	0.08	0.03	0.04	0.05	0.09	0.05	0.06	0.05	0.05

* Mean of two trees sampled.

Table 20. Variation of root density (number of roots *per* cm^2) for *S. sesban* and *Tephrosia* spp.with the distance from the tree base.

Treatment	Distance from the base of selected trees (cm) 0-5	5-15	15-25	25-35	35-45	45-55	55-65	65-75
SES*	0.18	0.12	0.11	0.16	0.11	0.12	0.13	0.10
TEP	0.07	0.04	0.05	0.06	0.02	0.03	0.01	0.03

* Mean of two trees sampled.

Map calibration: Table 21 shows the results obtained for the calibration of the root maps prepared for *S. sesban* and *Tephrosia* spp. The calibration corroborated that *Sesbania* presented higher abundance of roots than *Tephrosia* spp. and showed that root length decreased with depth, showing maximum values at 0-20 cm depth.

Table 21. Root length determination per unit volume of soil (cm^3) by the linear interception methodology for *S. sesban* (SES) and *Tephrosia* spp. (TEP). Root length (L) is give up by the formula: $L = \pi N D / 4$, where D is the grid size in mm (= 10)

Depth (cm)	Vertical Counts (V)		Horizontal Counts (H)		Total (N)		Root length in mm (L)	
	SES	TEP	SES	TEP	SES	TEP	SES	TEP
0-10	343	56	287	64	630	120	4948.0	942.5
10-20	246	42	319	44	565	86	4437.5	675.4
20-30	111	71	117	74	228	145	1790.7	1138.8
30-40	72	47	55	31	127	78	997.5	612.6
40-50	69	26	80	28	149	54	1170.2	424.1
50-60	78	26	86	24	164	50	1288.1	392.7
60-70	20	21	15	23	35	44	274.9	345.6

Root pattern graphics: In Figure 15 the root pattern graphic for *S. Sesban* and *Tephrosia* spp. (zone 1) is shown. Graphics illustrated details about root distribution and architecture down the soil profile and highlight the abundance of roots in *Sesbania*.

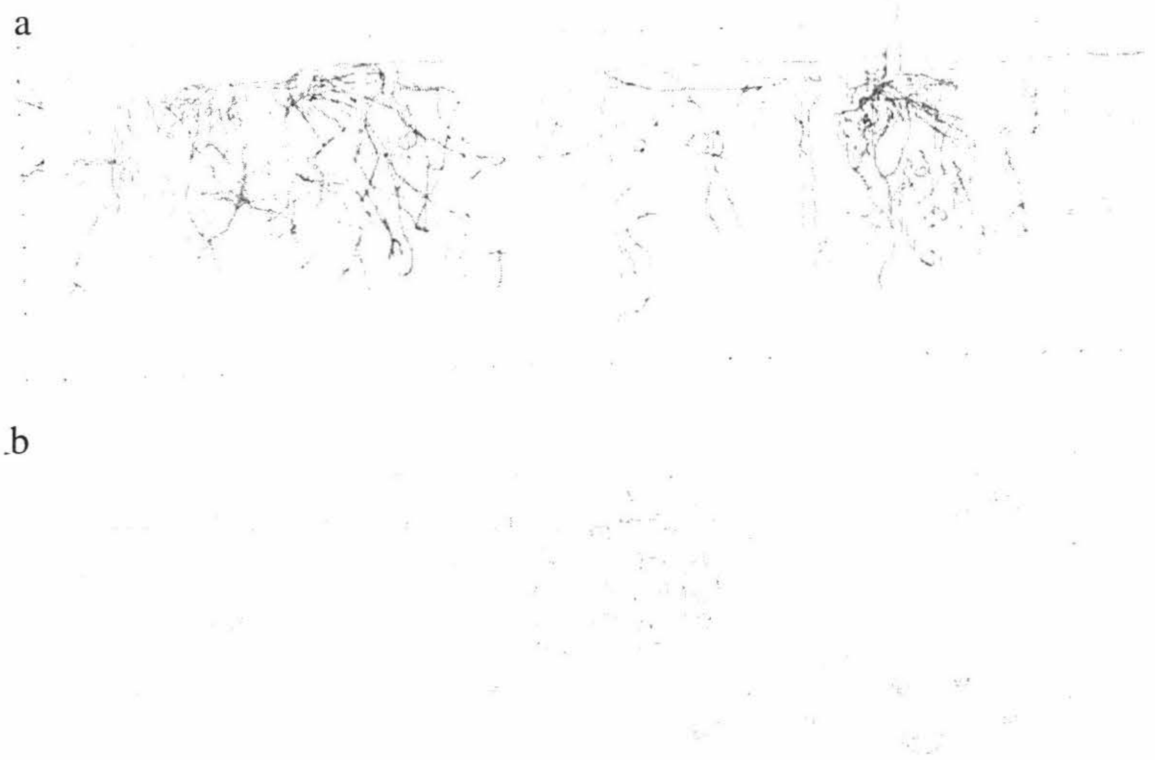

Figure 15. Root pattern graphics for *S. sesban* (a) and *Tephosia* spp. (b) in zone 1.

Impact:

Results indicate that *S.sesban* is a promising improved fallow species for the San Dionisio reference area provided its fast growing nature reaching about 3.5 m after one year producing a considerable root biomass and thus a good candidate for improved fallow agroforestry systems.

References:

Anderson J M and Ingram J S I 1993 Tropical Soil Biology and Fertility: a Handbook of Methods. 2nd. Edition. CAB International, Wallingford, Oxon, UK. 221 p.

Contributors:

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1.5.2 Determine the influence of no-till systems on rooting depth and grain yield of maize

Highlights:

- Showed that rooting depth and grain yield of maize could be markedly improved by direct drilling rather than chisel + direct drilling on plots planted from phase I of Culticore.

Purpose:

To determine the impact of direct drilling or chisel + direct drilling on rooting depth and grain yield of maize.

***Rationale*:**

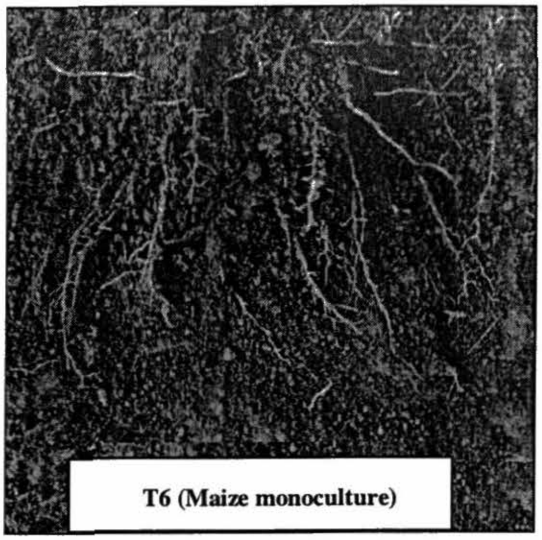
The intensification of the agricultural production in acids soils is possible through improved soil conditions in terms of fertility, structure and biological activity. Culticore (phase I) had the objective to improve the soil physical, chemical and biological conditions using different agropastoral systems. Results from phase I indicated that soil conditions were considerably improved with agropastoral systems when compared with monocropping. These improved soil conditions will permit the use of no-till systems to minimize soil degradation and sustain crop yields. Rooting strategies of crop and forage components could have important effects on nutrient acquisition, plant growth and grain yield as well as improving soil quality. As part of Culticore phase II, the present study was undertaken to determine the impact of direct drilling or chisel + direct drilling on rooting depth and grain yield of maize planted on different treatments of Culticore phase I.

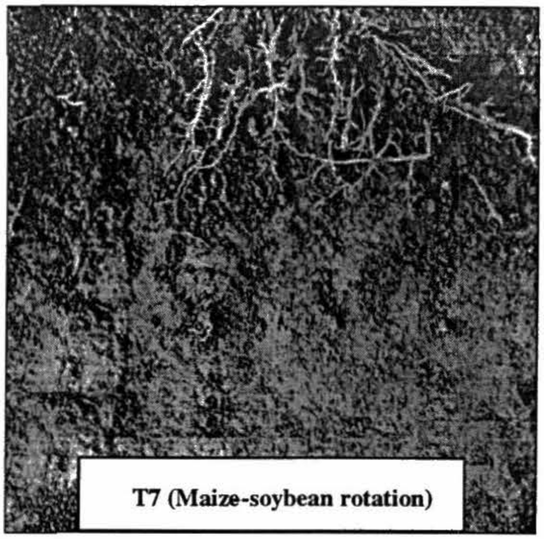
Materials and Methods:

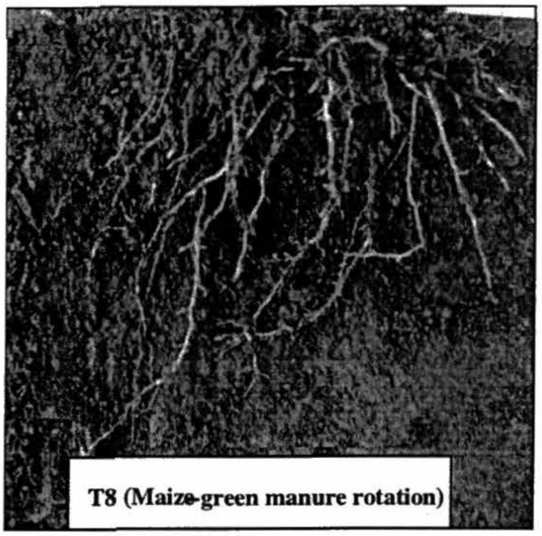
The effect of direct drilling or chisel + direct drilling on grain yields and rooting depth of maize was determined on plots from different treatments of Culticore phase I. Native savanna plots were used for baseline comparison. Rooting depth is defined as the depth of soil where the tip of the longest root is found in the soil profile. Grain yields of maize were measured at harvest.

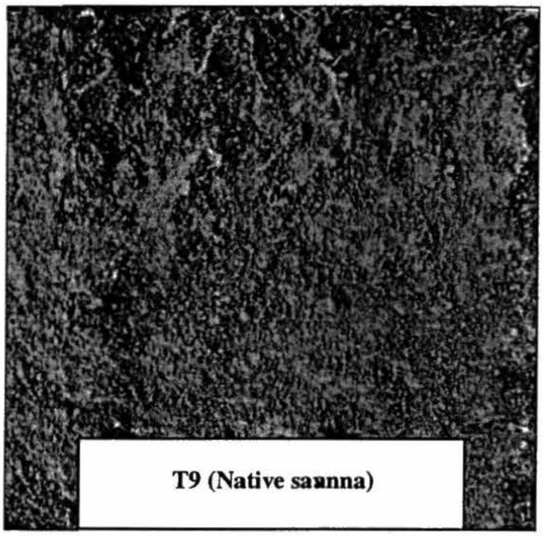
Results and Discussion:

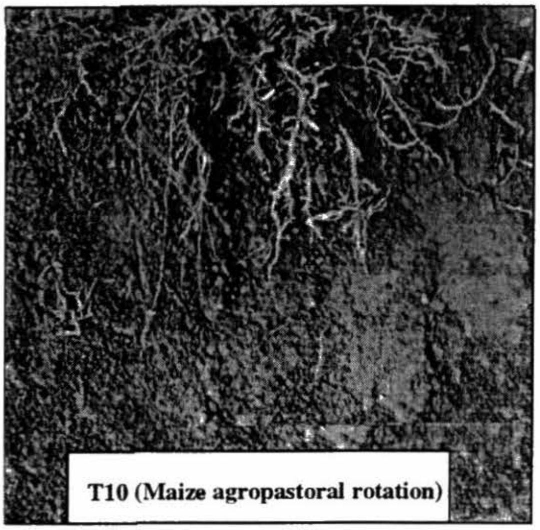
Direct drilling treatment improved maize grain yield on plots from all treatments of Culticore phase I when compared with chisel + direct drilling (Table 22). Values on mean grain yields indicate that grain yields were greater on plots from maize-based systems than from rice-based systems. Yield on plots from Native savanna were markedly lower than that of the introduced systems. The greater yields of 4.71 and 4.24 t ha^{-1} were observed with direct drilling on plots from maize + soybean (green manure) rotation and grass + legumes pasture, respectively of maize-based systems of phase I. This superior performance of maize on these plots with direct drilling was closely related ($r^2 = 0.70$) with rooting depth of maize (Table 22; Figure 16).





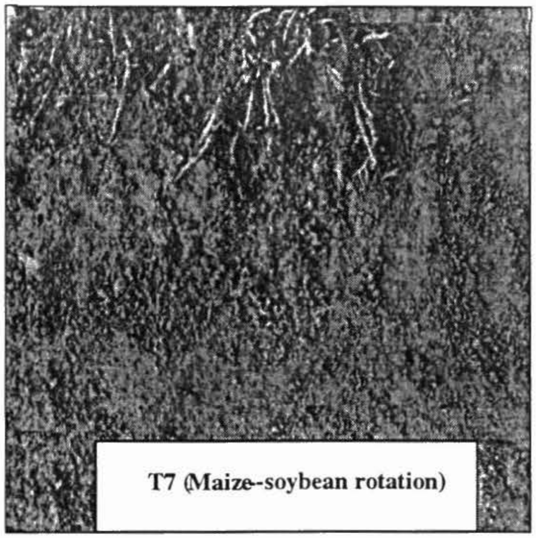


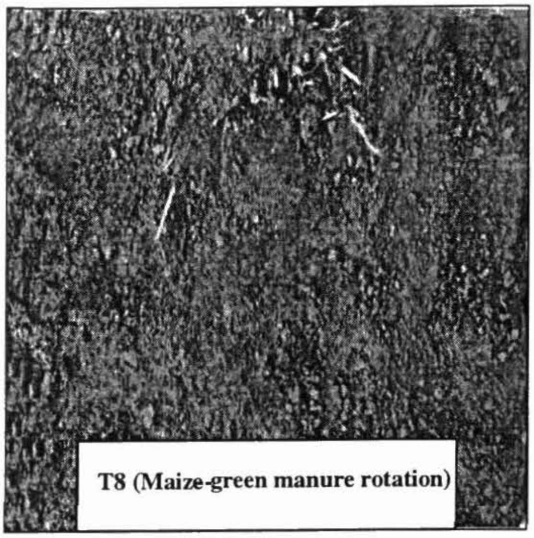


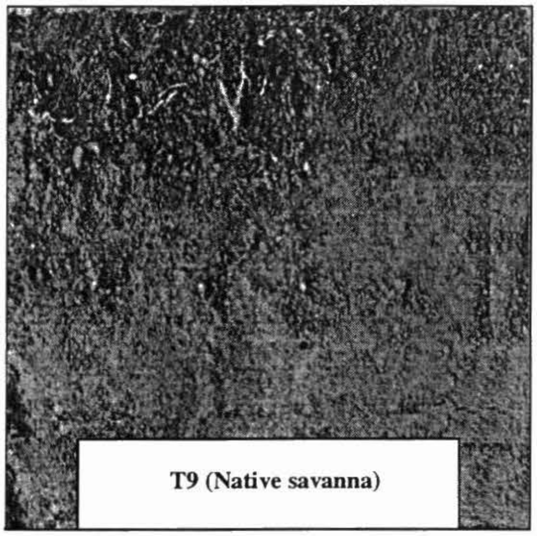


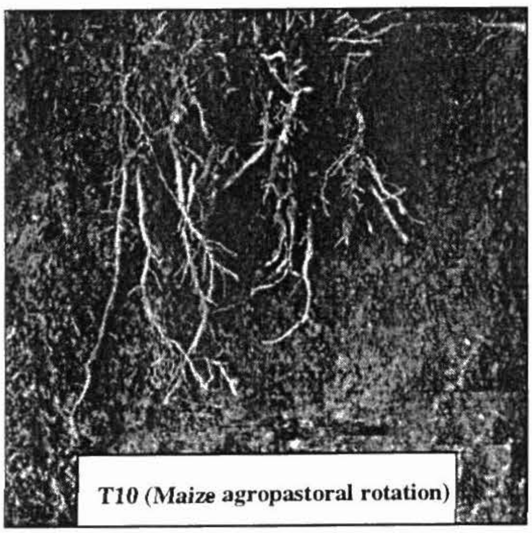
Picture 1. Influence of direct drilling on rooting depth of maize planted on different treatments of phase I of Culticore.


T6 (Maize monoculture)


T7 (Maize-soybean rotation)


T8 (Maize-green manure rotation)


T9 (Native savanna)


T10 (Maize agropastoral rotation)

Picture 2. Influence of chisel + direct drilling on rooting depth of maize planted on different treatments of phase I of Culticore.

Examination of soil monoliths showed marked differences in root penetration (Pictures 1 and 2) Chisel + direct drilling improved rooting depth of maize on plots from both rice-based and maize-based systems but direct drilling was more effective than chisel + direct drilling. Rooting depth was less than 14 cm for maize when it was planted on plots from Native savanna treatment. The greatest value of rooting depth of about 40 cm was observed on the plots from maize + soybean (green manure) rotation. This observation indicates that incorporation of green manure significantly improved soil physical conditions for root penetration. Results on rooting depth on savanna plots indicate that savanna soils do not support adequate root penetration.

Table 22. Effect of direct drilling or chisel + direct drilling on grain yield of maize planted on plots that were under different treatments of Culticore phase I (Carimagua, Colombia). LSD values are at 0.05 probability level.

Tillage method	*Culticore phase I systems*	Grain yield (t ha^{-1})	Rooting depth (cm)
Direct drilling	Rice monocrop – T1	3.29	15
	Rice + Cowpea (grain) – T2	3.71	17
	Rice + Cowpea (green manure) – T3	3.47	21
	Grass + Legumes pasture[1] – T5	3.70	34
	Native savanna – T4	1.28	9
	Mean	***3.09***	***19***
Chisel + direct drilling	Rice monocrop	3.22	20
	Rice + Cowpea (grain)	2.23	19
	Rice + Cowpea (green manure)	1.96	23
	Grass + Legumes pasture[1]	3.24	32
	Native savanna	1.15	12
	Mean	***2.36***	***21***
$LSD_{0.05}$		1.06	
Direct drilling	Maize monocrop – T6	3.80	34
	Maize + Soybean (grain) – T7	3.80	22
	Maize + Soybean (green manure) – T8	4.71	40
	Grass + Legumes pasture[2] – T10	4.24	36
	Native savanna – T9	1.64	13
	Mean	***3.63***	***29***
Chisel + direct drilling	Maize monocrop	2.04	20
	Maize + Soybean (grain)	2.69	14
	Maize + Soybean (green manure)	2.37	18
	Grass + Legumes pasture[2]	4.12	35
	Native savanna	1.31	9
	Mean	***2.51***	***19***
$LSD_{0.05}$		1.07	

[1] *Brachiaria humidicola + Centrosema acutifolium + Stylosanthes capitata + Arachis pintoi*
[2] *Panicum maximum + Glycine wightii + Arachis pintoi*

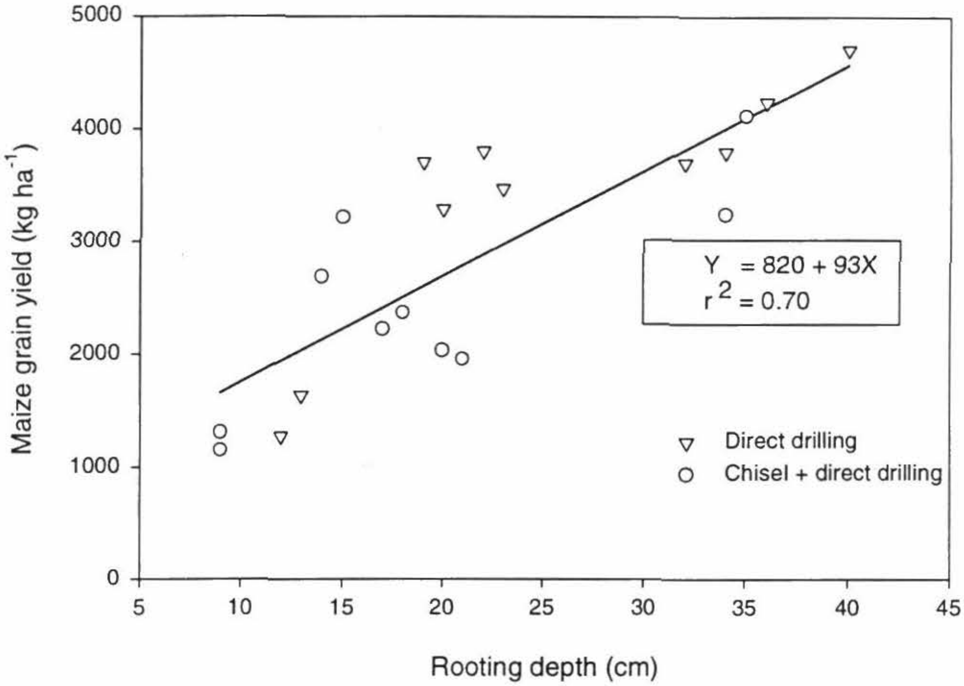


Figure 16. Relationship between grain yield and rooting depth of maize as influenced by direct drilling and chisel + direct drilling on plots that were under different treatments of Culticore phase I (Carimagua, Colombia).

Impact:
Results from this study illustrate the importance of improving rooting depth of maize to enhance crop performance and to sustain grain yields. This could be an important objective for maize breeders that are involved in developing acid soil adapted maize varieties and hybrids.

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Activity 1.6 Test compatibility of plant components in different systems (including farmer participation)

1.6.1 On-farm evaluation of green manures in Nicaragua

Highlights:

- Green manure evaluation sites established in 8 communities of San Dionisio
- Community field days carried out and key informants identified
- Participatory learning process initiated

Purpose:
To identify promising multipurpose legume components adapted to local conditions to be used in diversified cropping systems

Rationale:
Farmers are increasingly concerned about the market value of their harvest products in relation to increasing costs of purchased inputs. At the same time soil fertility on farmer fields is decreasing. Weeds become a larger problem over time. In order to overcome these limitations, with the support of CIAT, the local farmer organization "Campos Verdes" initiated a project to introduce, evaluate and promote the use of cover crops and green manures (CCGM) in the communities of San Dionisio. CCGM legumes may significantly contribute to enhanced soil fertility, water and soil conservation and weed suppression. Some of these green manure crops show high drought tolerance and can be used as forage or even for human consumption. It was also taken into account that growing CCGMs may result in a smaller amount of applied agrochemicals, which are already contaminating the scarce water resources of the people in San Dionisio. While plant adaptation/management and technical feasibility are important factors, economic viability is considered decisive for adoption. Therefore, cost-benefit analyses are one of the main objectives of the project in order to compare the current management including N-fertilizer and agrochemical application with the use of cover crops. Further objectives are the demonstration of the multiple uses offered by CCGM including their drought tolerance, participatory learning about CCGM, their management within the local community and the identification of key informants on local organic matter management techniques and indicators.

Materials and Methods:
A workshop was held in San Dionisio in April 2001 to which all members of Campos Verdes had been invited. A total of 27 farmers assisted the event and the proposed project was presented and discussed. Sites with different soil and climate conditions throughout San Dionisio were identified and CCGM options discussed. Farmers chose *Mucuna pruriens*, *Canavalia ensiformis* and *Lablab purpureus* as CCGMs for the experiment. At the end of September 2001 the experiments were established on 8 farms in different communities of San Dioniso (Table 23). The experiments consist of seven treatments which were arranged in a randomized block design with 3 replicates at each site. The treatments are summarized in Table 24. CCGM legumes were sown in maize plots (4 x 4 m) at the traditional bean sowing distance (0.4 x 0.4 m). Legume evaluation will be carried out on a monthly basis recording field emergence, plant height, ground cover, incidence of pests and diseases, weed presence, biomass production, drought tolerance, flowering patterns and seed production. Soil samples will be taken prior to the establishment of the experiments, prior to the maize planting and at the end of the experiments and analyzed. CCGMs will be kept in the maize plots throughout the dry season and maize will be planted into the CCGM mulch on the onset of the wet season. Fertilizer treatments will be applied and maize yields recorded. Pest, disease and weed incidence will be evaluated throughout the project. Cost-benefit analyses will be conducted and presented in a final workshop in November 2002. Field days will be held at strategic points of the project (legume establishment, legume drought tolerance, mulching and maize planting, maize harvest) in order to demonstrate and discuss practical management issues with the communities. By discussing soil fertility issues key informants for local soil organic matter management techniques and indicators will be identified and interviewed subsequently.

Results and Discussion:
Local on-farm evaluation data and economic analyses will be available for further promotion and dissemination of CCGM legume species. It is expected that a growing number of farmers in San Dionisio will adopt CCGMs technologies for growing maize in the future and will show further interest in other legume species. Local indicators for soil organic matter will be identified and the local knowledge on the management of soil organic matter documented.

Table 23. Location and site description of on-farm cover crop/green manure experiments in San Dionisio, Nicaragua.

Farmer	Community	Latitude	Longitud	Altitude	Observations
D. Salgado	Piedra Colorada	12° 49' 47.2 N	85° 51' 51.1" W	504	River valley
A. Castro	Susuli central	12° 48' 29.2" N	85° 50' 24.5" W	564	Slope
J. Hernández	Susuli arriba	12° 47' 48.0" N	85° 50' 05.2" W	565	Steep slope
V. Sevilla	Corozo	12° 47' 02.2" N	85° 52' 17.6" W	484	Slope
J. Orozco	Carrizal	12° 47' 08.2" N	85° 54' 15.0" W	715	Moderate slope
J. Jarquín	Piedras Largas	12° 43' 32.6" N	85° 49' 43.1" W	474	Slope
J. Hernández	Jícaro	12° 46' 19.2" N	85° 50' 15.6" W	530	Very steep slope
E. Ochoa	Ocote arriba	12° 43' 00.4" N	85° 52' 22.0" W	858	Slope

Table 24. Treatments included in on-farm cover crop/green manure experiments in San Dionisio, Nicaragua.

Treatment	Year 2001*	Year 2002
1	Maize	Maize without N-fertilizer (Control)
2	Maize	Maize with low N-fertilizer level
3	Maize	Maize with high N-fertilizer level
4	Maize	Maize with very high N-fertilizer level
5	Maize with *Mucuna*	Maize without N-fertilizer
6	Maize with *Canavalia*	Maize without N-fertilizer
7	Maize with *Lablab*	Maize without N-fertilizer

- Cover crops/green manures were sown into existing maize plots in September 2001when maize was entering its mature stage.

Contributors:

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Output 2. Strategies developed to protect and improve soil quality

Activity 2.1 Develop a concept of, and strategies for, the establishment and maintenance of an "arable layer" for sustainable production

2.1.1 Determine the impact of disc harrowing intensity on soil properties and plant growth of agropastoral systems in the llanos of Colombia

Highlight:

- Showed that the maize and green manure cropping systems were better than the grass alone pasture system at separating the effect of increased number of disc harrow passes on soil physical and chemical characteristics.

Purpose:

To determine the impact of intensive disc harrowing on soil physical and chemical properties, soil phosphorus dynamics, plant growth and nutrient acquisition of contrasting agropastoral systems on an oxisol.

Rationale:

The sustainable management of savanna Oxisols is of high ecological and socioeconomic significance. Production systems in the most intensified areas of the savanna are characterized by continuous monocropping and continuous tillage with heavy machinery. While these systems are economically profitable, they result in soil erosion, compaction, reduced microbiological activity, declining quality of organic matter and deterioration of other soil physical properties. These soils are more susceptible to degradation than most soils, often degrading within 5 years of being opened up for agricultural production.

Soils in the 'Llanos' are characterized as highly acidic and infertile Oxisols and Ultisols, whose mineralogy is dominated by kaolinite and the oxides and hydrous oxides of iron and aluminum. Oxisols have a stable microstructure caused by strong aggregation of negatively charged kaolinite and positively charged gibbsite and goethite. However, these soils are susceptible to physical, chemical, and biological degradation once brought into cultivation.

Tillage practices with heavy machinery physically break macroaggregates into smaller units, leading to new surfaces. These changes in soil structure act on the pore-size distribution and thus influence drainage or plant-available water content. Pore-size distribution is one sensitive soil physical property that can be used to evaluate the influence of tillage on the physical condition of the soil because it regulates the rate of water entry into the soil. It also influences soil water fluxes, which affect plant nutrient availability and plant growth. Three important phenomena related to plant nutrition, which are negatively affected by reduction in macropores are: root growth, nutrient interception by roots, and soil drainage and aeration. Soil porosity of below 10 % will generally limit crop and pasture production. Reduced water infiltration encourages surface water run-off and, consequently, soil and plant nutrient losses brought about by soil erosion.

Phosphorus (P), which has a low mobility, particularly in Oxisols, is likely to be greatly affected by tillage practice. Soil disturbance during tillage operations may increase the degree of contact between fertilizer-derived P and soil particles, thereby, promoting the formation of stable insoluble P compounds. Oxisols of the 'Llanos' are characterized by low total and available P contents, and a relatively high P retention capacity. Phosphorus deficiency often limits crop and pasture productivity in these soils and is caused mainly by strong sorption of inorganic P (P_i) to Al and Fe oxyhydroxides. The bioavailability of these secondary Al and Fe phosphates is considered to be low because of specific adsorption caused by ligand exchange. Knowledge on phosphorus cycling in these soils is limited. In the past, only readily available P was determined which may not effectively reflect plant-available P. This is because organic P (P_o) fractions are believed to contribute proportionately more with increasing P deficiency.

Soil compaction also hinders extensive root growth and reduces the soil volume from which plants can obtain P. Continuous cropping of a native soil also disrupts the peds (∅ > 2 mm), leading to loss of organic carbon and associated nutrients such as P. This implies that land preparation practices should be planned by taking into account the drastic reduction in soil aggregate size brought about by excessive use of machinery and it's resultant negative effect on physical, chemical and biological properties of the soil. A highly successful strategy for intensifying agricultural production sustainably and reversing problems of degradation involves the integration of crop/livestock systems, generally known as agropastoral systems.

In 1995 a field experiment was established in the 'Llanos' of Colombia to develop adequate soil tillage practices that could enhance the performance of agropastoral systems by improving plant growth, nutrient acquisition and nutrient cycling while minimizing the risk of soil degradation. The main objective of the present study was to determine the impact of intensive disc harrowing on: (i) soil physical and chemical properties; (ii) soil phosphorus dynamics; and (iii) plant growth and nutrient acquisition by contrasting agropastoral systems.

Materials and Methods:
Site description and experimental design: The experiment was carried out at Matazul farm (4° 9′ 4.9″ N, 72° 38′ 23″ W and 260 m.a.s.l.) located in the Eastern Plains (Llanos) near Puerto Lopez, Colombia. The area has two distinct climatic seasons, a wet season from the beginning of March to December and a dry season from December to the first week of March and has an annual average temperature of 26.2 °C. The area has mean annual rainfall of 2719 mm, potential evapotranspiration of 1623 mm and relative humidity of 81 % (data from the nearby Santa Rosa weather station, located at the Piedmont of the Llanos of Colombia). Prior to treatment application, the area was under a native savanna pasture consisting of native grasses. The land is generally flat (slope < 5 %), the soil is deep, well structured and has a textural distribution in the first 10 cm of about 40 % clay, 30 % silt and 30 % sand (loam texture). The bulk density in the native savanna is 1.30 g cm^{-3} in the top 0-5 cm soil layer, followed by lower values of 1.27 and 1.23 g cm^{-3} at the 5-10 and 10-20 cm soil layers, respectively. The soil has low fertility and the availability of P in the soil is low because of the soil's high P fixation capacity. The soil is classified as Isohyperthermic Kaolinitic Typic Haplustox in the USDA soil classification system.

The native savanna pasture (unimproved grassland) was opened in the third week of April 1995 and upland rice (cv. Oryzica Sabana-6) was planted with different intensities of tillage (2, 4 or 8 disc harrow passes) to a depth of 8 to 10 cm. Each tillage treatment had a plot size of 54 x 20 m. These treatments continued for 2 years with upland rice cultivation. At the beginning of the third year (third week of April 1997), each tillage main plot was used to introduce the following 3 cropping systems: (i) Grass alone pasture (*Brachiaria dictyoneura* CIAT 6133 cv. Llanero), (ii) Green manure (*Crotalaria juncea* cv. Common), and (ii) Maize (*Zea mays* cv. Sikuani 110). Native savanna was also included as a control to study changes in the soil conditions without tillage.

The treatments were arranged in a split-plot design (tillage intensity as main plots and cropping systems as sub-plots) and replicated four times. The size of each main plot was 42 x 10 m and sub-plot was 10 x 10 m leaving a border of 6 m between plots. Dolomitic lime (28% Ca and 10% Mg) was applied (Mg ha^{-1}) 1.0 for maize, 0.5 for Crotalaria and 0.5 for grass-alone pasture. Maize received (kg ha^{-1}) 80 N as urea; 50 P as TSP; 100 K as KCl; 8 Zn as $ZnSO_4$; 4 S as $ZnSO_4$; and 9 B as borax. *Crotalaria* received 22.5 N; 40P and 50 K. Grass-alone pasture received 20 P, 45 K and 4 Zn. Native savanna treatment received no fertilizer application as commonly practiced by farmers in the region.

Soil and plant sampling and analytical procedures: In the last week of June 1997 (2 months after establishment of agropastoral systems), soil samples from different agropastoral systems including native savanna were collected. The pore-size distribution was determined from the moisture characteristic curves. Undisturbed soil cores (50 x 25 mm) in four replicates per depth in each treatment were taken from: 0-5, 5-10 and 10-20 cm soil layers. Saturated soil cores were weighed and then subjected to different suctions (5, 10, 100, 300 and 1500 KPa). Pore-size distribution was calculated using Kelvin Equation. Pores were divided into macropores (> 50 μm; drained at a suction of less than or equal to 6 KPa), mesopores (50 to 0.2 μm; water retained between 6 – 1500 KPa), and micropores (< 0.2 μm; water retained over 1500 KPa. A composite soil sample, consisting of 50 cores, was also collected in a grid pattern from the whole plot. These samples were air-dried, and then visible plant roots were removed before they were gently crushed to pass through a 2-mm sieve. The < 2-mm fraction was used for subsequent chemical analysis. Other measurements that were made included: bulk density, soil nutrient availability, shoot biomass, plant nutrient composition, and shoot nutrient uptake.

Phosphorus fractionation and analysis: A shortened and modified sequential P fractionation procedure was used on 0.5-g sieved (< 2-mm) soil sample. 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 determined. (1) resin P_i, anion exchange resin membranes (in bicarbonate form) were used to extract freely exchangeable P_i. The remaining P_o in the H_2O of the resin extraction step was digested with potassium persulfate ($K_2S_2O_8$). (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. (3) Sodium hydroxide (0.1 *M* NaOH) was next used to remove P_i, which is more strongly bound to Fe and Al compounds and associated with humic compounds. (4) The residue containing insoluble P_i and more stable P_o forms ('residual P') was digested with perchloric acid ($HClO_4$). To determine total P in the $NaHCO_3$ and NaOH extracts, an aliquot of the extracts was digested with $K_2S_2O_8$ in H_2SO_4 at >150 °C to oxidize organic matter. 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 calorimetrically by the molybdate-ascorbic acid method. All laboratory analyses were conducted in duplicate determinations and the results are expressed on an oven-dry weight basis.

Statistical analysis: Analyses of variances were conducted to determine the significance of the effects of the planted fallows and the crop rotation system on soil parameters. Planned F ratio was calculated as TMS/EMS, where TMS is the treatment mean square and EMS is the error mean square. Where significant F-values (at the 5 % level) occurred, mean separation was performed. Unless otherwise stated, mention of statistical significance refers to $P < 0.05$.

Results and Discussion:

Soil properties: Changes in total porosity and macroporosity as influenced by the intensity of disc harrowing are shown in Figure 17. Intensive disc harrowing improved macroporosity values of 0-5 cm soil layer up to 59 % for grass alone pasture system compared to native savanna. In general, disc harrowing improved macroporosity values of different agropastoral systems compared to native savanna. Intensive disc harrowing (8 passes per year) increased macroporosity values of 0-5 and 10-20 cm soil depth layers of the maize system. At 10-20 cm soil depth, while total porosity was not affected by the intensity of disc harrowing for each system, macroporosity significantly increased for pasture system. Mesoporosity and microporosity values were not much affected by the intensity of disc harrowing for different agropastoral systems (results not shown).

Results on the influence of the number of disc harrow passes on soil bulk density are shown in Table 25. One important aspect to note with regards to bulk density in native savanna is the presence of a high value (1.26 $g.cm^{-3}$) in the 0-5 cm soil layer. Disc harrowing at 2, 4, and 8 passes per year significantly reduced bulk densities for pasture compared to the native savanna in the 0-5 cm soil layer (Table 25). Bulk density values were relatively unaffected by disc harrowing intensity for the green manure and maize systems. For 5 to 10 cm soil depth, disc harrowing resulted in a small decrease of bulk density for pasture system. Intensive disc harrowing (8 passes per year) significantly increased bulk density values of the green manure system at 5-10 cm soil depth. Volumetric moisture content values of the native savanna system were greater than those of the other systems at 0-5 cm soil depth (Table 25). Intensive disc harrowing (8 passes per year) significantly improved volumetric moisture content of green manure and maize systems at 5-10 cm soil depth compared with 2 passes per year. Grass alone pasture system showed no marked changes in volumetric moisture content across soil layers.

Soil chemical characteristics at different soil depth layers as influenced by the intensity of disc harrowing and agropastoral systems are shown in Table 26. Native savanna system without tillage and fertilizer application has shown low values of soil pH, available P and exgangeable K, Ca and Mg. The amount of available P (Bray II) decreased sharply below the 5-10 cm soil layer under all the systems tested. The amount of P was largest under the green manure and this was followed by the maize treatment (Table 26). At the 0-5 and 5-10 cm soil layers under the green manure and the maize cropping systems, the amount of P increased as the number of disc harrow passes per year were increased. However, for the maize treatment this increase was significant only at the 5-10 cm soil layer (Table 26). The grass alone pasture had the least amount of P and was, on average, 56 % lower at the 0-5 cm soil layer than the green manure treatment, which had the largest amount. The largest amount of exchangeable K was observed under the maize treatment and the second largest amount was observed under the green manure treatment. Most of K was found at the 0.5 cm soil layer in all the cropping systems and decreased rapidly after this soil layer, especially in the grass alone pasture system. Under the maize and grass alone pasture systems, the amount of K tended to decrease as the number of disc harrow passes were increased from 2, 4 to 8 per year (Table 26). The amounts of exchangeable Ca and Mg were largest in the maize treatment followed by the green manure cropping system. The number of disc harrow passes did not significantly affect the amount of Ca or Mg at all soil layers under the grass alone pasture and the green manure cropping systems. The amount of exchangeable Al was larger under the grass alone pasture compared to the green manure or the maize cropping system and it was not significantly affected by the number of disc harrow passes.

Soil P pools: The amount of extractable biologically available P was generally concentrated in the 0-5 and 5-10 cm soil layers and differed with the cropping system used (Figure 18). The largest amount of this fraction was obtained under the green manure followed by maize and then grass alone pasture cropping system, which, on average, represented respectively 19 %, 13 % and 12 % of the total P at the 0-5 cm soil layer. However, this fraction showed decreasing trend with increasing soil depth under all three systems at 2, 4, and 8 disc harrow passes per year (Figure 18). Eight disc harrow passes per year resulted in the highest amount of biologically available P under green manure and maize at the 0-5 and 5-10 cm soil layers. The high amount of available P at 8 disc harrow passes per year resulted in high P uptake of maize under this treatment (Table 27). Under grass alone pasture the biologically available P was less affected by tillage practices than under the green manure and maize cropping systems. The biologically available P under the grass alone pasture treatment was affected significantly by number of disc harrow passes only at the 0-5 cm soil layer, where 2 disc harrow passes per year had the largest amount. The number of disc harrow passes had little effect on the biologically available P at the 20-40 cm soil layer (Figure 18), and the amount was the same under all three cropping systems.

Similar to the biologically available P, moderately available P also showed different trends under green manure, maize and grass alone pasture and decreased with increasing soil depth. This fraction accounted for 37, 34 and 30 % of the total P for green manure, maize and grass pasture, respectively. Thirty-three, 45 and 49 % of the extracted NaOH-P_t was in the organic fraction (NaOH-P_o) for green manure, maize and grass pasture, respectively, at the 0-5 cm soil layer (results not shown). The number of disc harrow passes resulted in larger differences of moderately available P at the 0-5, 5-10 and 10-20 cm soil layers under the green manure followed by the maize cropping system. Under the grass alone pasture treatment, the number of disc harrow passes had little effect on moderately available P for all soil layers (Figure 18). Under the green manure the largest amount of the moderately available P was obtained when 8 disc harrow passes per year were used followed by 2 disc harrow passes per year at the 0-5 cm soil layer. Under maize, on average, the largest amount of moderately available P was obtained with 8 disc harrow passes per year (Figure 18).

The largest amount of P was obtained in sparingly available P fraction and, on average, accounted for 46 %, 51 % and 57 % of the total P for the green manure, maize and grass alone pasture cropping systems, respectively, for all soil layers. The largest amount of the sparingly available P was extracted at 8 disc harrow passes per year (Figure 18). However, this fraction was highly variable under the green manure treatment and was not significantly affected by disc harrowing. Treatment effects were better separated under maize than under the grass alone pasture system (Figure 18).

The sum of organic P (Sum-P_o) was quite stable through out the profile with a small decrease in the amount with increasing soil depth (Figure 18). The amount of H_2O-P_o, $NaHCO_3$-P_o and NaOH-P_o were uniform throughout the soil profile and under all cropping systems and were 3-5, 17-23, and 73-78 % of the Sum-P_o, respectively. Treatment effects on Sum-P_o were more pronounced at the 0-5 and 5-10 cm soil layers. Under green manure the largest amount of Sum-P_o was obtained at 2 disc harrow passes per year under green manure and at 4 disc harrow passes per year under maize at the 0-5 cm soil layer. The Sum-P_o profile distribution was uniform under grass alone pasture with no significant differences among the intensity of disc harrow treatments.

Plant growth and nutrient acquisition: The effects of the intensity of disc harrowing on leaf biomass, stem biomass and total shoot biomass production and nutrient uptake of different agropastoral systems are shown in Table 27. Two passes of disc harrow per year (6 passes in 3 years) are sufficient for best performance of grass alone pasture in terms of both biomass production and nutrient acquisition. Additional disc harrowing resulted in a decreased leaf biomass production and reduced nutrient uptake (Table 27). Maize showed greater leaf biomass production and nutrient acquisition with 8 passes of disc harrow per year (Table 27). The green manure cropping system had greater leaf biomass production and nutrient acquisition, particularly Ca, with 4 disc harrow passes per year.

Land preparation by machinery leads to a constant breakdown and reduction in soil aggregate size. The action of rainfall and gravity results in a re-packing of these aggregates and, consequently, the total soil porosity and pore-sizes are reduced. The resulting changes in macroporosity affect water flow, which in turn affects nutrient availability and thus impact negatively on the productive capacity of the soil. Considering the low pore space at plant-available matrix potentials in Oxisols, the low amount of mesopores could make the soil prone to drought during dry spells in the rainy season. But we found no marked changes in mesopores of different agropastoral systems.

Results on total porosity suggest that the real rooting depth promoted by tillage was limited only down to 10 cm soil depth. Results on porosity also indicate that tillage of savanna soils could increase the volume of desired pore sizes (macropores) especially in the 0-10 cm soil depth. Good tillage practices that stimulate root growth could also contribute to better soil conditions.

Bulk density values of the native savanna soils suggest that the surface layer, which regulates the entry of water and the flux of air into the profile, exhibits less total porosity than the other layers. Therefore, for crop and pasture production, this constraint at topsoil depth must be alleviated by adequate tillage practices that maintain lower values of bulk density and reduce the risk of soil compaction. Disc harrowing significantly reduced bulk density values of the pasture system compared to the native savanna. Below 10 cm of soil depth, disc harrowing had relatively small effects on different agropastoral systems. This implies that disc harrowing reduced bulk density in the vicinity of the action of discs. Improvement in volumetric moisture content in the 5-10 cm soil layer with intensive disc harrowing observed with green manure and maize systems might have contributed to superior leaf growth and nutrient acquisition.

Although separating total P into seven fractions helps to elucidate the differences in size of various P fractions, the P fractions are of greater practical value when divided into fewer functional pools of similar availability with management implications. These pools can then be used to improve soil P management and serve as decision-making tools. In this study the P fractions are divided into three groups: (1) biologically available P; (2) moderately available P; and (3) sparingly available P. The biologically available P pool (H_2O-P_o, resin-P_i, and $NaHCO_3$-P_i and -P_o) is the first to be removed by plant roots and mycorrhizal fungi from the soil and is considered to be available to plants in a short time (from days to a few weeks). The resin P_i is 'readily available' for plant uptake. The bicarbonate-P_i is highly related to P uptake by plants. The H_2O-P_o and bicarbonate-P_o are considered 'readily mineralizable' and highly related to P uptake by plants. A close relationship is known to exist between resin P_i and P_o on weathered soils. The major component of labile P_o is a diester PO_4, which prevents it from binding strongly to soil minerals and makes it susceptible to rapid mineralization.

The amount of biologically available P was markedly greater with the green manure treatment followed by maize and grass alone pasture system. Eight disc harrow passes per year resulted in the highest amount of biologically available P under green manure and maize that could contribute to high uptake of P by maize. Under grass alone pasture the biologically available P was less affected by tillage practices than under the green manure and maize systems. This could be explained by the fact that only the soil within the vicinity of the disc harrow action (0-20 cm) was disturbed.

Moderately available P pool consists of NaOH extractable Pi and P_o, which is assumed to be plant available for the medium term, i.e., from months to a few years. This fraction denotes the soil P reserve that is plant available when converted to readily available P through biological and physico-chemical transformations. This fraction is thought to be associated with humic compounds, and with amorphous and some crystalline Al and Fe phosphates. The sodium hydroxide (0.1 *M*, pH = 8.5) used to extract moderately available P is known to completely solubilize the synthetic iron and aluminium phosphate and labile-P_o. Similar to the biologically available P, moderately available P also showed different trends under green manure, maize and grass alone pasture and decreased with increasing soil depth. Since the moderately available P is plant available in the medium term as outlined above, the high amount of this fraction at 8 disc harrow passes per year also could have contributed to the high P uptake of maize.

Sparingly available P as used in this study is different from the residual P, because it includes the HCl and the hot concentrated HCl fractions. The sparingly available P contains insoluble P_i and more stable P_o forms and is not available on a short time scale such as one or more crop cycles. However, a small fraction of this pool may become available during long-term soil P transformations. The largest amount of the sparingly available P was extracted at 8 disc harrow passes per year and treatment effects were better separated under maize than under the grass alone pasture system.

Since P loss from systems occurs mainly through processes in the soil, minimizing P interaction with soil is an important management tool for increasing P cycling. Phosphorus maintained in organic pools may be better protected from loss through fixation than P flowing through inorganic pools in soil. Orthophosphate monoesters fractions dominate the P_o fraction and are less easily hydrolyzable, and thus less plant available, than the orthophosphate diester fraction. Systems that retain more of P_o are expected to cycle P better. We found that the sum of organic P (Sum-P_o) was quite stable throughout the profile with a small decrease in the amount with increasing soil depth. This shows that 24 % of the total soil organic P (Sum-P_o) is in the 'easily mineralisable' form and can contribute to plant available P, and the remaining 76 % is in more stable forms of P_o that are involved in the long term transformation of P.

Two passes of disc harrow per year (6 passes in 3 years) were found to be sufficient for best performance of grass alone pasture. Additional disc harrowing resulted in a decreased shoot biomass production and reduced nutrient uptake. A high number of disc harrow passes is likely to create a marked reduction in soil pore volume and affect nutrient uptake by plants. Results from a greenhouse experiment indicated that *Brachiaria* grass growth and N uptake were greatly influenced by the size of soil aggregates. This study also showed that N uptake from soil was a function of aggregate size, indicating that any excess preparation of soil could negatively affect the uptake of this nutrient. It is possible that excessive tillage might have reduced moisture content in the upper soil layer that could decrease the ability to acquire nutrients by the introduced pasture grass.

Soil organic matter is an important component of Oxisols because it carries the majority of exchange sites and also participates in the formation of stable microaggregates and controls the degree of clay dispersion. More than two disc harrow passes per year for the grass alone pasture treatment could decrease the amount of soil organic matter. This is because of the physical breakdown of aggregates during ploughing and the subsequent higher organic carbon mineralization, which may have resulted in N and P losses through leaching and fixation by soil, respectively. This could have resulted in reduced nutrient uptake, particularly N, and thereby growth of the pasture.

Maize showed greater aboveground production and nutrient acquisition with 8 passes of disc harrow per year. This result, especially for maize, is unexpected considering the negative attributes of reduced soil moisture content and soil compaction resulting from increased disc harrowing, as mentioned earlier. The better performance of maize under intensive cultivation (8 disc harrow passes) could be attributed to improved rooting ability that contributed to greater acquisition of nutrients. The improved amounts of biologically and moderately available P obtained from 8 disc harrow passes could have contributed to the good performance of maize. Previous research showed that maize is a very shallow rooted crop compared to native and introduced pasture species. Since the mobility of P in soil is low, high levels of biologically available P can benefit shallow-rooted crops. In contrast to the maize system, the green manure cropping system had higher yields with 2 disc harrow passes per year that resulted in greater nutrient (N, P, Ca and Mg) acquisition.

Table 25. Changes in bulk density (g cm $^{-3}$) and volumetric moisture content (%) at different soil depths as influenced by the intensity of disc harrowing and agropastoral systems. LSD values are at the 0.05 probability level. NS = not significant.

Soil depth (cm)	Number of disc harrow passes per year	Native savanna	Agropastoral system			$LSD_{0.05}$
			Pasture	Green manure	Maize	
	Bulk density (g cm $^{-3}$)					
0-5	0	1.26				
	2		1.16	1.28	1.37	NS
	4		1.17	1.20	1.39	0.19
	8		1.13	1.47	1.31	0.12
	$LSD_{0.05}$		NS	0.23	NS	
5-10	0	1.48				
	2		1.40	1.34	1.39	NS
	4		1.37	1.37	1.41	NS
	8		1.40	1.58	1.44	0.16
	$LSD_{0.05}$		NS	0.16	NS	
10-20	0	1.42				
	2		1.46	1.46	1.43	NS
	4		1.38	1.43	1.40	NS
	8		1.42	1.48	1.35	0.11
	$LSD_{0.05}$		NS	NS	NS	
	Volumetric moisture content (%)					
0-5	0	35.6				
	2		31.9	32.2	32.8	NS
	4		31.7	32.0	32.0	NS
	8		30.5	35.8	30.5	NS
	$LSD_{0.05}$		NS	NS	NS	
5-10	0	39.5				
	2		37.5	32.0	33.3	3.0
	4		40.3	35.0	32.7	5.9
	8		37.7	38.2	35.2	1.5
	$LSD_{0.05}$		NS	2.5	1.3	
10-20	0	37.5				
	2		38.3	34.3	34.5	1.7
	4		37.1	36.9	33.2	2.4
	8		37.4	35.3	33.9	2.7
	$LSD_{0.05}$		NS	2.1	NS	

Table 26. Soil chemical characteristics at different soil depth layers as influenced by the intensity of disc harrowing and agropastoral systems

Soil depth (cm)	Disc harrow passes per year	pH	C (%)	P (mg kg⁻¹)	K	Ca	Mg	Al
					(cmol kg⁻¹ soil)			
				Native savanna				
0-5	0	4.8	1.1	3.2	0.1	0.2	0.2	2.6
5-10	0	5.0	1.3	4.6	0.1	0.4	0.3	2.0
10-20	0	4.9	1.2	1.2	0.04	0.1	0.2	2.2
20-40	0	4.4	1.1	1.3	0.02	0.2	0.2	1.8
				Pasture				
	2	4.9	2.6a	12.0ab	0.15a	0.72	0.46	1.7
0-5	4	4.9	2.0b	15.8a	0.13ab	0.72	0.42	1.7
	8	4.7	2.0b	9.5c	0.10c	0.53	0.36	1.9
	2	4.7ab	2.1	6.0	0.10a	0.48	0.21	1.9
5-10	4	4.8a	1.9	4.6	0.08b	0.55	0.20	2.0
	8	4.6b	1.9	4.3	0.08b	0.57	0.20	2.0
	2	4.6	1.7	1.8	0.06a	0.25	0.13	2.1
10-20	4	4.6	1.5	1.3	0.06a	0.18	0.13	2.1
	8	4.6	1.4	1.3	0.04b	0.25	0.15	2.2
	2	4.7	1.2	1.1	0.06a	0.15	0.12	1.6
20-40	4	4.6	1.1	1.4	0.04b	0.12	0.11	1.7
	8	4.6	1.1	1.0	0.04b	0.13	0.12	1.6
				Green manure				
	2	5.0	2.5a	36.7b	0.16	1.22	0.50	1.3
0-5	4	5.0	1.8b	38.4b	0.15	1.00	0.48	1.4
	8	4.8	1.9b	56.8a	0.12	0.98	0.37	1.7
	2	4.7b	2.0a	6.6b	0.13	0.44	0.30	2.1
5-10	4	4.9a	1.6b	9.3ab	0.09	0.65	0.30	1.9
	8	4.7b	2.0a	10.7a	0.10	0.67	0.31	2.0
	2	4.6b	1.7	2.1a	0.12a	0.23	0.14	2.1
10-20	4	4.8a	1.5	2.1a	0.07b	0.26	0.17	1.9
	8	4.6b	1.5	1.4b	0.07b	0.19	0.15	1.9
	2	4.7	1.3	1.5	0.07a	0.16	0.12	1.8
20-40	4	4.7	0.9	1.0	0.04b	0.16	0.14	1.7
	8	4.6	1.3	1.1	0.05ab	0.15	0.13	1.7
				Maize				
	2	4.8	2.1	20.5	0.26a	0.96	0.45ab	1.1ab
0-5	4	5.1	1.9	21.0	0.22b	1.29	0.56a	0.9b
	8	4.9	1.8	27.0	0.22b	1.01	0.42b	1.5a
	2	4.8	1.9	18.5b	0.15a	0.64	0.30	1.7
5-10	4	4.9	2.0	17.1b	0.11b	0.87	0.37	1.5
	8	4.9	1.8	24.2a	0.15a	0.79	0.35	1.8
	2	4.7	1.8	7.0	0.13a	0.41a	0.22b	2.0ab
10-20	4	4.7	1.3	4.6	0.08b	0.30b	0.20b	1.7b
	8	4.7	1.5	6.4	0.11a	0.43a	0.26a	2.3a
	2	4.6	1.6	2.2ab	0.09a	0.26	0.14	2.1
20-40	4	4.6	1.4	1.3b	0.06b	0.21	0.16	1.8
	8	4.6	1.5	3.0a	0.08a	0.24	0.16	2.1

Means in a given column followed by common letters are not significantly different ($P < 0.05$) using Duncan's Multiple Range Test.

Table 27. Leaf, stem and total shoot biomass production and nutrient uptake by grass alone pasture, green manure and maize systems as influenced by the intensity of disc harrowing.

Cropping system	Disk harrow passes per year	Leaf biomass (kg ha^{-1})	Stem biomass (kg ha^{-1})	Total shoot biomass (kg ha^{-1})	Nutrient uptake (kg ha^{-1}) N	P	K	Ca	Mg
Pasture	2 passes	726	1030	1756	19 a	4.7 a	34 ab	3.6	6.0 a
	4 passes	506	1107	1613	17 a	4.8 a	43 a	2.4	4.8 a
	8 passes	415	1079	1494	12 b	2.5 b	28 b	2.0	3.7 b
Green manure	2 passes	5076	1257	6333 b	185 b	18 ab	81	90 b	21 b
	4 passes	6154	1679	7833 a	227 a	20 a	88	135 a	35 a
	8 passes	4923	1091	6014 b	192 b	14 b	70	82 b	22 b
Maize	2 passes	4472 b	1855 b	6327 c	40 b	10 b	65 b	12 b	9 b
	4 passes	5417 b	2049 b	7466 b	54 b	8 b	94 b	18 ab	12 ab
	8 passes	8803 a	3316 a	12119 a	99 a	16 a	141 a	23 a	14 a

Means followed by different letters within a column and within a cropping system are significantly different ($P < 0.05$) using Duncan's Multiple Range Test.

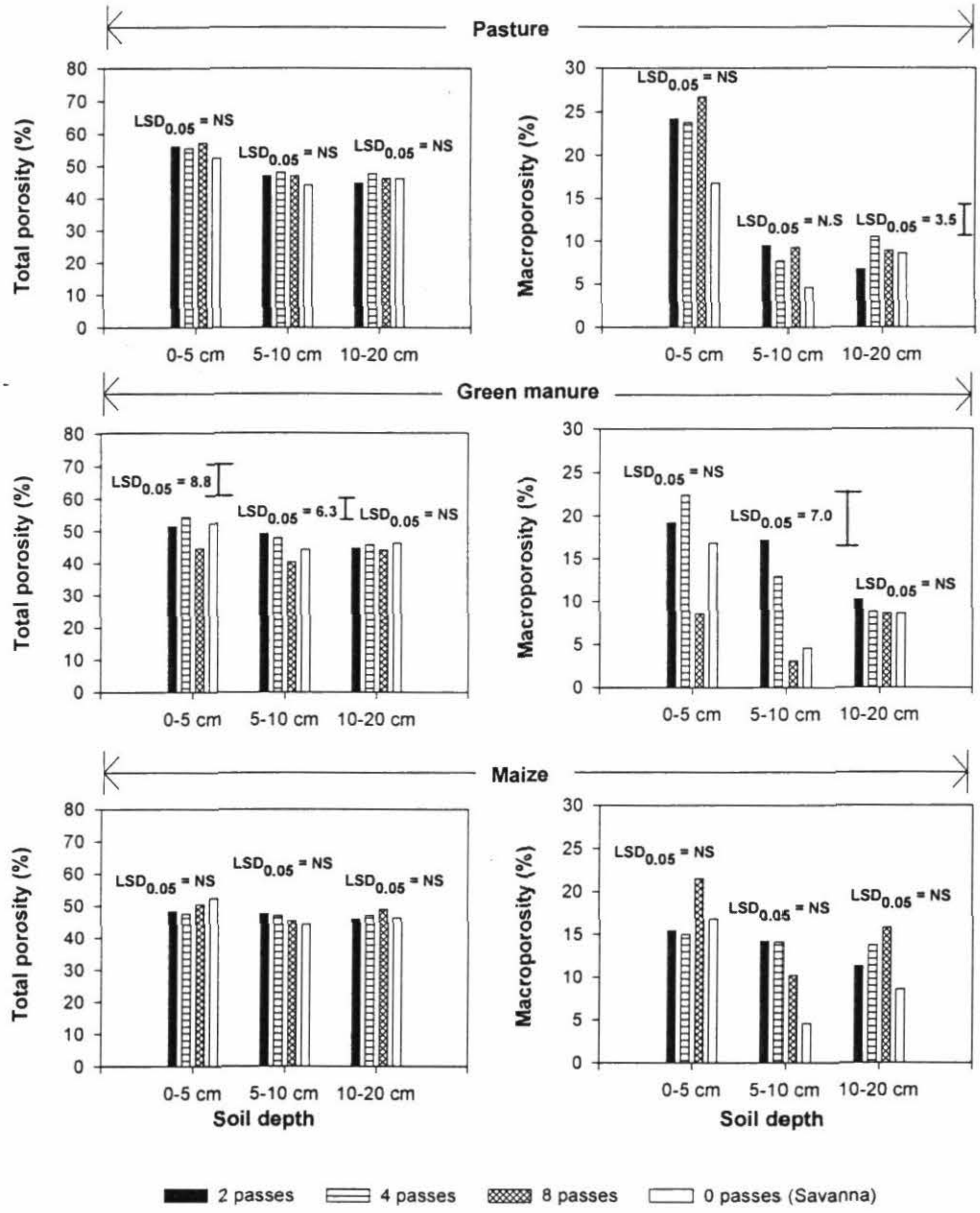

Figure 17. Changes in total porosity and macroporosity at different soil depth layers as affected by the intensity of disc harrowing and agropastoral systems. LSD values at 0.05 probability level. NS = not significant. The 0 number of passes represent the native savanna system.

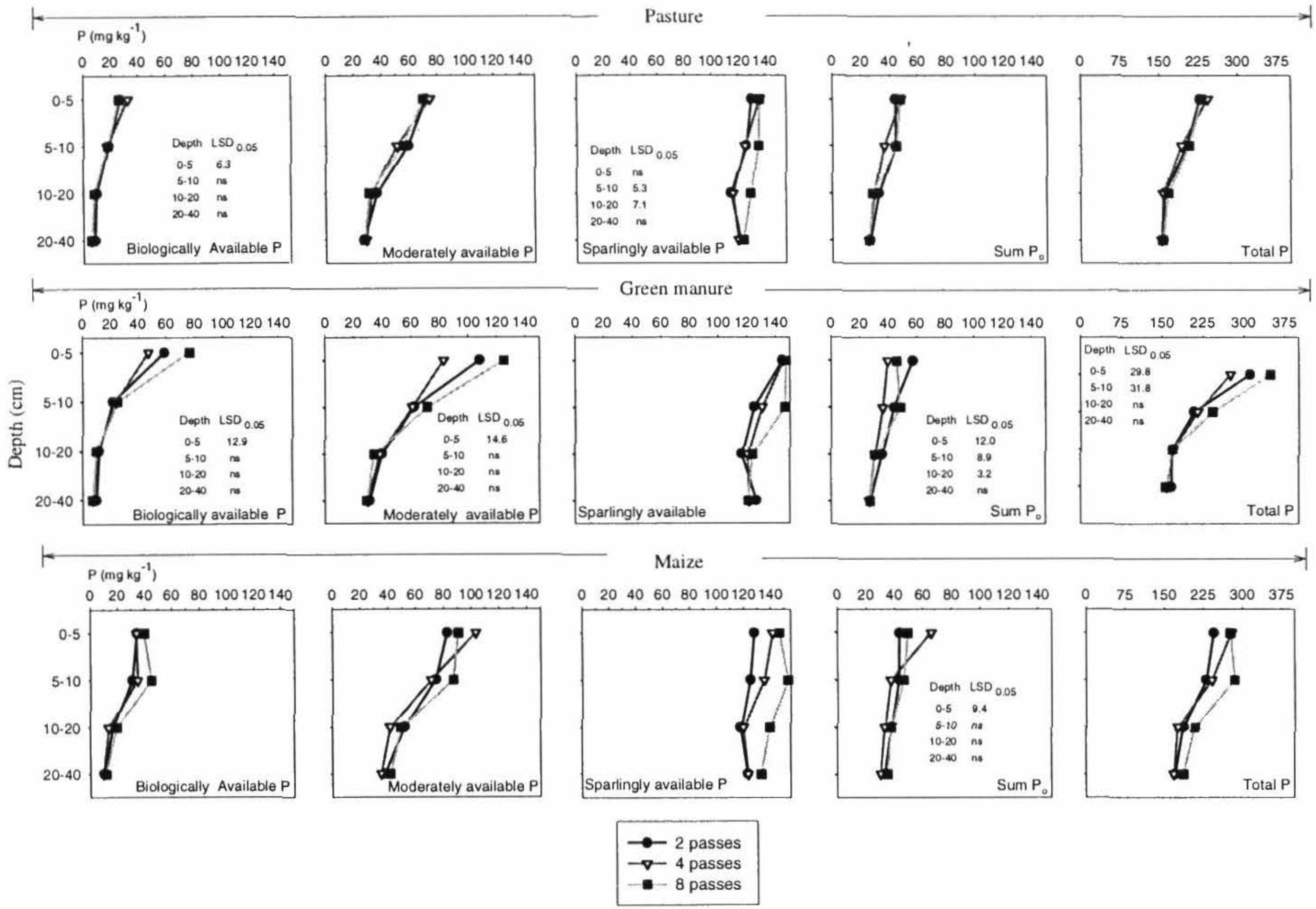

Figure 18. Soil profile distribution of the P fractions as affected by intensity of disc harrowing under the grass alone pasure, green manure and maize cropping systems.

Impact:
The results of this study showed that disc harrowing could reduce bulk density and improve total porosity and macroporosity, volumetric moisture content, and soil P availability in the topsoil layer of P-fixing Oxisols. However the impact of intensive disc harrowing (4 or 8 passes per year) on soil physical and chemical properties was dependent on the agropastoral system used. The maize and green manure cropping systems were better than the grass alone pasture system at separating the effect of increased number of disc harrow passes on soil physical and chemical characteristics.

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Activity 2.2 ***Develop strategies for nutrient acquisition and replenishment via efficient nutrient cycling and integrated nutrient management***

2.2.1 Impact of contrasting agricultural systems on P cycling as determined by sequential P extraction of ^{33}P-labelled oxisol

Highlight:
- Showed that organic P is involved in short term P dynamics in soils with low or no P fertilization.

Purpose:
To evaluate the impact of contrasting agricultural systems on P cycling as determined by Sequential phosphorus extraction of ^{33}P-labeled oxisol.

Rationale:
Knowledge of the P dynamics in the soil/plant system and especially of the short- and long-term fate of P fertilizer in relation to different management practices is essential for the sustainable management of tropical agroecosystems. Chemical sequential extraction procedures have been and still are widely used to divide extractable soil P into different inorganic and organic fractions. The underlying assumption in these approaches is that readily available soil P is removed first with mild extractants, while less available or plant-unavailable P can only be extracted with stronger acids and alkali.

In the fractionation procedure, the P fractions (in order of extraction) are interpreted as follows. Resin-P_i represents inorganic P (P_i) either from the soil solution or weakly adsorbed on (oxy)hydroxides or carbonates. Sodium bicarbonate 0.5 *M* at pH 8.5 also extracts weakly adsorbed P_i and easily hydrolysable organic P (P_o)-compounds like ribonucleic acids and glycerophosphate. Sodium hydroxide 0.5 *M* extracts P_i associated with amorphous and crystalline Al and Fe (oxy)hydroxides and clay minerals and P_o associated with organic compounds (fulvic and humic acids). Hydrochloric acid 1 *M* extracts P_i associated with apatite or octacalcium P. Hot concentrated HCl extracts P_i and P_o from more stable pools. Organic P extracted at this step may also come from particulate organic matter. Residual P, i.e. P that remains after extracting the soil with the already cited extractants, most likely contains very recalcitrant P_i and P_o forms.

Several studies related these different P fractions in tropical soils to plant growth. By testing the influence of land-use and the fate of applied fertilizers, these studies resulted in contrasting assignments of P fractions to pools of different availability. The results obtained in these studies suggest that, in tropical soils, the amounts of P in the different pools measured by sequential P extraction procedures and the fluxes of P between pools are controlled both by physico-chemical factors such as sorption and desorption and by biological reactions such as immobilization and mineralization. However, the importance of these processes for different land-use systems, such as monocropping, pasture or intercropping, remains largely unknown.

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

Materials and Methods:

Soils: The soils included in the study were sampled during the rainy season in September 1997 from a field experiment located at CORPOICA-CIAT (Corporacion Colombiana de Investigacion Agropecuario; Centro Internacional de Agricultura Tropical) research station, Carimagua, Meta, Colombia (4°30'N, 71°19'W). Mean annual temperature is 27° C, average rainfall 2200 mm. The soils are well drained Oxisols (tropeptic haplustox, isohyperthermic).

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

SAV (Native savanna): native grassland annually burned in February, not grazed; no fertilizer application.

GL (Grass-legume pasture): rice in 1993, with undersown pasture, since then grass-legume pasture with *Brachiaria humidicola* CIAT 679, *Centrosema acutifolium* CIAT 5277, *Stylosanthes capitata* CIAT 10280, and *Arachis pintoi* CIAT 17434. The pasture was partly resown for renovation in June 1996 with legumes (the same *Arachis pintoi*, additionally *Centrosema acutifolium* cv Vichada CIAT 5277 and *Stylosanthes guianensis* CIAT 11833). Grazing intensity was on average 2.7 steers ha^{-1} during 15 d followed by a 15 d ley regrowth phase.

CR (Continuous rice): rice (*Oryza sativa* cv Oryzica Sabana 6, cv Oryzica Sabana 10 since 1996) grown in monoculture; one crop per year followed by a weedy fallow incorporated with early land preparation at the beginning of the rainy season before sowing rice.

RGM (Rice green manure rotation): Rice followed by cowpea (*Vigna unguiculata,* var. ICA Menegua) in the same year. The legume was incorporated at the maximum standing biomass level in the late rainy season before sowing rice in the following rainy season.

At the beginning of the experiment all treatments except SAV were limed using 500 kg dolomitic lime ha^{-1}. Fertilization of rice was 80 kg N ha $year^{-1}$ (urea, divided among three applications), 60 kg P ha $year^{-1}$ (triple superphosphate), 99 kg K as KCl, 15 kg Mg and 20 kg S (as $MgSO_4$) and 10 kg Zn ha^{-1} at establishment and according to plant needs afterwards. With cowpea additionally 20 kg N and 40 kg P ha $year^{-1}$ and 60 kg K, 10 kg Mg, 13 kg S and 10 kg Zn ha^{-1} at establishment and in adequate rates afterwards were applied. The introduced pasture (GL) received additional fertilization only in 1996 (per ha: 20 kg P, 20 kg Ca (lime), 10 kg Mg (lime), 10 kg S (elemental) and 50 kg K (KCl)). Phosphorus input-output balances were estimated by subtracting the P removed from the system by grain and/or with animal live weight gains from the P applied in mineral fertilizers. Phosphorus exports in grain were calculated by multiplying weighed rice grain yields with measured P contents in grains. P exported in the animals was assumed to be 8 g per kg of live weight gain. Live weight gains in GL were on average 68 kg ha^{-1} yr^{-1}. Cultivated soils were tilled to a maximum of 15 cm depth. Topsoil samples (0-20 cm) were air-dried and sieved at 2 mm before they were used for chemical analysis in the analytical service laboratory of CIAT or shipped to Switzerland where they were stored in air-dried condition until use for the fractionation experiment in 2000.

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

Soil characterization: Bray-II P was extracted using dilute acid fluoride (0.03 *M* NH_4F, 0.1 *M* HCl) at 1:7 soil solution ratio using 2 g soil and 40 sec shaking time. Total soil P (P_{tot}) was determined on samples of 0.25 mg soil with addition of 5 mL concentrated H_2SO_4 and heating samples to 360° on a digestion block with subsequent stepwise (0.5 mL) additions of H_2O_2 until the solution was clear. Microbial P, C and N (P_{Chl}, C_{Chl} and N_{Chl}) were determined on the same moist, preincubated samples as for the sequential P fractionation by extraction, of chloroforme fumigated and unfumigated samples, with Bray I (0.03 *M* NH_4F, 0.025 *M* HCl) (P_{Chl}) or K_2SO_4 (C_{Chl} and N_{Chl}). No k-factors were used to calculate P_{mic}, C_{mic} or N_{mic} from measured P_{Chl}, C_{Chl} and N_{Chl} since there are no proper estimates for these acid tropical soils. P_{Chl} was corrected for sorption of released P. Dithionite-citrate-bicarbonate extractable and oxalate extractable Fe and Al (Fe_d, Fe_{ox}, Al_d, Al_{ox}) were determined. The mineralogy of the soils was determined on total soil samples, pretreated with H_2O_2 to remove organic C, using X-ray diffraction analysis (XRD) (Table 28). The samples were ground under acetone in a tungsten carbide vessel of a vibratory disk mill (Retsch RS1) for 10 minutes. Longer grinding times were not applied due to the detrimental effect that further grinding can have on the crystallinity of minerals, especially Fe (hydr) oxides. For the Cu Kα, the Bragg-Brentano geometry was chosen as an XRD routine setup. The measurement were carried out on a Scintag XDS 2000 equipped with a solid-state detector.

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

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

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

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

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

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

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

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

As fractionation data were compared to parameters measured with an isotopic exchange batch experiment described below, the influence of the experimental conditions of the isotopic exchange procedure on the ^{33}P and ^{31}P distribution in the different P fractions was checked. Six 1 g samples of each soil were shaken for 16 h on an overhead shaker with 9.9 mL deionized water. The samples were then stirred on a magnetic stirrer plate and labeled with the same amount as above of ^{33}P per g soil introduced in 100 µl deionized water per 1 g sample. The samples were stirred for 100 minutes to simulate the conditions of an isotopic exchange experiment and afterward left without further stirring at room temperature. The sequential soil P fractionation was started 4 hours after labeling by adding two resin strips to each sample. Whether the soil was labeled in a 1:10 shaken soil suspension or at 50 % of water holding capacity did not significantly influence either the ^{31}P or the ^{33}P concentrations in the different fractions 4 hours after labeling (data not shown).

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

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

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

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

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

Results and Discussion:

The mineralogy (Table 28) and the Fe and Al (oxy)hydroxides contents (Table 29) of the surface soil from the four treatments was normal for this type of soil and were almost identical among the different land-use systems (SAV, GL, CR, RGM). This implies that any difference seen in the P dynamics among land-use systems was mainly due to the land-use system and not to differences in the soil mineralogy.

Total soil P and P balance induced by the different treatments: The amounts of total P directly extracted from the soil samples (P_{tot}) were not significantly different from the sum of P (P_{sum}) extracted in the different fractions of the sequential extraction for SAV and CR while the direct extraction led to significantly higher values ($P<0.05$) for GL and RGM (Table 30). To evaluate whether differences in total P content in soils were related to P fertilization, the increase in P_{tot} content (calculated as the difference between total P extracted from fertilized GL, CR or RGM) and P_{tot} extracted from non fertilized SAV was compared to the estimated P balance of these treatments (significant correlation, r^2=0.87; $P<0.001$). The increases in P_{tot} were of the same order of magnitude as the calculated P balance. Given the imprecision of the methods used to determine total P contents and of the estimations made to calculate the P balance, these results suggest that most of the P added with fertilizers and not taken up by plants remained in the surface layers of the studied soils. Soil tillage may have mixed P in the 0-10 cm soil layer with soil in the 10-20 cm layer, resulting in incomplete recovery of P in the 0-10 cm sampling depth.

Isotopic exchange characteristics: The effect of the four land-use systems on P_i exchangeability in the surface layer of the studied soil is presented in Table 4. The ratio r_1/R, which is inversely correlated to the P sorbing capacity of soils, was below 0.05 for all treatments suggesting that these soils have a high P sorbing capacity. Furthermore, the r_1/R-values of the four treatments were positively correlated with the directly extracted total soil P (r^2=0.76 $P<0.001$). This suggests that the different land-use systems have resulted, through their different P fertilization and cropping, in different sorption rates of P_i on soil minerals. Since in Oxisols P sorption is governed by the Al and Fe (oxy)hydroxides, these treatments probably induced different degree of P_i saturation on the soil metallic (oxy)hydroxides such as gibbsite, which has been identified in these samples (Table 28).

The P_i concentration in the soil solution (C_p) was close to the detection limit in SAV, GL and CR treatments (Table 31). Although significantly different between all treatments, C_p was significantly increased only in the RGM treatment ($P<0.001$). In SAV, GL and CR, C_p was much lower than the critical concentration needed to sustain optimal growth for a large range of crops. The P_i concentration in the soil solution was not correlated with the total soil P content. The clear C_p increase in RGM was therefore not only due to an increase in total P but also to other mechanisms. The strong increase in soil biological activity observed in land-use systems including legumes might partly explain this higher C_p value. Variation in the amount of P_i isotopically exchangeable in one minute (E_1) followed the same trend as the variation in C_p.

P concentrations in different fractions of the sequential extraction: The positive P balances of the fertilized GL, CR and RGM treatments resulted in significantly higher P concentrations ($P<0.001$) compared to the savanna soil in all fractions except the organic fractions and residual P (Table 32). Our results show that resin-P_i, Bic-P_i and NaOH-P_i increased with P fertilizer input, with the NaOH-P_i fraction being the main sink for the applied P. This P sink function of the NaOH-P_i fraction can be explained by the adsorption of P_i through ligand exchange with hydroxyl groups located on the surface of Fe and Al (oxy)hydroxides and by the desorption of P_i from the surface of (oxy)hydroxides in the presence of 0.5 M NaOH.

During the continuous 2-week incubation of the soil samples, the resin and the Bic-P_i fractions increased significantly ($P<0.05$) between the first and second fractionation date for all soils (between 4 and 14 mg kg^{-1} for the sum of resin and Bic-P_i). There was no significant and corresponding decrease in any fraction although total extractable P_o tended to decline (between 8 and 18 mg kg^{-1}) for all soils (Table 32). The absence of significant compensating movements of P out of P_o fractions may be due to the high variability of the results, especially for the organic fractions where coefficients of variation for Bic-P_o were between 13 and 70 % and for NaOH-P_o between 7 and 45 %. Since P_o is determined by the difference between P_t and P_i there are multiple sources of error.

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

Distribution of ^{33}P among P fractions and dynamics over time: The fraction of ^{33}P recovered in the resin-P_i fraction 4 hours after labeling varied between 22 % in SAV and 60 % in RGM (Figure 19). The ^{33}P recovery in this fraction was positively correlated to the content of total P of the soils (r^2=0.87; $P<0.001$, 4 h after labeling). The corresponding decrease of ^{33}P in the resin fraction in RGM and CR corresponded with an increase in label recovery in Bic- and NaOH-P_i, while in SAV and GL the decline in resin ^{33}P was accompanied by an increase in ^{33}P in NaOH-P_o (GL also NaOH-P_i), HCl-P_i and residual-P. For SAV and GL, the label recovered in the resin-P_i, and Bic-P_i did not change much between the 1^{st} and the 2^{nd} week and the amount of ^{33}P in NaOH-P_i was stable over the entire incubation time. This shows that in SAV and GL the label was rapidly exchanged between these fractions and that equilibrium with the (labeled) soil solution was reached. In contrast, ^{33}P in the Bic-P_i and the NaOH-P_i of CR and RGM was still increasing after one week while the resin-$^{33}P_i$ continued to decrease, showing that the exchange between these fractions was incomplete.

Only small amounts of the label were found in organic fractions after 4 hours, but there were already significant differences in NaOH-^{33}Po ($P<0.001$) in the order:
SAV (4%) ≈ GL (2%) > CR (0.4 %) ≈ RGM (0.1 %).
This might be due to differences in microbial activity. Actually, the microbial biomass in incubated soils, indicated by measured P_{Chl}, C_{Chl} and N_{Chl} values, was significantly different between the soils (Table 33),

despite the fact that the samples had been stored in air-dried condition for more than three years before being used in this study. The assumption that recovery of the label in organic fractions was actually due to active processes and not to any analytical artifact is supported by the observed increases of NaOH-$^{33}P_o$ and HCl-$^{33}P_o$ for all soils over time. The total recovery of 20 % (SAV) or 14% (GL), respectively, of the label in organic fractions two weeks after labeling shows that these compartments have to be taken into account to understand the fate of P in these very low-P soils.

The proportion of label in the hot HCl and residual P fractions increased significantly with incubation time in all soils. This contradicts the prevailing opinion of recalcitrance of the P in these fractions. While the total P content in the residual fraction varied significantly with time (Table 32), this was not the case for hot HCl extractable P_i, while hot HCl extractable Po tended to decrease. This suggests that the movement of the label to these fractions was not due to net P-movement but to exchange processes.

Total ^{33}P label recovery: At all fractionation dates, in total between 67 % and 94 % of the applied ^{33}P label could be recovered in the sum of all fractions (Figure 19). This sum was generally in the order SAV < GL < CR < RGM. These incomplete recoveries can be explained by the fact that the method used to assess total P or residual P was not efficient enough to extract all P. Comparative studies have shown that total P can only be reliably extracted by alkali fusion, which could not be used in this work. The analysis of soil residues after the acid extraction of residual P (Table 34) indicated indeed that significant amounts of the label remained unextracted, these being higher for SAV and GL than CR and RGM. Although counting of ^{33}P bound to solid phases is generally possible, problems of phase, impurity, self absorption of scintillations by the soil particles or color quenching effects are difficult to correct, as these influences might be highly variable between samples. However, the recovery of standard additions of ^{33}P to our soil residues was complete and the correlation of the measured radioactivity in the different soil treatment residues with the sample weight was linear (data not shown), thus confirming the qualitative information obtained from the counting of the soil residues.

Altogether the results suggest that the transfer of ^{33}P among the different fractions determined by the sequential extraction was strongly dependent on the degree of saturation of soil Al and Fe (oxy)hydroxides with P_i, and therefore on the bonding energy of P_i to the soil minerals. It is indeed known that a high P_i saturation of metal oxide surfaces causes a more negative charge on the surface and prevents the specific sorption of further P_i ions. In the P poor soils (SAV and GL), most P_i would be sorbed with such a high energy that their exchangeability would be very limited. A specific sorption of ^{33}P to the surface of Al and Fe (oxy)hydroxides of these soils, although unlikely, cannot be excluded. In contrast, in the P rich soils (CR and RGM), the annual P additions might have resulted in the build up of relatively larger quantities of P_i exchangeable with ^{33}P.

Specific activities in the fractions determined by the sequential extraction: The highest specific activities (SA) observed in this incubation experiment were obtained in the resin extract after 4 hours of incubation (Table 35). This is consistent with the assumption that the amount of P desorbed from the soil by a resin is in very rapid exchange with P_i in the soil solution, as suggested by other studies. The subsequent decrease in the SA of resin-P_i reflected the process of isotopic exchange between ^{33}P and stable P_i located on the soil's solid phase. The order of the SAs in the P_i fractions after 4 hours of incubation followed the extraction sequence (resin-P_i>Bic-P_i>NaOH-P_i>HCl-P_i>residual P), showing that the strongest reactants extracted either large quantities of slowly exchangeable P or a large quantity of P in which only a small part was rapidly exchangeable. After 2 weeks the SAs of resin-P_i, Bic-P_i and NaOH-P_i became closer, suggesting that equilibrium with respect to P transfer between these fractions was being approached. The SAs of resin-P_i, Bic-P_t and NaOH-P_i were not significantly different in SAV and GL while the SA of resin-P_i was still significantly higher than the SA of Bic-P_i and NaOH-P_i in CR and RGM. These observations show that it is not possible to discuss the exchangeability of a certain P fraction without relation to a defined time of exchange.

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

Table 28. Mineralogy of the studied Colombian Oxisol under different agricultural systems, determined with X-ray diffraction.

Treatment †	Quartz	Kaolinite	Anatase	Rutile	Gibbsite	Vermiculite
	% of total soil weight					
SAV	72	21	3	2	2	<1
GL	67	23	4	2	·4	<1
CR	65	25	4	2	3	<1
RGM	67	24	4	2	3	<1

† SAV: Native savanna, GL: Grass-legume pasture, CR: Rice monoculture, RGM: Rice-green manure rotation.

Table 29. Selected chemical and physical properties of the surface soil (0-20 cm) of studied Colombian Oxisol under different agricultural systems. Values are the average of four analytical replicates, except Fe- and Al-contents (three replicates#).

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

† see Table 28.

‡ Extraction with dithionite.

§ Extraction with oxalate.

Means followed by the same letter are not significantly different (*P*=0.05) by Tukey's multiple range test. The absence of letter in a column shows that no significant differences were observed between the treatments.

Table 30. P status and calculated P balances of the studied Oxisol under different land-use systems. Total P as sum of the sequential P fractionation (P_{sum}) or extracted directly with H_2O_2 and H_2SO_4 (P_{tot}).

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

† see Table 28.

‡ P concentrations followed by the same lower case letter (within columns) or upper case letter (comparison of P_{sum} and P_{tot} within rows) are not significantly different (*P*=0.05) according to Tukey's test.

§ Δ P calculated as the difference between P_{sum} or P_{tot} of fertilized treatments – SAV.

¶ Calculated by subtracting the P removed by grain and/or animals from the P applied with mineral fertilizer.

Table 31. Parameters of isotopic exchange †

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

† Values are the average of three replications.

‡ see Table 28.

§ ratio of radioactivity remaining in soil solution to radioactivity added at time 0 after 1 minute of isotopic exchange.

¶ P concentration in the soil solution measured at soil:water ratio 1:10.

Quantity of P exchangeable within 1 minute.

Table 32. Distribution of P in various fractions of the modified Hedley fractionation in different agricultural systems with and without P application on an Oxisol, at three times of incubation after mixing the soils for label application.

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

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability level, respectively

† values within a column followed by the same letter do not differ significantly (P=0.05) according to Tukey's test.

‡ see Table 28.

Table 33. Size of the soil microbial biomass nutrient pool in different agricultural systems after 20 days of incubation of the formerly air-dried soils. Values are the averages of three replicates†.

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

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

† Means followed by the same letter are not significantly different (*P*=0.05) by Tukey's multiple range test.

‡ see Table 28.

Table 34. Radioactivity measured in soil solid residues by scintillation counting after extraction of residual P by sequential P fractionation starting 1 week after soil labeling.

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

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

Table 35. Specific activities ($^{33}P/^{31}P$) in isotopic exchange soil solution and in extracts of the Hedley sequential fractionation in the labeled Oxisols derived from different agricultural systems at different times after labeling. †

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

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

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

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

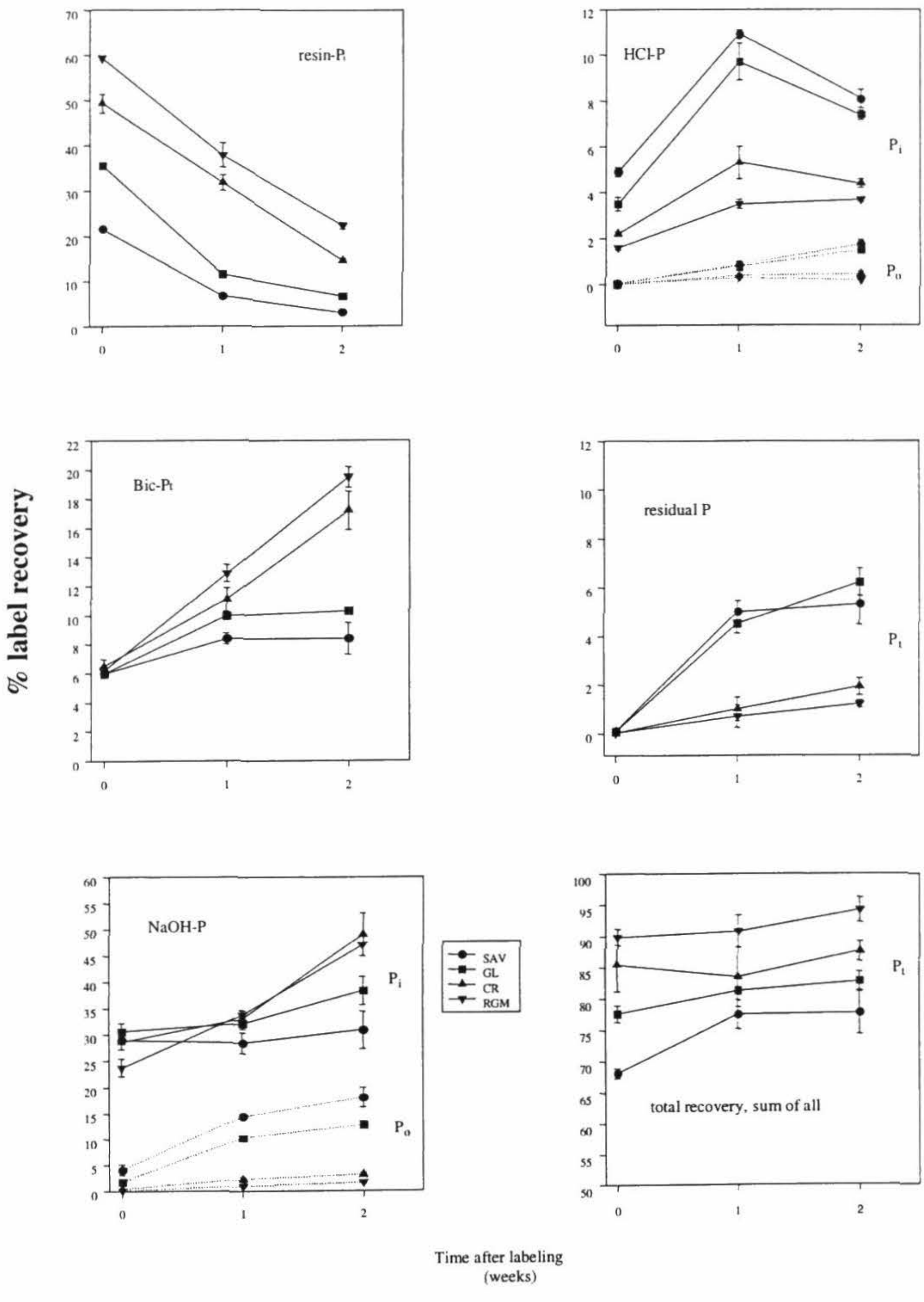

Figure 19. Percentage of label recovery in the different fractions of the sequential P extraction and in the sum of all fractions at 4 hours, 1 and 2 weeks after labeling soil (Means of three replicates ± SD).

Impact:
The effect of contrasting land-use systems on the P fractions extracted by the sequential fractionation procedure was assessed in an Oxisol during a 2-week incubation on soils labeled with carrier free ^{33}P. The results show that in the studied Oxisol, the quantities of ^{31}P and ^{33}P recovered in the different fractions were strongly dependent on the total P content of the soil, which was determined by the amount of P added by fertilizers and by plant P uptake. The importance of organic P pool for natural and low P input systems was pointed out from this detailed study. The extensive native savanna systems and introduced grass alone pasture systems in tropical Latin America on low P acid soils function with almost either no or very little external inorganic P inputs. This study indicates that an efficient cycling through organic P may be an important mechanism for the survival and adaptation of native and introduced tropical grasses in acid low P soils.

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2.2.2 Phosphorous fractions and dynamics in surface earthworm casts under native and improved grasslands in a Colombian savanna Oxisol

Highlight:
- Showed that earthworm surface casts represent a significant source of easily available P for plant roots.

Purpose:
To assess the effect of a native earthworm species on phosphorous availability in an Oxisol from the Colombian Llanos.

Rationale:
At present there exists increasing evidence of improvement of soil fertility through the effects of soil macroinvertebrate activities due to their role in soil organic matter transformations and nutrient dynamics at different spatial and temporal scales, what probably improves nutrient uptake by plants. Within the numerous animals that inhabit the soil, a few invertebrates have been defined as the "soil ecosystem engineers". By definition, ecosystem engineers are "those organisms that directly or indirectly modulate the availability of resources to other species by causing physical state changes in biotic or abiotic materials". This means that they are capable to regulate the trophic (organic matter) and spatial (habitat availability) resources in the soil through the production of physical bio-structures (e.g. casts, galleries and nests). Soil invertebrates are major determinants of soil processes, especially in tropical ecosystems.

Earthworms through their burrowing activities, mixing soil with litter and egesting casts inside the soil or at the soil surface, they affect the physical properties of soils, nutrient cycling and plant dynamics. To assess the contribution of these organisms in soil processes and ecosystem function, a previous step is the description of the phenomena that occur in the casts. Yet the impact on nutrient cycling has not been investigated in detail in tropical anecic earthworms, even though they significantly cast at the soil. For example, some studies have revealed higher contents of available phosphorous (P) (that can be uptaken by plants) in earthworm casts than in the control soil. Effects of earthworms on P are especially interesting since part of the pool, which is normally adsorbed onto the soil solid phase, may be desorbed after gut transit. These organisms have a notorious impact on mineralisation of P[δ], and are able to increase its

[δ] Phosphorous mineralization is an enzymatic process and a group of phosphatases are involved in the catalysis and release of phosphate from organic P compounds to the soil solution.

availability for plants in their casts. This process has been largely documented even for tropical and temperate species, and is the result of their high efficient digestive system while they excrete intestinal and cutaneous mucus that leaves nutrients in excess. In consequence, earthworms have an important role in improving nutrient availability and cycling in natural and agricultural ecosystems.

About 75% of soils in Neotropical savannas are strongly weathered, acidic and infertile soils belonging to the order of Oxisols. Low total and available P contents and a high P fixation capacity due to high contents of Fe and Al oxides characterize them. Most crops recover less than 20% of total fertilizer P applied to soils in these agroecosystems. The remainder is gradually rendered less available to succeeding crops by processes that slowly move P into more stable inorganic and organic pools in the soil. One strategy to increase the productivity and sustainability of production in such agroecosystems is to increase P recovery from these less accessible forms using crop and forage cultivars that are more efficient in acquiring P from theses pools and cycling it into pools more available to crops. The role of soil macroinvertebrates in P cycling must also be considered for their potential to release and make soil P available for plant uptake.

The potential of the Colombian savannas, an isohyperthermic ecosystem dominated by Oxisols, for both crop and livestock production systems is limited by the lack of available P for primary production. The conversion of native savanna into intensive pastures generally leads to a huge increase in earthworm biomass. *Martiodrilus carimaguensis* (Glossoscolecidae) is a large anecic native savanna earthworm from the Colombian "Llanos" which has been shown to affect soil processes and potential to take advantage from its activities in tropical agroecosystems.

Casts of large anecic *M. carimaguensis* are enriched in labile organic P, which suggests that this species improves the supply of P in soil under pastures by creating an available organic P pool. There is some evidence from soil P fractionation analyses which indicated that a high level of P cycling in intensive pastures contributed to their sustainability with very low P inputs. Based on these observations, we hypothesized that *M. carimaguensis*, through greatly increased population and their effect on soil P dynamics, is a major contributor to the sustainable productivity of intensive pastures on Colombian savannas Oxisols. The objective of this study was to determine the temporal dynamics of P fractions in casts and quantify P availability and enhanced P cycling in an Oxisol of the Colombian Llanos. The study involved both laboratory and field experiments to assess the impact of this species of high casting surface activity in nutrient cycling. Since earthworms can accelerate the mineralisation of organic matter by reducing the size of residues to particles more available to microbial populations one laboratory experiment aimed at the effect of incorporating finely ground vegetative material on P mineralization.

Materials and Methods:

Study site: This study was conducted during May-September 1994 at the CIAT-CORPOICA experimental station at Carimagua (4°30'N; 71°19'W; 150 m above sea level) located 320 km east of Villavicencio in the Eastern Plains of Colombia. The site is representative of the well-drained isohyperthermic savanna ecosystem. Mean annual rainfall and temperature are 2240 mm and 26.5 °C respectively. Rainfall distribution is characterized by a 4-month sharp dry season from December to March. Native vegetation varies with topography accordingly: open herbaceous savannas in the uplands ("altos"), and gallery forests or flooding savannas in the low-lying areas ("bajos"). Samplings were done in a well-drained silt-clay Oxisol (typic haplustox, fine kaolinitic, isohyperthermic). They are characterised by favourable physical properties, e.g. porosity and water retention, but high Al saturation (>80%) and low chemical fertility (Table 36).

Table 36. Soil physico-chemical properties in the native savanna and intensive pasture.

Treatment	$pH(H_2O)$	Total C	Total N	Bray-II P	Exchangeable cations				
					Al	Ca	Mg	K	H
		------- $mg\ g^{-1}$	---	$mg\ k^{-1}$	---------------		$cmol^+\ kg^{-1}$		----------
Savanna	4.80	23.5	1.45	1.3	2.42	0.26	0.11	0.08	0.27
Pasture	4.96	24.9	1.67	2.2	1.90	0.89	0.23	0.09	0.26

Background ecology of M. carimaguensis: Martiodrilus carimaguensis is a large dorsally pigmented earthworm 9.3 mm in diameter, 194 mm in length and weighing 9.2 g (in 4% formaline) on average. Its morphology and life history traits are like most anecic species but its feeding regime seems to be close to endogeic type and it only eats litter in an opportunistic way and exhibits a feeding regime mostly based on small casts of other earthworm species. The species is native to the well-drained savannas and is quite common in both the natural and managed ecosystems of Carimagua. The establishment of intensive pastures results in a spectacular increase of density compared to the native savanna, and the strategy to support the drought stress during the dry season is quite surprising. Juveniles enter into a physiologically-induced diapause deep in the soil by the middle of the rainy season, whereas adults present a similar behaviour with a lag of several months, i.e. at the end of the rainy season or just after their reproductive period, i.e. when they lay large cocoons (16% of adult weight) from September onwards.

Casts of M. carimaguensis: Martiodrilus carimaguensis remains active in the same burrow during at least the first week after cast deposition begins on the soil surface. The size of these towerlike casts ranges from 3 to 6 cm in diametre, 2 to 10 cm in height and 25 g dry weight on average, and large casts can reach up to 15 cm height and 400 g dry weight. At the beginning of the deposition casts are a fresh pasty structure, and during the following week, a combination of dry and fresh material at the bottom and the top of the cast, respectively, can be observed. Whether the earthworm leaves its semi-permanent burrow or it goes deep into the soil profile to begin diapause the cast dries completely, and remains at the soil surface for more than one year after having been excreted. Their half-life range from 2 to 11 months in a trampled and protected pasture, respectively, and 5 months in ungrazed natural savanna. The disappearance of casts from the soil surface is attributed to several environmental and anthropogenic factors, i.e. rainfall impacts, fire, cattle trampling and the activity of burying small invertebrates.

Experimental design: Three experiments were performed during the rainy season of 1994: one field study and two laboratory/incubation studies using soils collected from the same plots where the field work was conducted.

Field experiment: The field experiment was carried out from May to August 1994 in adjacent paddocks of open herbaceous native savanna dominated by *Andropogon bicornis* L. and *Trachypogon vestitus* Anders. and a 18 year-old pasture of *Brachiaria decumbens* cv Basilisk and *Pueraria phaseoloides* (Roxb.) Benth. CIAT 9900 (Kudzu). In each paddock, three areas (repetitions) of 4x4 m and 1 m^2, respectively, were located at random and cleaned of all existing surface earthworm casts. In the *B. decumbens*-Kudzu pasture, plots were protected from cattle trampling with wire exclusion cages. On the following day, plots were surveyed and freshly deposited casts of *M. carimaguensis* were identified, displaced slightly to the side of the earthworm gallery and tagged with a plastic peg to identify the time of in situ ageing at which it would be sampled (the day of displacement being "day 0"). Samples were taken at six different ages, i.e. 1, 4, 8, 16, 32 and 64 days. For a given date, casts from each area were picked up and placed in an ice chest for transport to the laboratory. Approximately 70 g were collected for each sample, of which approximately 40 g were dried under forced draft in an oven at 40 °C and 30 g were stored in a refrigerator at 4 °C prior to analysis as described below. Control soil samples were taken in each paddock by splitting it into four areas where five 0-15 cm soil cores were taken per area and mixed. Samples were further prepared for analyses by crushing and sieving through a 2-mm mesh. Samples for microbial P determinations were maintained fresh under refrigeration as mentioned above.

Laboratory experiment: Twelve pots or experimental units were prepared using 6 kg of soil (air-dried and sieved to 2 mm) collected from the top 15 cm of the two paddocks where the field experiment was conducted. Two different laboratory experiments were conducted. In the first (LE1), no additional treatments other than the paddock field treatments were applied. In the second (LE2), two additional treatments were applied in factorial combination with the two field treatments, one without and the other with added green vegetative material collected from the same field treatments. The vegetative material was oven-dried and finely ground and mixed with the corresponding soil at a rate of 20 g kg^{-1} soil, in order to test the effect of plant material addition on P dynamics. The twelve experimental units corresponded to the systems studied, savanna and introduced pasture, two treatments (with and without organic amendments) and three replications. In each pot the soil was adjusted to pF 2 moisture content (25 g g^{-1}) 5 days prior to earthworm introduction. A total of 160 adults of *M. carimaguensis* were collected in the field, and twelve individuals were placed in each pot for a 6-day period of conditioning to void field-ingested material. Afterwards, all earthworms were transferred directly to pots containing 2-kg of sieved and similarly preconditioned soil. After 1 day, these second pots were examined and earthworms were moved to another set of similar pots. This procedure was repeated six times to complete the temporal lag, i.e. 1, 4, 8, 16, 32, 64 days. Surface cast material in the pots was also sorted from the soil and placed in a Petri dish containing moistened filter papers to maintain the humidity of the samples, which were incubated at ambient temperature (24 ± 3 °C) in the laboratory for periods of 1, 4, 8, 16, 32 and 64 days. After incubation, casts were broken up, mixed and separated into two other samples (one air dried, and the other moist) as described for the field experiment above. Control (non-ingested) soil was sampled from pots when earthworms were introduced and prepared in the same manner as the incubated casts.

Determination of soil P fractions in casts and controls: Phosphorous in soil and earthworm casts were fractionated according to a modified method of Hedley et al. using successively the following increasingly aggressive extractants: H_2O with anion exchange resin in HCO_3^- form, 0.5 M $NaHCO_3$, 0.1 M NaOH, 1 M HCl, and hot concentrated HCl. Inorganic P in extracts was determined by the molybdate-ascorbic acid method. Total P in the H_2O, $NaHCO_3$ and NaOH was measured after digestion with $K_2S_2O_8$. Total soil P was determined by perchloric acid digestion. Controls and one day-old casts were fractionated according to the full method while a reduced method using the first three extractants was applied to the remaining samples.

Inorganic P removed by anion exchange resin comes either from solution or is desorbed from the Al and Fe oxyhydroxide colloid surfaces in the soil. Sodium bicarbonate (0.5 M at pH 8.5) also extracts weakly adsorbed Pi. Together these two Pi fractions constitute a highly available Pi pool in soil. More slowly available Pi (also called "secondary Pi") is extracted by 0.5 M NaOH and is associated with amorphous and crystalline Fe and Al oxyhydroxides. Highly labile soluble organic P compounds are found in the water phase of the resin-H_2O extractant. The weakly alkaline $NaHCO_3$ extractant also removes easily hydrolyzable organic P (Po) compounds such as ribonucleic acids and glycerophosphate while the more strongly alkaline NaOH solution extracts less labile Po associated with fulvic and humic acids. Dilute HCl (0.1 M) extracts Pi from apatite or octocalcium phosphate, neither of which are likely to be present in Oxisols unless they have been fertilized with phosphate rocks. Hot concentrated HCl extracts more stable pools of Pi and Po, some of which may be associated with particulate organic matter. The P remaining in the sample (residual Pt) contains very recalcitrant Pi and Po forms that likely participate in P cycling processes only at long term.

Phosphorus in the microbial biomass and acid soil phosphatase activity were estimated on moist samples using procedures described by several authors. This procedure was used since air drying of cast and soil samples may cause loss of inorganic P from microbial biomass and give erroneous results.

Total carbon and nitrogen were analyzed on previously 2 mm sieved subsamples. A LECO CR-12 furnace with CO_2 infrared detection was used to determine total C, and the standard Kjeldahl digestion to measure total N contents. A titration method was used to extract exchangeable Al and H using 1 *M* KCl. Cations were extracted with 1 *M* NH4-acetate and determined by atomic absorption spectrometry using standard methods.

Statistical analysis: Data were log transformed prior to analysis to reduce the asymmetry of the frequency distribution. A two-way analysis of variance (ANOVA) was performed with system and cast age as the fixed main effects. The organic and inorganic P fractions extracted with H_2O/resin, bicarbonate and NaOH solutions, and for total P, total C, Bray-II P, phosphatase activity, microbial P and pH were analysed. Comparisons of means were performed by the Tukey HSD test. The software Statistica 5.1 for Windows was used in all statistical analyses.

Results and Discussion:

Total P, microbial P, phosphatase activity and other chemical properties: Total P content was significantly (MANOVA, $F = 20.25$; $p<0.001$) higher in 1-day old earthworm casts than in control soil for both laboratory incubated and field aged samples (Table 37). Total P calculated from the sum of P fractions did not differ significantly from that determined directly by perchloric acid digestion for any particular treatment (not shown). In the laboratory experiments, casts contained 10-20 mg-P kg^{-1} soil or 5-10% more total P than the soil from which they were produced. Casts produced in the field had approximately 100 mg-P kg^{-1} soil or 50% more P in native savanna, and >200 mg-P kg^{-1} soil or >100% more P in introduced pasture than the bulk soil (Table 37).

Phosphatase activity in soils and casts ranged from 120 to 313 mg-nitrophenol kg^{-1} $hour^{-1}$ in laboratory experiment samples, and from 249 to 312 mg-nitrophenol kg^{-1} $hour^{-1}$ in the *in-situ* (field collected) pasture and savanna samples, respectively. Except in *in-situ* samples from the native savanna phosphatase activity was significantly lower in casts than in the control soil (Table 37), probably due to the manipulation of soil or because enzymes were partly degraded during gut transit. In field samples, phosphatase activity was significantly higher in earthworm casts than in soil in the native savanna system but significantly lower in the intensive pasture.

Bray-II P and microbial biomass P as well as total C concentrations were significantly higher in 1-day-old casts than in the corresponding control soil for field samples while no significant differences were observed for the laboratory samples (Table 37). The pH was increased significantly in earthworm casts compared to the control soil in both native savanna and intensive pasture systems and for both field and laboratory produced samples.

P dynamics: The immediate effects of casting on the concentration of P in soil P pools in the field and laboratory are shown in Tables 38 and 39, respectively. Under field conditions, almost without exception P fractions were larger in casts than in the bulk soil (corresponding to the increase in total P content). Increases ranged from 0% (HClhc-Po) to 875% (Resin-Pi) in the egested savanna soil and 46% (Residue Pt) to 814% (Resin-Pi) in the egested pasture soil, and were relatively greater in the labile Pi fractions (resin-Pi and $NaHCO_3$-Pi). In both savanna and pasture derived casts, about 60% of the increased P content was found in Pi fractions, 30% in Po fractions and 10% in the residual Pt fraction. Most of the total P increase in cast over soil was found in secondary (NaOH) Pi and Po pools in both savanna and pasture derived casts, with significant amounts entering stable P pools as well, especially in the pasture casts.

Table 37. Chemical properties (mean ± *standard deviation*) of soil and one day-old casts of *M. carimaguensis* in the laboratory (LE1 experiment) and field experiment.

Experiment	pH (H_2O)	Total C (%)	Bray-II P (mg-P kg^{-1})	Phosphatase activity (mg kg^{-1} h^{-1})[§]	Microbial P (mg-P kg^{-1})	Total P[‡] ($HClO_4$ dig.) (mg kg^{-1})
Laboratory Experiment						
Native savanna						
Soil	4.6 ± 0.01	2.6± 0.8	2.6 ± 0.3	215 ± 23	4.1 ± 0.1	208 ± 2
Casts	5.2 ± 0.04	2.5 ± 0.01	2.9 ± 0.2	120 ± 18	4.1 ± 0.8	225 ± 7
B. decumbens – Kudzu pasture						
Soil	4.6 ± 0.01	2.9 ± 0.05	4.2 ± 0.3	313 ± 29	6.0 ± 0.9	248 ± 1
Casts	5.2 ± 0.1	3.0 ± 0.06	4.1± 1.1	242 ± 12	5.4 ± 0.4	272 ± 1
Field Experiment						
Native savanna						
Soil	5.1 ± 0.1	2.1 ± 0.1	1.0 ± 0.2	254 ± 15	2.5 ± 0.3	179 ± 5
Casts	5.4 ± 0.1	4.1 ± 0.1	6.3 ± 0.6	312 ± 7	4.0 ± 0.6	267 ± 15
B. decumbens – Kudzu pasture						
Soil	5.2 ± 0.1	2.1 ± 0.1	2.5 ± 0.6	299 ± 14	4.1 ± 1.3	194 ± 5
Casts	5.8 ± 0.1	5.2 ± 0.3	11.0 ± 2.3	249 ± 12	10.9 ± 1.5	396 ± 69

[§] mg ρ-nitrophenol kg^{-1} h^{-1}
[‡] from laboratory experiment 2 (LE2)

Under laboratory conditions where the increase in total P content due to casting (11-17%) was much smaller than in the field, increases in the sizes of P fractions ranged from 0% to 344% (Table 39). In the savanna soil casts, most of the added P was found in the secondary P pools (20% NaOH-Pi and 64% NaOH-Po) whereas substantial amounts were also found in the stable P and residual Pt pools in the pasture soil casts. The addition of green material residues had no significant effect on either Pi or Po fractions in the laboratory experiment, neither in the soil nor in the casts.

The dynamics of labile pools of P in ageing casts is shown in Figures 20 and 21 for laboratory and field incubation experiments, respectively. Pi extracted by resin was increased strongly in fresh casts but then slowly declined to the levels in soil during the following 64 days of incubation. In contrast, organic P (Po) extracted by bicarbonate and hydroxide increased during 1 to 8 days after casting, rather than during transit of the earthworm gut, and then remained relatively constant. Afterwards these Po-fractions remained relatively constant or declined slightly during the remaining 56 days of incubation. Inorganic P in bicarbonate and hydroxide was not affected significantly by casting and did not change significantly with time of incubation.

Similar patterns in P dynamics in Pi and Po fractions were observed during *in situ* ageing of *M. carimaguensis* casts produced in the field although of much lower magnitude, especially for Po fractions. The most marked changes occurred during transit of the earthworm gut whereas, after the initial increase, Pi and Po in all fractions remained relatively constant during the 64 days of field incubation.

Table 38. Phosphorus fractions in soil and fresh (1-day-old) casts of *M.. carimaguensis* collected in the field from the native savanna and the intensive pasture[1].

		H_2O-Po	Resin-Pi	$NaHCO_3$		NaOH		1*M* HCl-Pi	HCl hc		Residue -Pt	Total Pi	Total Po	Total P
				Pi	Po	Pi	Po		Pi	Po				
		mg P kg^{-1} soil												
Savanna	Soil	0.5 b	0.8 b	1.6 c	8.6 b	22 bc	42 ac	0.3 b	38 c	22 ac	59 b	63	73 b	195 c
	Cast	1.4 a	7.8 a	9.9 b	17.0 a	52 ac	68 a	0.9 b	52 b	21 ac	68 b	123	108 a	299 b
	%increase	180	875	519	98	137	64	200	36	-5	15	95	47	53
	%P added[2]	1	7	8	8	29	25	1	13	-1	9	58	33	100
B. decumbens + Kudzu	Soil	0.8 b	1.4 b	2.8 c	9.1 b	26 b	43 bc	0.8 b	45 bc	10 bc	60 b	76	62 b	199 c
	Cast	2.0 a	12.8 a	19.0 a	18.8 a	82 a	82 a	5.6 a	83 a	32 a	88 a	202	136 a	425 a
	%increase	150	814	579	107	213	92	600	83	234	46	165	117	114
	%P added	1	5	7	4	25	17	2	17	10	12	56	32	100

[1] values within a column followed by te same letter do not differ significantly ($p<0.05$) according to Tukey's HSD test.
2 percentage of total P increase in cast over soil found in respective fraction,

Table 39. Phosphorus fractions in soil and fresh (1-day-old) casts of *M carimaguensis* produced in the laboratory (LE1) from soil collected in the native savanna and the intensive pasture

		H_2O-Po	Resin-Pi	$NaHCO_3$		NaOH		1*M* HCl-Pi	HCl hc		Residue -Pt	Total Pi	Total Po	Total P
				Pi	Po	Pi	Po		Pi	Po				
		mg P kg^{-1} soil												
Savanna	Soil	1.6 ab	0.9 d	4.1 b	1.8	25 d	32 c	0.3	41 b	16	43	71	51 bc	165 b
	Cast	1.9 b	4.0 b	4.3 b	2.4	30 c	50 b	0.4	42 b	17	42	81	71 ac	193 bc
	%increase	19	344	5	33	23	57	33	2	6	-3	14	39	17
	%P added[2]	1	11	1	2	20	64	0	2	3	-5	35	70	100
B. decumbens + Kudzu	Soil	1.7 ab	2.8 c	6.5 a	1.0	34 b	54 a	0.2	51 a	22	46	94	78 a	218 ac
	Cast	2.5 a	6.3 a	6.5 a	1.4	39 a	57 a	0.7	55 a	20	55	108	80 a	243 a
	%increase	47	125	0	40	14	5	250	9	-12	20	14	2	11
	%P added	3	15	0	2	20	11	2	20	-11	38	57	5	100

[1] values within a column followed by the same letter (or no letter) do not differ significantly ($p<0.05$) according to Tukey's HSD test.
2 percentage of total P increase in cast over soil found in respective fraction.

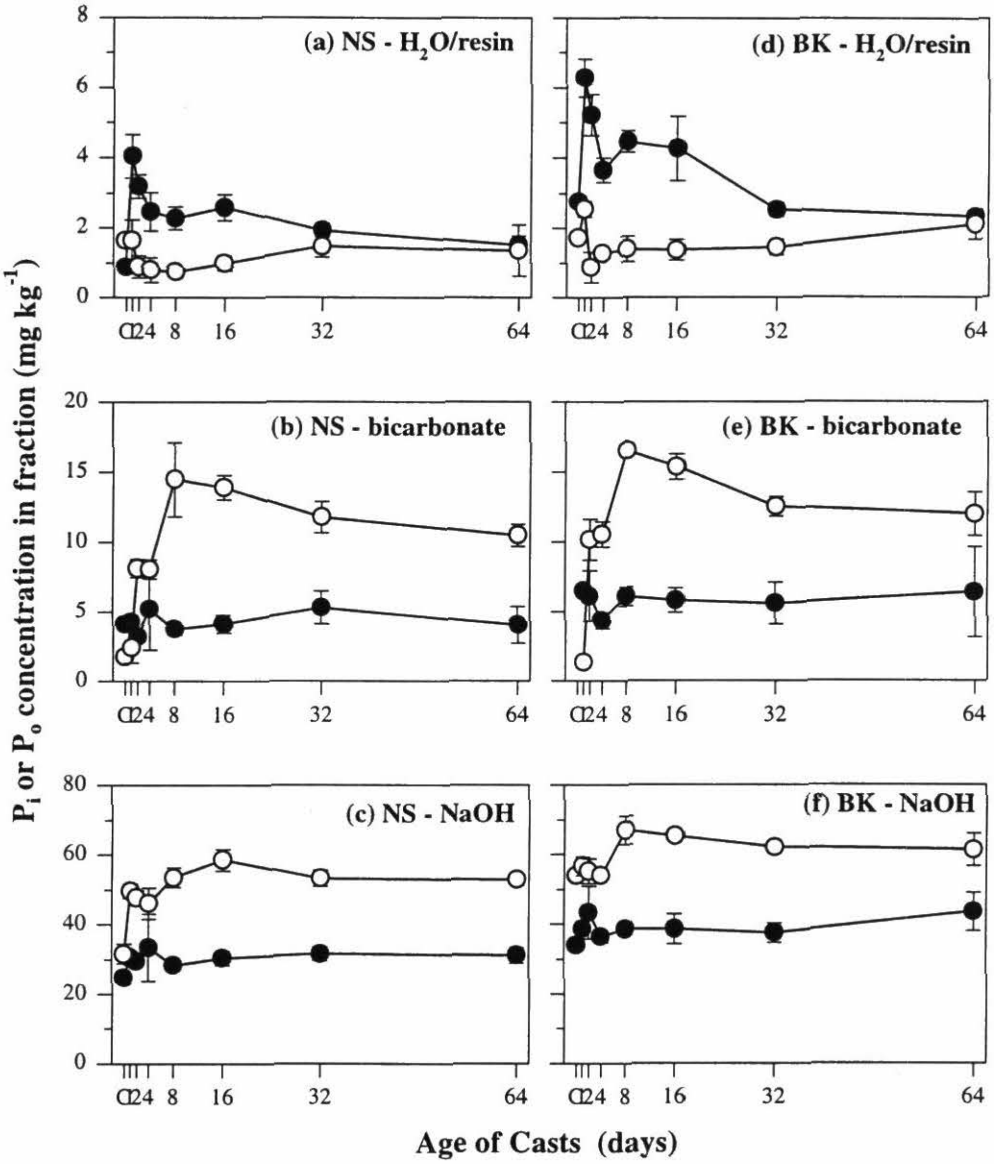

Figure 20. Dynamics of Pi and Po fractions in casts of *M. carimaguensis* produced and incubated in the laboratory (LE1 experiment). *C* Control soil (non-ingested) Bars indicate standard deviation. NS Native savanna, BK *B. decumbens* + Kudzu pasture.

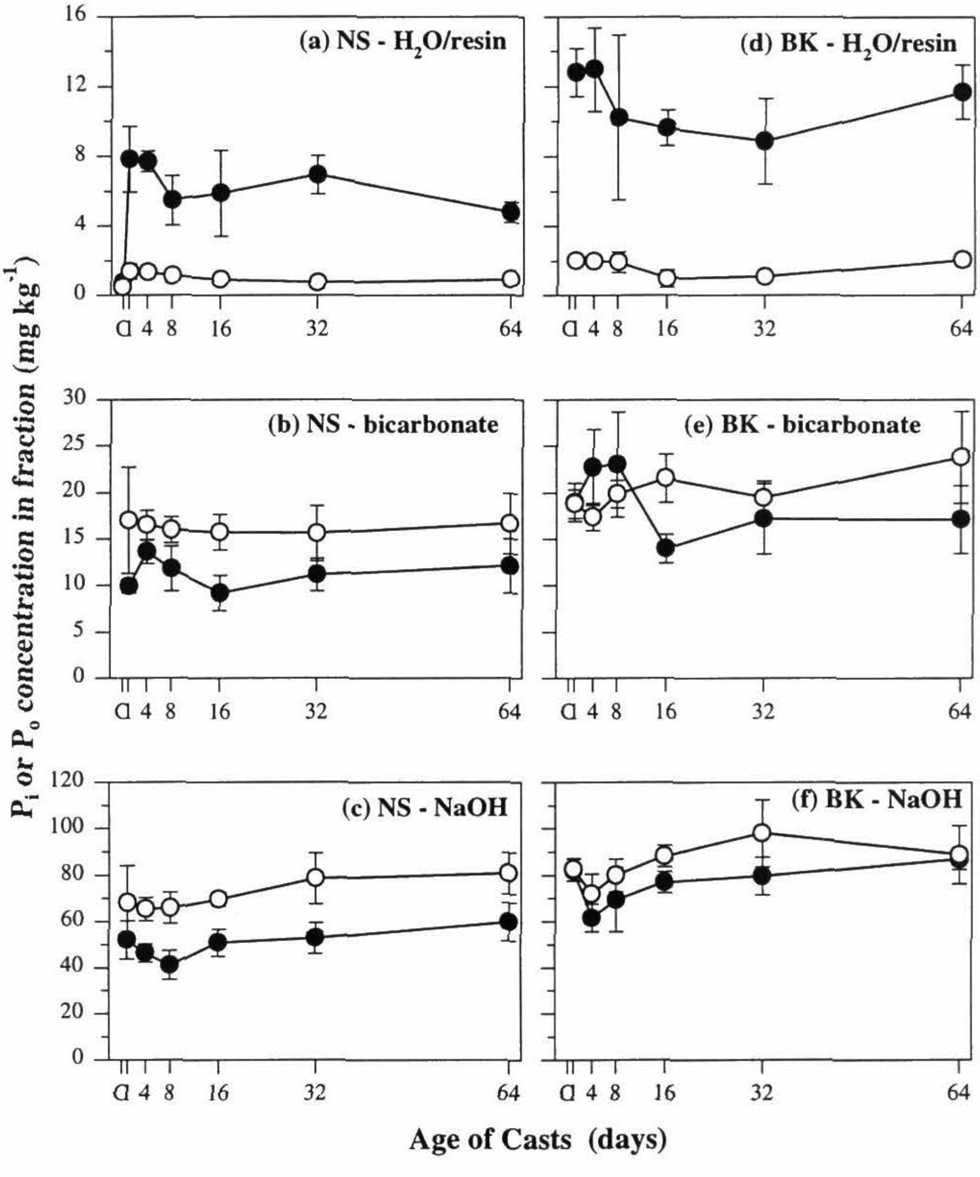

Figure 21. Dynamics of Pi and Po fractions in *in-situ* ageing casts of *M. carimaguensis*. *C* Control soil (non-ingested). Bars indicate standard deviation. NS Native savanna, BK *B. decumbens* + Kudzu pasture.

The use of both field and laboratory experiments in this study helps to better understand the actual dynamics of nutrients in soil and in biogenic structures produced by soil macroinvertebrates. Although the total P contents of control soils in the field and laboratory experiments were similar, ingestion by *M. carimaguensis* increased total P by 53% to 114% under field conditions but by <20% under laboratory conditions. Under field conditions, *M. carimaguensis* apparently incorporated P from sources such as litter, undecomposed plant debris and roots and other holorganic casts that were not present in the soil under laboratory conditions. Together with mixing of soil and litter, both coprophagy and necro-rhizophagy seem to be the dominant feature of the *M. carimaguensis* diet.

Phosphorus incorporated into soil from "non-soil" sources may enter into all P fractions (organic and inorganic) but the fractionation data indicate that a greater proportion entered into labile Pi fractions, particularly under field conditions (Tables 38 and 39). It is not possible to conclude that *M. carimaguensis* promoted the mineralization of organic P since the proportion of labile P in the substrate may have been greater than that of stable P forms. However, the fact that under laboratory conditions, where organic litter substrate was not provided (LE1) and where the increase in total P due to casting was quite small, relatively large increases especially in the secondary (NaOH-Pi and -Po) pool sizes accompanied by decreases in stable fractions suggests that ingestion of the soil by the earthworm did promote movement of P from stable to more labile P forms. Moreover, the relatively large increases observed in resin-Pi in the laboratory experiment, and in all labile fractions (H_2O-Po, resin-Pi, bic-Pi and bic-Po) in the field experiment (all small pools), suggests some mineralization of less available P from large more stable pools where relative changes would be difficult to detect. This would agree with the interpretation that *M. carimaguensis* likely acts as an endogeic (soil consumer) rather than an anecic (soil + litter consumer) species in terms of feeding regimes.

Although beginning with almost identical total soil P contents, casts produced *in situ* in the *B. decumbens* and *P. phaseoloides* pasture had more than twice the total P content and correspondingly higher P content in all fractions than casts produced from savanna soil (Table 38). This was probably due to higher biomass production, both aboveground and roots, of legume and deep-rooting grasses in the pasture resulting in greater litter fall and root turnover as well as greater dung deposition from greater stocking of cattle. Our study confirmed the results obtained by several authors who reported higher P contents in earthworm casts than in the surrounding soil from grassland ecosystems. Phosphorus contents were at least 30% higher in casts of several earthworm species than in the soil. In our study, water extractable P was 300% higher in casts than in the adjacent control soil under field conditions. Stabilization of P in casts of *M. carimaguensis* occurred between 16 and 64 days after cast deposition, whilst this lag was of 4 days in casts of the endogeic *P. corethrurus*.

In permanent pastures from a New Zealand watershed it was estimated that the total amount of organic-P was 14 kg ha^{-1} yr^{-1} and 11 kg ha^{-1} yr^{-1} accumulated in 30 tons ha^{-1} yr^{-1} of surface earthworm casts. Estimated surface cast production by *M. carimaguensis* at the study site was 1.2 and 13.2 t ha^{-1} yr^{-1} in the savanna and in the pasture, respectively, based on a density of 0.2 and 2.2 fresh casts m^{-2} and considering the active period of the species, at least 4 months. The average dry weight of casts ranges from 25 to 35 g.

Thus, 0.36 kg ha^{-1} yr^{-1} and 5.61 kg ha^{-1} yr^{-1} of total P may be accumulated in fresh casts of *M. carimaguensis*, respectively, in the savanna and the pasture (0.13 and 1.8 kg ha^{-1} yr^{-1} of total Po). This represents a fair contribution to the overall P fluxes in these agroecosystems. For example, the total P uptake in above-ground biomass of a grass-legume pasture (*B. humidicola* plus several legumes), a maize monocrop and the native savanna was found to be 14, 18 and 4 kg P ha^{-1} at the same site. We may say then that, in the case of pasture, total P accumulated in casts is ≈ 40% of the total annual P uptake by grasses, whereas in the case of the savanna it is equivalent to only ≈ 9% of the total P uptake in above-ground biomass. Nonetheless, the global contribution to availability of P for plants may be even greater due to the presence of other earthworm species in the soil and the casts deposited in the soil. Thus, our results confirm that earthworm activity at Carimagua had a significant effect on P availability.

Measurements of phosphatase activity and microbial P on field experiment samples further indicate that *M. carimaguensis* participates in the mineralization of available Po fractions. In the field experiments, phosphatase activity was greater in *M. carimaguensis* casts than in the control soil from the savanna. The contrary observation seen in the laboratory experiment was probably an artifact of the methodology since the organic residues added to earthworm cultured pots could have already mineralized before ingestion by the earthworms. The high values of phosphatase activity obtained in our study for all treatments show the importance of both biological and biochemical processes in Po mineralization, although these are not always markedly detected, for example, in the case of termite mounds and surrounding soil where no significant differences were observed in the Venezuelan Llanos. A strong enzymatic activity has been reported in fresh earthworm casts from temperate regions as well as in tropical sites.

Microbial activity is enhanced in casts of tropical earthworms due to strong enzymatic activity and available organic C. In this study values of microbial P were similar in both soil and cast samples from the lab experiment, and slightly higher in samples from the pasture. In summary, therefore, the increase in total P content of casts over soils in the field can be explained by organic matter, litter (including roots) and cast selection by *M. carimaguensis* while the comparative increases in labile fractions extracted with water, $NaHCO_3$ and NaOH are due to the reorganization or translocation of P from stable to available pools for plant uptake. Evidence for the latter is found in the increased enzymatic activity (phosphatase and microbial) in casts.

"Ecosystem engineers" and P dynamics in savanna soils: Phosphorous is a limiting nutrient in tropical savannas, especially if aluminum saturation is high since P is immobilized in highly stable Al based compounds. Studies on the role that ecosystem engineers play in P dynamics in Neotropical savannas are very scarce. The activity of soil ecosystem engineers, which include ants, termites and earthworms, influence and control both the amount and distribution of P in savanna soils by construction of nests and galleries. As an example, both the quantity and distribution of P in the savannas of Venezuela depends upon the biological activity of the termite *Nasutitermes ephratae* (Holmgren) (Nasutitermitidae). Termites feeding on plant debris have been shown in other studies to have little or no impact on available P, but soil feeding termites, i.e. humivorous, can increase available P in their nests two or five-fold. This is the result of the alkaline conditions in the anterior hindgut of most humus-eating termites. The availability of mineral P derived from litter or soil can be increased by the activity of earthworms as we have shown in our field study. But P availability also changes with time as casts aged in the field. Similar results have been reported where P retention declined in the biogenic structures produced by the African savanna termite *Cubitermes oculatus*.

There is still a lack of studies dealing with the interactive role that ecosystem engineers play in nutrient cycling both within and among major taxa. For example, casts of *M. carimaguensis* are large resistant structures that persist at the soil surface from two to eleven months on average in intensive pastures (protected or exposed to cattle trampling, respectively), and 5 months in native savannas. Termite species *Armitermes* sp. and *Velocitermes* sp. (Nasutitermitinae) colonize these compact casts and creates channels and deposits faecal pellets at the cast surface. When cast finally splits into smaller aggregates, the nutrients that were preserved from further mineralization processes in these casts are release. Thus these surface casts represent a significant source of direct P easily available for plant uptake, and possibly also explains the increase in root biomass observed under earthworm casts. Further studies should consider the effect on P dynamics of other soil ecosystem engineers' biogenic structures that are also abundant in the savannas of the Colombian Orinoco basin, for example, *Microcerotermes* sp., *Spinitermes* sp. (Termitidae) and *Velocitermes* sp. (Nasutitermitinae) species and the ants *Atta laevigata* and *Acromyrmex landolti*.

Only when the total volume of soil processed by earthworm species including *M. carimaguensis* in the Carimagua savannas is considered can their engineering feat be truly appreciated. Based on an ingestion rate of nearly 20 g dry soil^{-1} day^{-1} by *M. carimaguensis* under laboratory conditions we estimated that the entire first 10 cm of the topsoil passes through the gut of the entire population of earthworms in only 6 years.

Impact:

The importance of *M. carimaguensis* activity in natural and introduced pastures on incorporating P from organic sources into soil P pools, in increasing the labile P pools and improving P cycling was demonstrated in our short-term studies under laboratory and field conditions. The ecological significance of earthworms in P cycling in the native savanna and the introduced pasture is based on the improved nutritional basis of plant litter from the pasture. There is an enhancement of biotic processes in the pasture, since populations of this species are quite abundant and there is also higher microbial biomass P. The long-term effects of earthworms on P cycling and other nutrients must therefore be tremendous and merit further investigation. The net benefits of earthworms involved in soil quality improvement and soil fertility are still ignored.

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Activity 2.3 ***Develop appropriate and diverse strategies for controlling soil erosion***

- Results of scaling out sugarcane double-purpose live barrier technologies developed in Colombian hillsides to Honduran hillsides will be reported next year. The agronomic information will be complemented with evaluation of the economic contribution of sugarcane live barriers under traditional management to hillside farmers in Honduras and also agroenterprise approaches to make sugarcane live barriers profitable in Cauca, Colombia.

Activity 2.4 ***Develop strategies to maximize C sequestration in soils and minimize emissions of greenhouse gases***

- Results from one PhD thesis in the Colombian savannas in collaboration with Ohio State University and results from collaborative work with Cornell University in the Brazilian Amazon will be reported next year.

Activity 2.5 ***Characterize soil biodiversity and develop strategies to manage beneficial soil biological processes***

2.5.1 The impact of soil organisms on plant diversity and abundance. A case study of a native anecic earthworm species

Highlight:
- Observed direct preference by *M. carimaguensis* for seeds from the soil seed bank and found considerable loss of viability of seeds in earthworm casts.

Purpose:
To describe the main biological and ecological effects of a native earthworm species, i.e. *Martiodrilus carimaguensis* (Oligochaeta, Glossoscolecidae) on permanent soil seed banks in a natural savanna and several introduced pastures from the Eastern Plains of Colombia.

Rationale:
The substitution of the native savanna by introduced grasses from Africa has been a widely accepted practice in the Colombian "Llanos" and in the Brazilian savannas or "Cerrados" during the last 20 years in order to increase the proportion of land used for more intensive food production. Improved pastures based on introduced grasses from Africa, principally *Brachiaria* spp., and *Panicum* spp., with or without forage

legumes, e.g. *Stylosanthes* sp., *Arachis* sp. and *Pueraria* sp., and annual crops with inputs of fertilizers and lime, mainly upland rice and soybeans, are land management options normally found in these areas. In addition, we know little about biological processes involved in these land use changes and how these can alter fundamental ecosystem processes and services. This is especially relevant when it is evident, from studies carried out in the Brazilian "Cerrados", that biodiversity of the neotropical savannas is more threatened than that of the Amazon forest.

The study of diversity and ecological processes linked to ecosystem functioning constitute the basis for an understanding and better management of natural and derived ecosystems. Communities of soil fauna are, in general, sensitive to climatic and edaphic factors that in turn determine the availability of food resources and microclimatic conditions. Besides, human-induced disturbance of natural ecosystems will alter the macroinvertebrate communities in the soil.

Earthworms are the most abundant group of macrofauna in the soil in terms of biomass and they generally participate in the regulation of important soil processes through their functional domains. The effects of earthworms on soil physical properties, nutrient dynamics, organic matter and plant growth have been studied in detail. However more efforts are needed to evaluate the role of the biogenic structures produced by theses organisms in soil functioning and ecological processes.

The substitution of the natural ecosystem (native savanna) by introduced pastures influences the functional structure of the earthworm communities although species richness is the same. *Andropogon gayanus* and *Brachiaria decumbens*, alone or in association with the forage legume *Pueraria phaseoloides*, *Brachiaria humidicola*, alone or in association with *Arachis pintoi* or other legumes are systems that conserved the native macrofauna at Carimagua. These results are exceptional as disturbances to natural systems result generally in a decrease or disappearance of the native species. Normally, pantropical species with a wide range of tolerance to physico-chemical properties (peregrine species) such as *Pontoscolex corethrurus* Müller and *Polypheretima elongata* Perrier become predominant. Of the many life forms that inhabit soils only a small number of macroinvertebrates (earthworms, termites and ants) are capable to plow soil and produce a large variety of organo-mineral structures, e.g. nests, mounds, macropores, galleries and excretions. These organisms are named "ecological or ecosystem engineers" of the soil and their structures have been described as "biogenic structures".

In agreement with the high species richness of the savanna a high functional diversity exists in Carimagua, in terms of different biogenic structures. The soil ecological engineers from Carimagua produce fourteen types of these structures on the soil surface, i.e. 4 termite structures, 8 types of ant nests and 2 types of earthworm casts. It is on one of these biogenic structures and the species that produce them, the anecic *Martiodrilus* sp. (Glossocolecidae, Oligochaeta) where the research presented here has been focused on. These surface casts are formed by a continuous deposition of egested material at the opening of the burrow during several days. The final structure is a towerlike cast with a fresh pasty structure in the top and dry material at its base easily recognisable from other soil surface casts. The term towerlike was prefered although Madge originally created it to describe casts of *Hyperiodrilus africanus*. When the earthworm *Martiodrilus* sp. leaves its semi-permanent U-shaped burrow or when it sinks to start diapause the cast dries completely. Dry casts remain at the soil surface for more than one year after having been egested, and the disappearance of casts is mostly attributed to rainfall drop impacts and to cattle trampling in the grazed pastures.

The functional role of these structures is believed to be of utmost importance and represent sites where certain pedological processes occur. These include the stimulation of microbial activity, the formation of soil structure, the dynamics of soil organic matter or the exchange of water and gases. In this study our objective was to assess some ecological processes at the scale of the biogenic structure and relate them with the living habits of the species. The effects on permanent soil seed banks in surface casts of *Martiodrilus* sp. were the main objective addressed in this study.

Materials and Methods:

Study site: The study was carried out at the "Centro Nacional de Investigaciones" Carimagua (CIAT-CORPOICA agreement), in the well-drained isohyperthermic savannas of the Eastern Plains of Colombia (4° 37' N and 71° 19' W, 175 metres altitude). Climate is subhumid tropical with a four-month dry period from December to March and an average yearly rainfall and temperature of 2280 mm and 26°C, respectively. Vegetation is characterised by open herbaceous savannas with scattered trees and bushes in the uplands ("altos") and gallery forests and palm trees ("morichales") in the low-lying savannas ("bajos"). Burning is used to get rid of excess vegetation and to stimulate the re-growth of those more nutritional plant material. Soils at the study site are Oxisols (Tropeptic Haplustox Isohyperthermic) in the uplands and Ultisols (Ultic Aeric Plintaquox) in the lowlands (USDA). These soils are characterized by their acidity (pH 4.5, water), a high Al saturation (> 80%) and low concentrations of exchangeable Ca, Mg and K. Phosphorous is a limiting nutrient for plants as it remains fixed by Al in stable compounds, what reduces the productivity of these acid soils.

All the research was done on the same upland edaphic unit (pedon Carimagua) where different plots were located: A native savanna without grazing nor burning where *Andropogon bicornis* and *Gymnopogon* sp. were the predominant plant species, and a grazed pasture, in a two ha plot, that combines an exotic African grass, *B. decumbens* cv. Basilisk, and a tropical herbaceous legume, *P. phaseoloides* CIAT 9900 ("Kudzu"). Cattle stocking rates were 1 animal unit (AU) ha^{-1} in the dry season and 2 AU ha^{-1}in the wet season (1 AU = 250 kg live weight).

Earthworm population sampling: With the objective to assess the biology, ecology and population dynamics of species across time a stratified sampling procedure was performed during 17 months. Physical methods of extraction were applied to collect earthworms. These are often very tedious, hard working and time-consuming. From April 1994 to September 1995 earthworms were hand-sorted from five 1 m^2 soil monoliths monthly. A trench was dug around the monolith to avoid earthworm escaping and ease the separation of 10 cm sucessive layers. Normally, five soil layers were revised, till 50 cm. However, as some species migrate deeper into the soil, e.g. *Martiodrilus* sp., sampling depth varied accordingly. Vertical distribution was not much affected by sampling since a positive correlation between the number of fresh casts in the soil surface and the number of earthworms in the topsoil exists. Soil blocks were carefully hand revised and all earthworms and cocoons collected. Whether any earthworm was in dormant stage, i.e., quiescence or diapause, or not is annotated.

All earthworms were carried to the laboratory where complete specimens were weighed and the maximum preclitelar diameter measured in fragmented worms, since it has been very useful to estimate the weight of the complete earthworm. Biomass is based on formalin preservation, 12% lower than fresh weight on average for *Martiodrilus* sp.

Sampling of biogenic structures: Cast and soil seed banks: Three experimental plots were selected to compare native savanna with different pastoral systems under study at the research site:

(a) A *Paspalum pectinatum* Nees, *Axonopus purpusii* (Mez.) Chase, and *Trachypogon vestitus* Anders. native savanna, protected from grazing for four years and traditionally managed by fire during each dry season.

(b) An 18 year-old associated pasture of *B. decumbens* Stapf. and *P. phaseoloides* Benth. (pasture A), grazed by cattle and maintained with a stocking rate of 1.0 animal unit. ha^{-1} during the dry season and 2.0 animal units. ha^{-1} during the wet season.

(c) A 3 year-old associated pasture of *B. humidicola* (Rendle), *A. pintoi* Krap & Greg, *S. capitata* Vog. and *C. acutifolium* Benth. (pasture B), grazed by cattle with an average stocking rate of 2.0 animals units. ha^{-1}.

Fieldwork was conducted in August 1996 and August 1999, i.e. at the middle of the rainy period. Our idea was to take samples from the permanent soil seed bank, assuming that most of the temporary seed banks had already germinated at the onset of the rainy season. Twenty soil cores (8 cm diametre and 6 cm depth) were taken in each experimental plot and 300 fresh casts were randomly collected. Both soil and casts were air-dried for 15 days and weighed.

Each sample was put on a 2-cm layer of river sand in a plastic seed tray (26x27x6 cm). Soil layers were less than 5 mm in order to allow the germination of the larger part of the seeds as recommended by some authors. Forty trays were used for each plot (20 for each type of sample, i.e. soil and casts) and 10 trays were filled up with sand alone and used as control. Germination trays were located randomly in a greenhouse, kept moistened and exposed to natural light and temperature regimes (approximately 12h/12h darkness/light and 26 °C, respectively). Once a week, the emerging seedlings were identified at the species level and removed. After three months, casts were broken in small fragments (< 5 mm of diameter) before being placed in the trays to continue the evaluation. For each sample, 40 g of dry soil or casts where randomly taken at the beginning of the experiment. Each sample was soaked for a minimum of 30 minutes in a solution of sodium hexametaphosphate (50 g. l^{-1}) and sodium bicarbonate (25 g. l^{-1}). Afterwards, the suspension was poured through a 0.125-mm sieve. Organic debris were washed with a fine spray of water and oven-dried for 48 hours at 70°C. Both damaged and undamaged seeds (i.e. seeds which visually seemed to be intact and resisted gentle pressure) were separated under a stereo-microscope and counted.

Statistics: Simple linear regression analysis (Pearson *r*) was used to study the correlation among variables. Analysis of variance (ANOVA) was employed to test for significant differences between means, and a non-parametric Kruskal Wallis ANOVA was used to compare variables under the assumption of distinct sample size. Asymmetry of data frequency distribution was reduced by Box-Cox transformation with the software Vernorm.

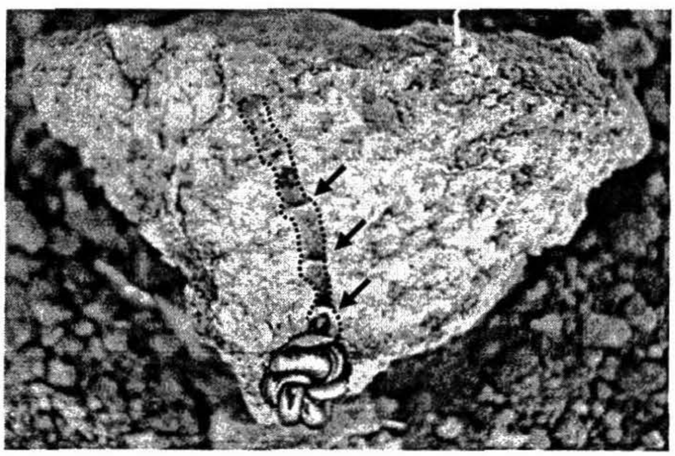
Results and Discussion:

Species ecology: Martiodrilus sp. is an endemic anecic earthworm from Carimagua. It is a large size, dorsally dark-grey pigmented, and surface-casting species. Surface casts of *Martiodrilus* sp. are large and ranged from 3 to 6 cm Ø and from 2 to 10 cm height, with an average dry weight of 25 g (Picture 3). Average monthly fresh cast and total cast numbers were significantly higher ($P < 0.01$, t-test) in the improved pasture than in the native savanna. The number of surface fresh casts declined during the middle of the rainy period due to the fact all the juveniles have already descended to deeper layers to enter diapause. A strong positive correlation between the number of fresh casts and the density of individuals in the first 10 cm was observed in the improved pasture ($r = 0.907$; $P < 0.01$) and it has been proved to be a good estimator of population density.

The highest population density was recorded at the beginning of the rainy season and the new juveniles hatched in October 1994 increase the total number of individuals, despite a reduction in theses numbers due to severe seasonality occurs. Earthworm biomass ranged from 0.24 g m^{-2} (March 1994) to 8.76 g m^{-2} (September 1995), and from 26.5 g m^{-2} (January 1995) to 94.8 g m^{-2} (May 1994), in the native savanna and in the improved pasture, respectively. In the native ecosystem *Martiodrilus* sp. comprised 15.1% of total earthworm biomass, while this value rose to 85.1% in the improved pasture, the highest ever recorded to date for an anecic species. Population density remained stable during the dry season months, therefore it is assumed that mortality occurs during the rainy period and that other factors seem to be responsible for it

Picture 3. Turricule of *Martiodrilus* sp. in the natural savanna from Carimagua (scale: length of picture = 20 cm).

The extremely effective adaptive strategy of *Martiodrilus* sp. is the reason why there is negligible risk of mortality during the dry season. The species has a true diapause, although different patterns were found between adults and juveniles. The latter were only active during the four months following the onset of the rainy period and entered diapause much earlier than adults, which remained active until December. The cease of activity occurred after they sank to deeper soil layers. An aestivating chamber is built, at the end of its semi-permanent burrow, where they coiled themselves up, after emptying their gut contents. The end of the burrow was usually sealed with several septae to avoid loss of tegumental moisture, which is vital to support a minimal rate of respiration (Picture 4). They remained still until the onset of the next rainy season.



Picture 4. Pattern of diapause in *Martiodrilus* sp. with the aestivation chamber at the end of the burrow (dotted line) and the septae (arrows) built with cast material.

A diapause process, physiologically induced, was assumed to be occurring because in controlled conditions there was no response when aestivating earthworms were introduced into soil with water content near field capacity. Aestivating juvenile earthworms were normally found in the 40- to 50-cm layer, whilst both adults and subadults were located in the 50- to 60-cm layer. A significant non-linear correlation was found between diapausing earthworms weight and the depth at which they were found

(Kruskal-Wallis ANOVA, $P = 0.011$). The larger the individual is the deeper it aestivates (Figure 21). The average weight of diapausing earthworms ranged from 1 to 2.5 g (4 g maximum), quite low when compared with fresh adult weight, ca. 11.2 g. This is the result of the earthworms emptying their guts to coil themselves up in their aestivating chambers.

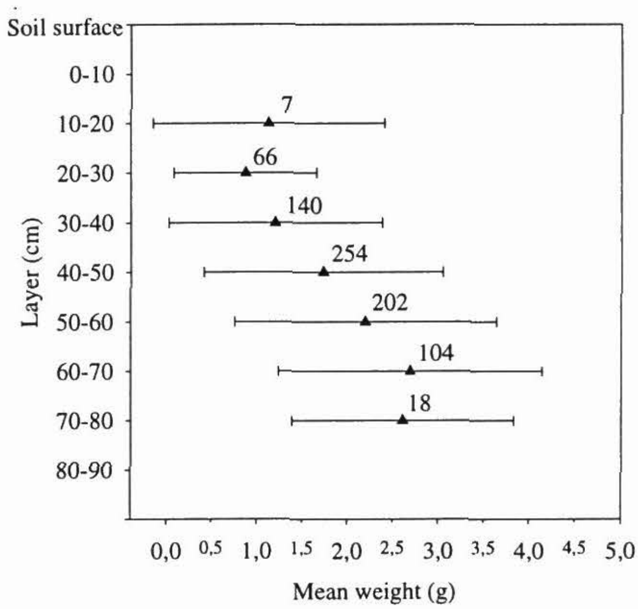


Figure 22. Relationship between the vertical distribution in the soil profile of aestivating individuals of *Martiodrilus* sp. and their weight.

Owing to the life cycle of the species, it is a clear K-strategist with a relatively long life period. New juveniles emerged from cocoons just before the end of the rainy period rapidly sank towards the deeper horizons to inititiate diapause. In the next year they will become active at the onset of the rainy season and be so during the following 3-4 months (July-August), entering again in a new diapause phase (the weight of these juveniles is 4 g maximum) until the next wet season. At the beginning of the following rainy period (second year) these worms will be active until the middle or the end of the humid season, depending on the developmental stage. In the next year (3rd) these worms become adults and two possibilities must be considered here: i) these new adults will not reproduce until the next year (4th), as some inactive adults were found when no cocoon was collected (see below), or ii) in some years of unusual lower rainfall all reproduction will be initiate by most adults. Adults that constitute, in a given period, the population of *Martiodrilus* sp., seemed not to actively participate in the reproduction, as the number of adults was double-fold than cocoons. We actually ignore if these adults participated during the reproductive period, but it seems improbable since no cocoons at the onset of the wet season were found.

Effect of Martiodrilus sp. on plant diversity at the scale of biogenic structures:

- *Cast seed banks*: Martiodrilus sp. seemed to ingest preferentially large quantities of seeds as part of its diet from 58 to 163 seeds 100 g^{-1} of ingested soil. The percentage of germination of seeds is 3 to 40 times lower in earthworm casts than in soil, probably as a consequence of damages suffered by ingested seeds during gut transit.

In all systems seedlings were observed in casts and only 41% of seeds emerged from casts, and the remaining 59% needed cast destruction to germinate (data not presented). In addition, the number of viable seeds within casts were negligible in comparison to soil seed bank and it only accounted for 0.2-0.6% of the total (Figure 23). However, the total number of seeds collected per 100 g sample was normally higher in casts than in the soil, and the number of viable seeds was greater in the intensive pastures than in the native savanna, and in all systems it was higher in the soil compared with the casts.

Differences were found in the species composition of soil seed banks between both pastures and the savanna, and it was certainly similar in the two pastures. The species composition of the soil seed banks was dissimilar to the above ground vegetation, where dominant species did not germinate in greenhouse experiment and on the other hand, the most abundant species of soil seedlings were rare in the plant community. The cast seed bank was relatively closer to that of the standing vegetation than soil seed banks in the native savanna, whilst the opposite pattern was found in *B. decumbens* and *P. phaseoloides* pasture.

The number of viable seeds egested in *Martiodrilus* sp. surface casts is up to 8.7 million seeds. ha^{-1}. yr^{-1}, and from 18 to 878 viable seeds. m^{-2}. yr^{-1} can be egested in surface casts, representing from 1% to 13% of the total viable soil seed bank. From 64 to 97% of seed viability was lost in earthworm casts, probably due to damages suffered by seed during gut transit, as suggested by the higher percentage of damaged seeds observed in casts.

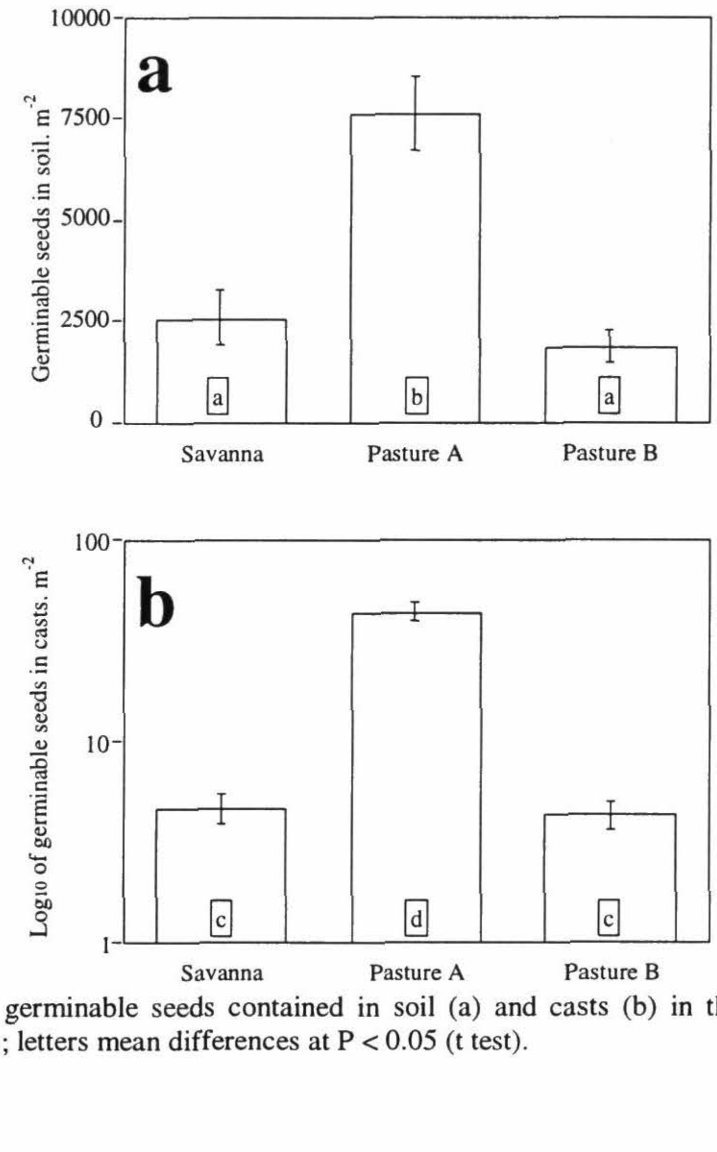


Figure 23. Density of germinable seeds contained in soil (a) and casts (b) in the three systems. Bars indicate standard errors; letters mean differences at $P < 0.05$ (t test).

Casts of *Martiodrilus* sp. are sometimes large and reach up to 15 cm height and 400 g weight. Casts do not dry completely till the earthworm abandons its burrow and the half-life of casts ranges between one and three weeks in native and non-native pastures, respectively. Afterwards, casts are progressively broken until they completely disappear, sometimes by water run-off after a big storm or incorporation into the soil profile.

The results of the present study confirm the complex role played by earthworms in the process of seed bank formation and contribution to the above ground vegetation. In such systems, the number of viable seeds egested each year in the surface casts of *Martiodrilus* sp. is important (up to 8.7 million seeds. ha^{-1}. yr^{-1}), compared with results obtained with *Lumbricus terrestris* L. in temperate pastures (890 thousand seeds. ha^{-1}. yr^{-1} on average). From 18 to 878 viable seeds. m^{-2}. yr^{-1} can be egested in surface casts, representing from 1% to 13% of the total viable soil seed bank.

In our study from 64 to 97% of seed viability is lost in earthworm casts, probably due to damages suffered by seed during gut transit, as suggested by the higher percentage of damaged seeds observed in casts. Earthworm burying activity of seeds may have important consequences for plant community dynamics as seeds of many species survive better buried than when left at the soil surface, and there are few other natural mechanisms that explain how seeds are buried in soil. Moreover, earthworm faeces may protect seeds from early germination processes and participate in the formation of important and persistent seed banks.

In the savanna protected from fire, casts sometimes remain at the soil surface for more than one year, while burning of the savanna suddenly leads to their destruction by depriving them of the protective effect of the vegetation and litter cover. This may lead to the formation of a pool of seeds potentially ready to germinate, that may be indirectly dispersed by fire on the nearby soil surface where they further benefit from suitable conditions to germinate (*i.e.* bare ground, higher light intensity, available nutrients in ashes). Important chemical constraints on seedling emergence and survival (e.g. low nutrient content, high aluminum saturation) may also be alleviated in casts. Therefore, seeds in casts, egested at the soil surface may be more likely to germinate than in the soil seed bank. This can explain why the composition of the cast seed bank was closer to that of the standing savanna vegetation than that of the soil seed bank. Further research should focus on the effects of earthworm activities in above standing vegetation at larger spatial and temporal scales.

Impact:
Martiodrilus sp. is an endemic earthworm from the natural savannas of Carimagua (Colombia) well adapted to introduced pastures, where it increases its abundance significantly and for instance its effects on some soil processes. The adaptive strategies of earthworms are diverse and are the result of living in a complex environment and facing limiting factors such as poor nutrient contents, movement in a compact environment and sometimes a strong seasonality. This species maintains quite abundant populations in the introduced pastures and its adaptive strategy is extremely efficient to maintain an almost constant density through the dry season. Earthworm casts could be considered as an important regeneration niche for the plant community, and earthworm activity could be an indispensable factor of ecosystem sustainability and diversity.

Contributors
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2.5.2 Properties of the structures created by ecosystem engineers on the soil surface of a Colombian savanna

***Highlight*:**

- Showed that biogenic physical structures produced by soil macrofauna on the soil surface can be related to their ecological function in the soil.

Purpose:

To assess the diversity, abundance and physical (aggregate size and stability, and bulk density) and chemical (C, N, and P contents, and pH) properties of the biogenic structures and establish a functional classification for the savannas of the Eastern Plains of Colombia

Rationale:

"Ecosystem engineers" or "ecological engineers" are those organisms that can physically structure the environment in which they live by producing "biogenic" structures or artefacts. Through these structures the engineer organisms can modulate the availability or accessibility of one or more resources used by other organisms. Their activities, including the building of biogenic structures, are therefore capable of modifying the abundance and/or community structure of populations of other organisms without being directly involved in any trophic relationship (e.g., predation, parasitism, mutualism, or competition).

Earthworms, termites, and ants form the main groups recognized as "soil engineers", and the spatio-temporal scale of their structures (e.g., casts, galleries, and domes) may serve to evaluate the impact on both the soil and other organisms living in it. The physico-chemical nature, abundance, size, and, morover, dynamics of construction and degradation of these structures are therefore parameters with which to evaluate the type and breadth of indirect effects that these structures have on the environment. So biogenic structures reflect certain functional attributes of the species that produce them (attributes directly linked to the definition of engineers). Their description can be used to establish a functional classification of soil engineers.

This study aimed to develop a classification of engineer organisms based on the nature of the physical structures that they build. Toward this end, we described the "biogenic structures" most commonly found on the soil surface in a well-drained savanna of Colombia. A typology of structures was thus established, based on 12 variables that describe the physical nature of the aggregates produced (bulk density and aggregate size), their structural stability, and their organo-chemical nature (pH, organic C, N, P, Ca, K, Mg, Al, and Al saturation).

Materials and Methods:

Study area: The study was carried out at the Centro Nacional de Investigación Agropecuaria at Carimagua (jointly run by the Corporación Colombiana de Investigación Agropecuaria [CORPOICA] and CIAT). Located at 4°37'N, 71°19'W, the center is situated in the phytogeographic region of well-drained isohyperthermic savannas in the Colombian Eastern Plains. The climate is subhumid tropical, with an average annual temperature of 26 °C, an average annual rainfall of 2300 mm, and a highly marked dry season from November to March. Vegetation is influenced by topography, with herbaceous savanna in the higher zones, and gallery forests and flooding zones in low-lying savanna. The soils are ferrallitic and kaolinitic (Oxisols) in the higher zones, with ferrisols and plinthites (Ultisols) occurring in the low-lying zones. The two types of soil have a characteristically granular structure and very low chemical fertility, with a pH (H_2O) <5, Al saturation >80%, and CEC <5 meq/100 g (CIAT database).

Experimental plots: Observations and sampling were carried out in plots on a savanna with ferrallitic soil. Vegetation consisted of ungrazed native savanna, dominated by *Trachypogon vestitus* Anders. and *Paspalum pectinatum* Nees. The plots were managed traditionally, with an annual burn during the dry season (February). Sampling was carried out in 1996 at the beginning of the rainy season (May), a period when soil macrofauna are mostly active.

Identification and morphological description: The plots were thoroughly checked (one hour per plot) by three people. All biogenic structures found on the soil surface of the native savanna were described, and the macroinvertebrates responsible for their construction identified as precisely as possible (family, genus, or species). This sampling did not aim toward an exhaustive list of all biogenic structures found in the savanna but, instead, to establish a detailed description of the most representative found in this type of vegetation. The color, size, shape, and general aspect of the structures were described for each species inventoried. The forms were likened to simple geometric forms to more easily evaluate the volume of soil moved through each type of structure on the soil surface. About 500 g of fresh material were collected from each structure found.

Chemical analysis: Contents of organic C and mineral elements were determined for those biogenic structures that were sufficiently abundant to permit the collection of enough material. We sampled the top layer of soil (0 cm–10 cm) with a cylinder 5 cm Ø × 10 cm long. Analyses were carried out, using standard procedures recommended by the Tropical Soil Biology and Fertility (TSBF) Programme. Hydrosoluble carbohydrates are considered to play an important role in stabilizing soil aggregates. The concentration of these carbohydrates were measured in both soil aggregates (0 cm–10 cm) and a representative selection of biogenic structures such as two types of earthworm casts, two types of termite mounds, and two types of ant nests, all chosen for their abundance on the soil surface being studied. The biogenic structures were air-dried, then sieved to 0.25 and 2.0 mm. Later, 2 g of each sample were agitated for 8 h in 20 mL of hot (80°C) water. The resulting solution was centrifuged for 6 min at 13,000 rpm. The supernatant was centrifuged again under the same conditions. Carbohydrate contents were determined, using a standard colorimetric method.

Bulk density: Bulk density was evaluated for all biogenic structures, using samples dried at 75 °C for 48 h. For soft structures (ant nests), apparent density was measured according to the volume occupied by the sample in a metal cylinder (5 cm Ø and 10 cm height). Hard structures (earthworms casts and termite mounds), however, were made impermeable with paraffin paper (Parafilm), then measured, using the displacement-of-water method. For savanna soil, bulk density was estimated by weighing a known volume of soil that had been sampled with a cylinder, 5 cm Ø × 10 cm long, and dried at 75 °C for 48 h.

Soil aggregates' distribution among size classes and their structural stability: Distribution of soil aggregates into size classes was determined for all biogenic structures. A minimum of four samples for each structure described was collected from the savanna. Eight cylinders (8 cm Ø × 10 cm long) of soil were also extracted to compare the aggregates in the structures with those in the topsoil. To evaluate the distribution of aggregates into size classes, we used a method of dry sieving, already used in other studies of Colombian savanna soils. The samples were air-dried for 4 days before being dropped from a height of 2 m onto a hard surface to break up the aggregates. They were then sieved, 20 times, through a sieve column of 0.053, 0.125, 0.250, 0.5, 1.0, 5.0, and 10.0 mm opening. Each fraction was dried for 48 h at 75 °C, then weighed. Aggregate distribution for an entire sample was expressed as the mean weight diameter (MWD), according to the following equations:

$$MWD = \sum_{i=1}^{n} \bar{x}_i w_i \qquad [1]$$

and the fraction of aggregates $(w_i) = \frac{M_{sieve\ i}}{M_{total\ sample}}$ [2]

where,

$\bar{x}_i$ is the average diameter of each fraction of aggregates;

$M_{sieve\ i}$ is the dry weight of particles retained in sieve i; and

$M_{total\ sample}$ is the dry weight of the total sample.

The water stability of aggregates (WAS) was evaluated in those samples used for estimating the concentration of hydrosoluble carbohydrates. The method used involved the application of a destructive force of a certain range. Five grams of aggregates (2 cm–5 cm Ø) were air-dried, then humidified by placing them on a humid sand layer at a suction of about 1 cm of water for less than 45 min. The sample was then placed on a sieve with a 1-mm mesh, immersed in water, and, using an automatic apparatus, agitated up and down for 3 min at a rate of 34 oscillations per minute and through a 3-cm range. The soil remaining on the sieve was dried at 105 °C and weighed.

Sand contents were estimated for the total sample and for the soil left in the sieve by dispersing the aggregates in a solution of 5% hexametaphosphate, then sieved (1-mm mesh). The WAS was expressed as the weight of the stable aggregates (corrected according to sand contents) divided by the weight of the sample (corrected according to sand contents), as follows:

$$WAS = \frac{M_{stable\ sample} - M_{sands\ in\ stable\ sample}}{M_{total\ sample} - M_{sands\ in\ total\ sample}} \times 100\% \qquad [3]$$

where,

$M_{total\ sample}$ is the dry weight of the initial sample;

$M_{stable\ sample}$ is the dry weight of the particles retained by the sieve after dispersion by water;

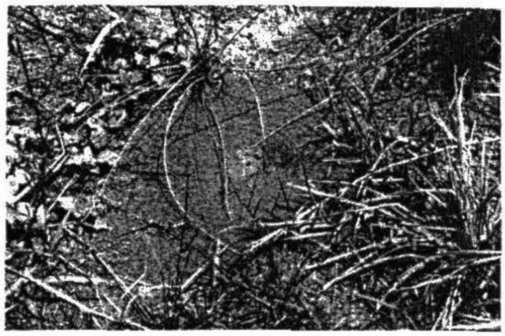
$M_{sand\ in\ total\ sample}$ and $M_{sand\ in\ stable\ sample}$ are the dry weights of sand contents in, respectively, the initial sample and the sample dispersed with water.

Statistical analysis: Mean comparisons were performed with ANOVAs and with Fisher PLSD tests at the significance level of 0.05. To establish the typology of structures, a principal component analysis (PCA) was carried out. The chemical and physical parameters available for each structure identified (chemical properties, apparent density, and weighted average diameter of aggregates) were included in the analysis. Of the structures built by ants we only used those for which a complete data set was available. The matrix used contained 11 rows (objects = 11 sampled structures) and 12 columns (variables = physical and chemical characteristics). The analysis was conducted with the help of the computer package ADE-4.
Linear regressions were used to evaluate relationships that could exist between carbohydrate contents of the samples and the WAS. The normalcy of the data had been previously verified through the Kolmogorov-Smirnov test, carried out with the statistics program, VerNorm 3.0 of the «R Package». The normalcy of the data was accepted at the 0.05 significance level for all sets of data.

Results and Discussion:

Micromorphological identification and descriptions: Fourteen species of macroinvertebrates were identified as being responsible for the construction of biogenic structures found on the soil surface in native savanna. Of the structures, we collected eight types of epigeic ant nests (Pictures 5 and 6), three types of epigeic termite domes (one was made of a pasteboard-like material and the other two of an organo-mineral mixture) (Pictures 7 and 8), one type of surface slab, built by a termite species (solid, surface galleries, Picture 9), and two types of earthworm casts (Picture 10). Table 40 lists the 14 species of macroinvertebrates identified, and briefly describes the respective structure built.

Picture 5. Epigeic ant nest and colony entrance for *Trachymyrmex* sp. in the native savanna (scale: length of photo = 40 cm).



Picture 6. Epigeic ant nest and colony entrance of *Camponotus* sp. in the native savanna (scale: length of photo = 50 cm).

Picture 7. Epigeic termite mound of a *Velocitermes* sp. colony in the native savanna (scale: length of photo = 30 cm).

Picture 8. Epigeic termite mound of a *Spinitermes* sp. colony in the native savanna (scale: length of photo = 1 m).

From a micromorphological viewpoint, the biogenic structures could be considered in terms of Bal's definitions, as follows:

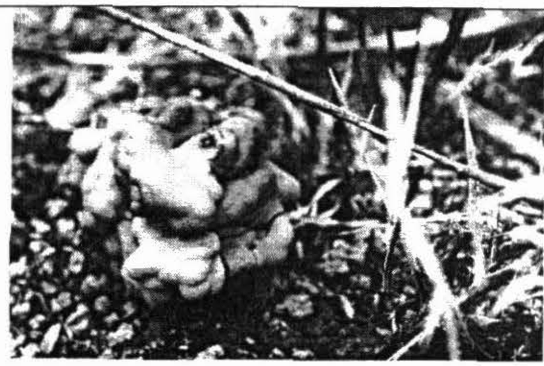
- The result of β-accumulation of aggregates coming from deep soil horizons and transported by invertebrates to the soil surface (terrepleins of ant nests).
- «Agrotubules», that is, tubular structures composed of aggregates cemented together in no particular direction (termite surface channels).
- «Modexis», that is, excrements produced by the animals as individualized three-dimensional structures (earthworm casts). The casts of *Martiodrilus carimaguensis* could be classified more precisely as «modexotubules» because they also have a central, tubular hole that correspond to the earthworm's gallery entrance.
- The three-dimensional networks of the «scatotubules», that is, of those tubular structures consisting of invertebrate excrements that are not clearly individualized from each other (epigeic termite domes).

Table 40. Taxonomic position of macroinvertebrates together with a description of the physical structures they produce.

Code	Macroinvertebrates					Structures					
	Order	Family	Subfamily	Species	Feeding regime	Type	Average dimension		Colour	Shape	Aspect
							In soil	Height			
	Ants										
Campo	Hymenoptera	Formicidae	Formicinae	*Camponotus* sp.	Omnivore	Dome	10-20 cm	1-3 cm	orange	paraboloid	Mobile rubbish
Odon	Hymenoptera	Formicidae	Ponerinae	*Odontomachus* sp.	Predator	Dome	20-25 cm	5-10 cm	grey	paraboloid	Mobile rubbish
Crema	Hymenoptera	Formicidae	Myrmicinae	*Crematogaster* sp.	Nectívoro	Dome	15-30 cm	10-15 cm	grey	truncated cone	Mobile rubbish
Pheid1	Hymenoptera	Formicidae	Myrmicinae	*Pheidole* sp.1	Omnivore - predator	Dome	3-5 cm	2-5 cm	orange	truncated cone	Mobile rubbish
Pheid2	Hymenoptera	Formicidae	Myrmicinae	*Pheidole* sp.2	Omnivore - predator	Dome	5-10 cm	5-10 cm	orange	truncated cone	Mobile rubbish
Atta	Hymenoptera	Formicidae	Myrmicinae	*Atta laevigata*	Fungi growers	Dome	50-100 cm	20-50 cm	orange	truncated cone	Mobile rubbish
Acrom	Hymenoptera	Formicidae	Myrmicinae	*Acromyrmex landolti*	Fungi growers	Dome	15-30 cm	10-15 cm	orange	cone	Mobile rubbish
Trachy	Hymenoptera	Formicidae	Myrmicinae	*Trachymyrmex* sp.	Fungi growers	Dome	10-20 cm	10-20 cm	orange	cone	Mobile rubbish
	Termites										
Micro	Isoptera	Termitidae	Termitinae	*Microcerotermes* sp.	Geophagous	Dome	10-20 cm	10-20 cm	black	cylinder	Pasteboard-like material
Spini	Isoptera	Termitidae	Termitinae	*Spinitermes* sp.	Geophagous	Dome	20-30 cm	20-50 cm	black	cone	cemented material
Veloci	Isoptera	Termitidae	Nasutitermitinae	*Velocitermes* sp.	Litter feeder	Dome	5-20 cm	10-25 cm	grey	cone	cemented material
Rupti	Isoptera	Termitidae	Apicotermitinae	*Ruptitermes* sp.	Geophagous	Slab	5-20 cm	0.5-1 mm	orange	slab	cemented rubbish
	Earthworms										
Mca	Oligochaeta	Glossoscolecidae	Glossoscolecinae	*Martiodrilus carimaguensis*	Anecic	Turricule	3-8 cm	1-10 cm	grey	cylinder	compact material
Andio	Oligochaeta	Glossoscolecidae	Glossoscolecinae	*Andiodrilus* sp.	Geophagous	Turricule	5-10 mm	5-10 mm	grey	sphere	Compact material

Chemical properties: Contents of organic C and mineral elements found in earthworm casts and termite mounds were usually present at levels higher than those of the savanna topsoil; for example, +8.6% and +248.3% of organic C in the casts of *Andiodrilus* sp. and domes of *Microcerotermes* sp., respectively (Figure 24). Likewise, pH increased, whereas Al contents dropped significantly. In contrast, contents of organic C in ant nests and termite slabs were much lower than those of the topsoil, that is, –47.6% for the ants *Pheidole* sp., and –69.2% for the ants *Atta laevigata* Smith and *Acromyrmex landolti* Forel. Contents of mineral elements and pH did not change or were lower, compared with the topsoil, and Al saturation dropped slightly.

Picture 9. Slabs of *Ruptitermes* sp. and casts of *Andiodrilus* sp. in the native savanna (scale: length of photo = 30 cm).



Picture 10. Casts of *M. carimaguensis* in the native savanna (scale: length of photo = 20 cm).

The concentrations of hydrosoluble carbohydrates found in ant nests and casts of *Andiodrilus* sp. were equivalent to or less than those found in the savanna topsoil, at –29.7% for *Trachymyrmex* sp. and–70.3% for *A. laevigata* (Figure 25a). In contrast, the soil aggregates forming the casts of *M. carimaguensis* and termite mounds had concentrations that were higher than those of the topsoil, that is, +12.8% for *M. carimaguensis*, +78.4% for *Spinitermes* sp., and +132.4% for *Velocitermes* sp.

Physical properties: Bulk density of biogenic structures varied widely according to the invertebrate species being considered. Earthworms constructed, for example, compact casts with an apparent density of more than 1.3 g/cm^3, that is, 10% to 20% higher than that of the top 10 cm of savanna soil (Table 41). In contrast, termites and ants built nests that were less compact that the surrounding soil, with an apparent density of 0.90 g/cm^3 or less.

The distribution of size classes of the «bioformed» aggregates differed widely. Earthworm casts and termite mounds were composed of large aggregates, that is, more than 50% of aggregates had diameters larger than 5 mm. In contrast, termite slabs and ant nests were composed exclusively of aggregates smaller than 5 mm in diameter (Figure 26). The MWD of biogenic aggregates therefore differs according to the species that produce them (Table 41). Compared with savanna soil aggregates, MWD increased in earthworm casts and termite mounds (e.g., +12.9% in *Andiodrilus* sp. and +51.0% in *M. carimaguensis*) or, in contrast, was reduced in antnests and termite slabs (e.g., –79.5% and –97.0% in *Odontomachus* sp. and in *Pheidole* sp. 1, respectively).

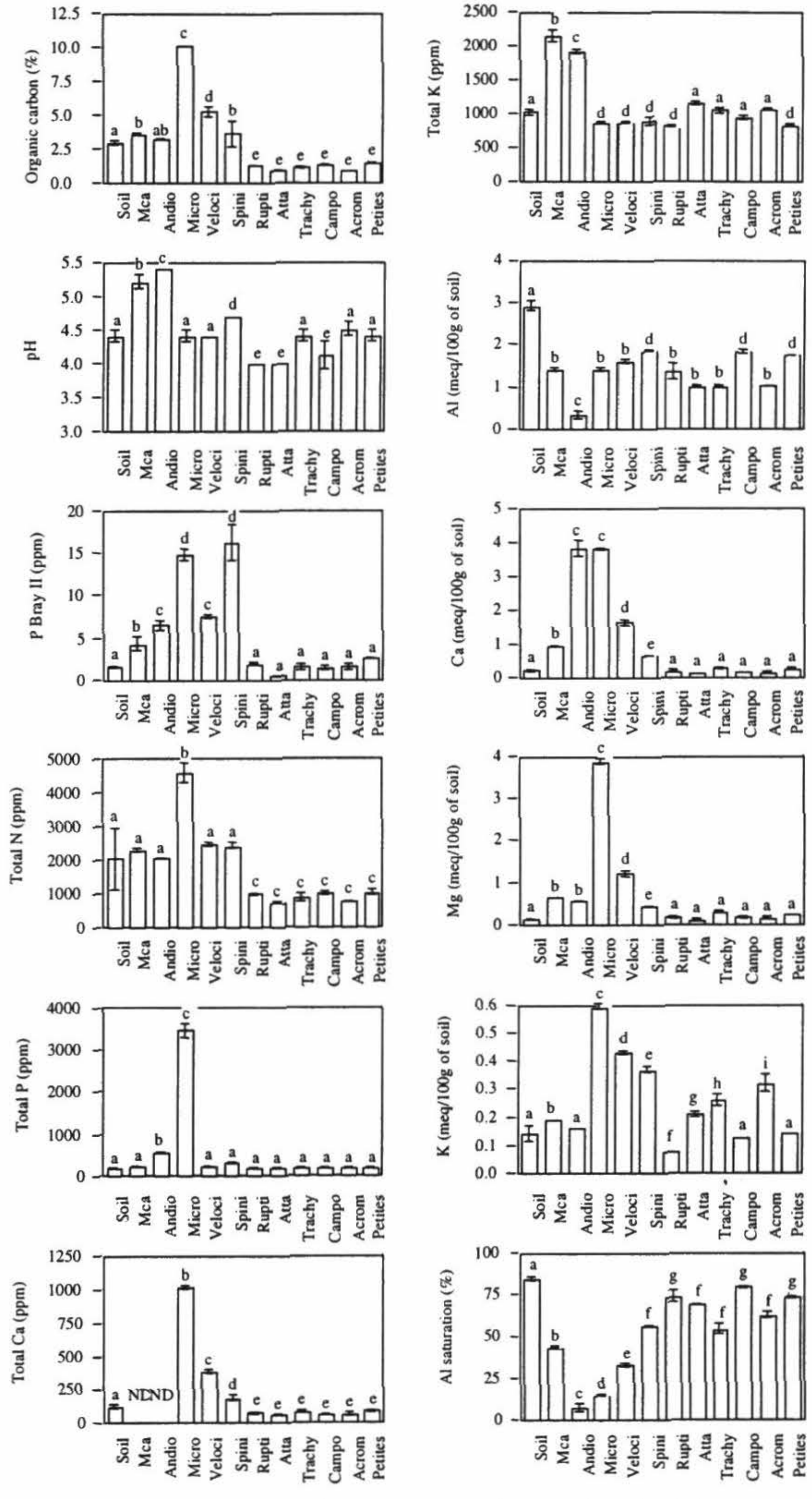


Figure 24. Chemical properties of the biogenic structures and control soil of the native savanna (codes of the structures correspond to those from table 1, except the word «petites» which refers to a combined sample of the structures produced by the smallest ants; different letters mean significant differences at P<0.05).

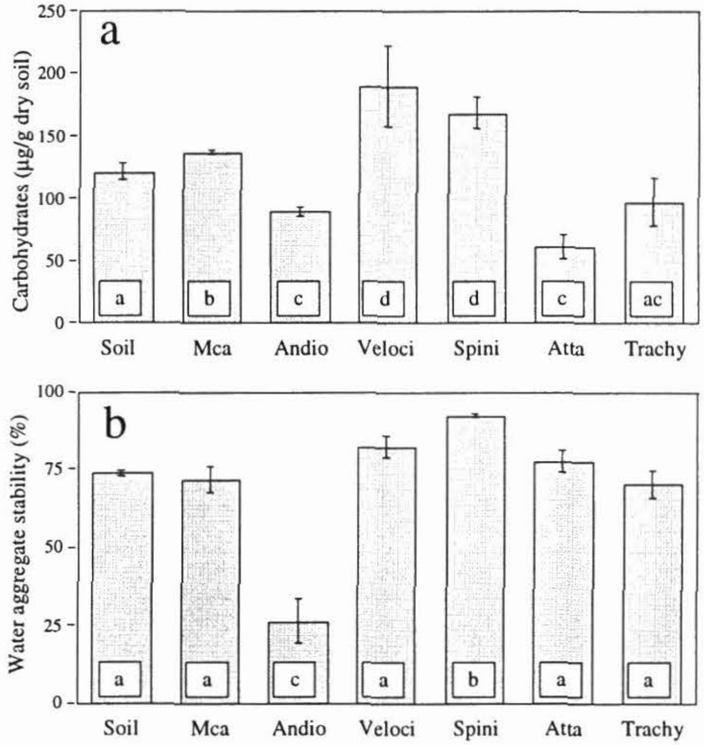


Figure 25. Hydrosoluble carbohydrates contents (a) and water aggregate stability (b) of aggregates (2-5 mm) from the biogenic structures. The results correspond to a representative selection of structures (codes correspond to those from table 1; different letters mean significant differences at P<0.05).

Table 41. Mean weight diameter (MWD) of aggregates and bulk density (BD) of biogenic structures and control soil in the native savanna (standard error within brackets; different letters mean significant differences at P<0.05).

Species	Code	MWD (mm)			BD (g/cm^3)		
Control soil		6.69	(0.78)	a	1.18	(0.07)	a
Earthworms							
Andiodrilus sp.	Andio	7.55	(0.38)	a	1.33	(0.16)	b
M. carimaguensis	Mca	10.10	(1.17)	b	1.39	(0.02)	b
Termites							
Microcerotermes sp.	Micro	-	-		0.60	(0.03)	c
Ruptitermes sp.	Rupti	1.35	(0.32)	c	0.70	(0.03)	c
Spinitermes sp.	Spini	9.05	(0.88)	e	0.91	(0.03)	e
Velocitermes sp.	Veloci	8.50	(0.83)	e	0.73	(0.05)	c
Ants							
A. landolti	Acrom	0.80	(0.04)	cd	0.54	(0.03)	c
A. laevigata	Atta	1.08	(0.05)	c	0.64	(0.02)	c
Camponopus sp.	Campo	0.54	(0.03)	cd	0.80	(0.05)	ce
Crematogaster sp.	Crema	0.32	(0.03)	cd	0.63	(0.09)	d
Odontomachus sp.	Odon	1.37	(0.05)	c	0.46	(0.02)	c
Pheidole sp.1	Pheid1	0.20	(0.02)	d	0.61	(0.09)	c
Pheidole sp.2	Pheid2	0.92	(0.03)	cd	0.71	(0.01)	c
Trachymyrmex sp.	Trachy	0.82	(0.04)	cd	0.71	(0.02)	ce

The WAS for ant nests and termite mounds was about 75% under test conditions. This figure is comparable or higher than that of savanna soil aggregates of equivalent size (–4.8% in *Trachymyrmex* sp. and +25.0% in *Spinitermes* sp.; Figure 25b). Aggregates from casts of *Andiodrilus* sp. were much less stable than those from other biogenic structures and the surrounding soil (–64.2%, compared with the soil). No significant correlation was found between structural stability of aggregates produced by engineer organisms and the concentration of hydrosoluble carbohydrates (Figure 27).

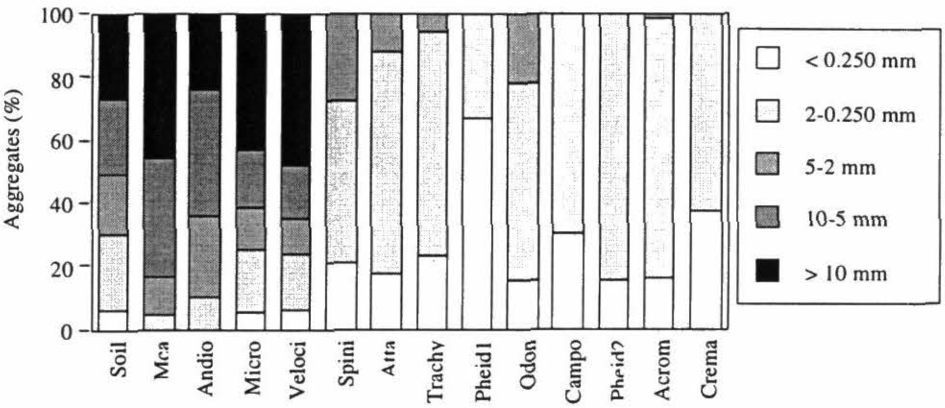


Figure 26. Size class distribution of aggregates from the biogenic structures (codes correspond to those from table 1).

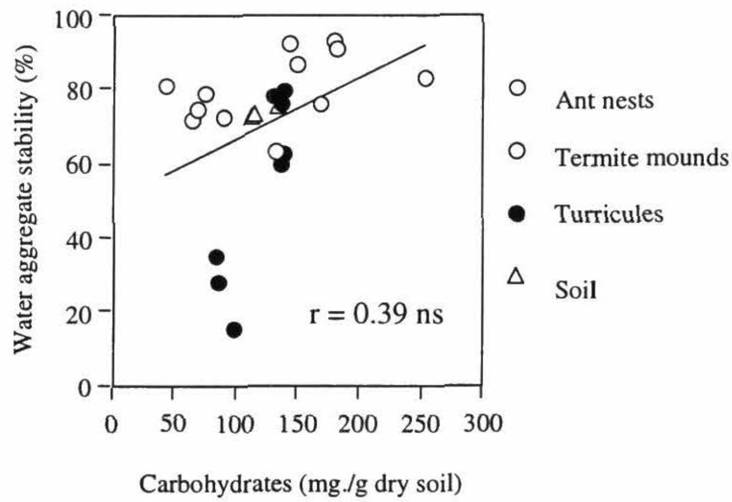


Figure 27. Simple linear regression between water aggregate stability and hydrosoluble carbohydrate concentration (NS = not significant; * = significant at P<0.05; ** = significant at P<0.01; *** = significant at P<0.001).

Principal component analysis: The first two axes of the PCA explained 82.2% of the total inertia (59.6% and 22.6% for the first and second axes, respectively; Figure 28a). The correlation coefficients associated with the variables in axis 1 showed opposition between (1) high percentages of Al saturation and (2) an important MWD and high content of organic C in mineral-element contents of the aggregates (Figure 28b). The representation of objects on axis 1 showed marked opposition between (1) ant nests and termite slabs and (2) termite mounds and earthworm casts (Figure 28c). Axis 2 was defined by an opposition between (1) Al saturation, and (2) structural density and pH (Figure 28b). On this axis too, termite mounds and ant nests were in opposition with the compact casts of earthworms (Figure 28c).

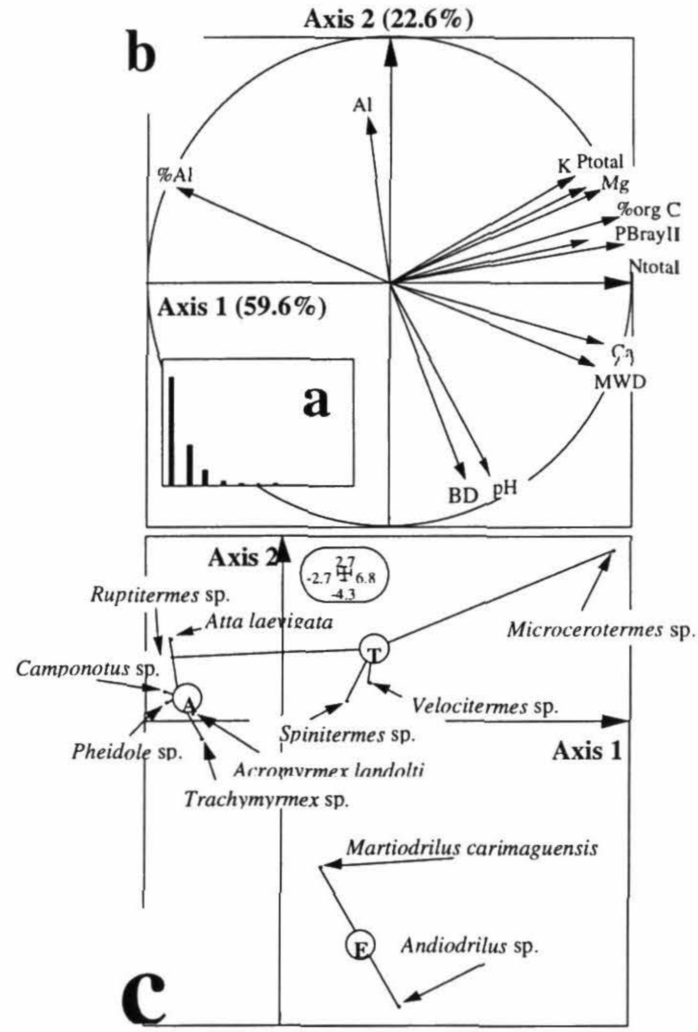


Figure 28. Results from the PCA performed on physico-chemical properties of the biogenic structures collected in the native savanna: (a) Eigenvalues; (b) Correlation circle associated to the first two axes (% org C = organic carbon; PBrayII = Phosphorous (BrayII); N total = total Nitrogen; Ptotal = total phosphorous; Al = exchangeable aluminium; Ca = exchangeable Calcium; Mg = exchangeable magnesium; K = exchangeable potassium; %Al = aluminum saturation; BD = bulk density; MWD = mean weight diameter of aggregates); (c) ordination of the different biogenic structures onto the plane defined by the first two axes (circles correspond to the baricenters within the cloud of points: E = earthworm casts; T= termite mounds and slabs; A = epigeic ant nests).

The strong concentrations of organic C and mineral elements measured in the feces of earthworms from Carimagua are common to numerous oligochaete species that build casts on the soil surface. This result, corroborated by previous findings for feces of *M. carimaguensis*, is explained by the food habitats occupied by the species under study. *Andiodrilus* sp. and *M. carimaguensis* belong, respectively, to the ecological categories "polyhumic" endogeic and "anecic", where specialization consists of selectively ingesting a substrate (e.g., organic soil and/or fresh plant material) that is richer in organic matter than the surrounding soil.

Termites that build epigeic domes normally cement soil particles with variable quantities of salivary secretions and excrements rich in organic matter. In certain cases, the walls of the termite mounds are made of a pasteboard-like material that is very rich in organic C (e.g. *Microcerotermes* sp.). The enrichment of fecal organic matter explains the differences in concentrations of both C and mineral elements observed between termite mounds and the soil. The walls or panels of aerial galleries produced by *Ruptitermes* sp cover accesses to food sources, probably playing a role in protection from heat, predators, and competitors. Contrary to what is usually described in the literature the walls analysed in our study were not enriched with organic matter and exchangeable bases.

The epigeic dome built by ants was, in contrast to the structures built by termites and earthworms, in this study, all pale yellow. The soil used was brought up from the deeper horizons of the soil profile, and left to accumulate little by little, on the soil surface. The dome's height is a measure of the excavation for the nest's subterranean spaces. Poor in organic matter, this soil does not undergo significant modifications. Neither is it enriched, as shown by its low contents of C and mineral elements.

The casts of *M. carimaguensis* and *Andiodrilus* sp., compared with the surrounding soil, were compact structures that were composed of large aggregates. The aggregates had a stability that was equivalent to or less than that found in aggregates of the surrounding soil. This finding was surprising because earthworm casts are usually more stable than soil aggregates of comparable size, and a recent study showed that the casts of *M. carimaguensis* to have considerable structural stability. Our result is probably linked to our use of casts that were recently deposited. In fact, earthworm deposits acquire their structural stability as they age, probably under the combined effects of (1) physical processes (hardening under either constant humidity or alternate phases of humidity and dryness), and (2) biological processes (fungi developing on the surface of the aggregates or the production of polysaccharides of microbial origin).

Fecal pellets deposited by termites are composed of organo-mineral aggregates that are smaller than those deposited by earthworms. These are used, together with salivary secretions, to cement soil particles in the construction of walls for the termite mound. During this process, soil porosity diminishes and the reorganized material is much more compact than the original soil. In our study, however, the presence of numerous galleries makes termite mounds cavernous, which explains the low apparent densities observed. Moreover, after a blow, the walls of termite mounds break up into macroaggregates of significant size. One can imagine the same phenomenon occurring naturally, as for example, under the impact of raindrops, thus leading to a slow redistribution of macroaggregates over the soil surface. These aggregates are particularly stable, allowing us to believe that the effects of such processes on soil stability are significant at important spatio-temporal scales. The stability of aggregates produced by termites has been pointed out by other studies, although the processes involved have not been precisely identified.

Although research on the structure of earthworm casts and termite mounds has increased in the last 10 years, the stability of aggregates produced by ant activities has only just begun attracting significant attention. In Carimagua, ant nests are composed of loose aggregates that are brought up to the soil surface from deep horizons of the soil profile and simply piled on top of each other. It is known that the average size of the aggregates is proportional to the size of mandibles of the ants carrying them. Structural stability is comparable with that of similar-sized aggregates in the topsoil. The aggregates are not cemented together with any organic adhesive, thus giving rise to granular structures. Nor are the aggregates joined, and the numerous spaces between them explain the structures' low apparent density.

Hydrosoluble carbohydrates are considered as important components of the stabilization mechanisms of soil aggregates in the Colombian savannas. Among the carbohydrates involved in soil aggregation are those that represent a specific and important fraction that is derived principally from microbial metabolism and, perhaps, plant tissues. However, our results do not show any correlation between structural stability of the biogenic aggregates and the presence of such components. This result indicates that other mechanisms, and not carbohydrates, are involved in aggregate stability at the soil's surface. For example, certain physical mechanisms, such as hardening of structures under the effects of variable humidity, may play an important role.

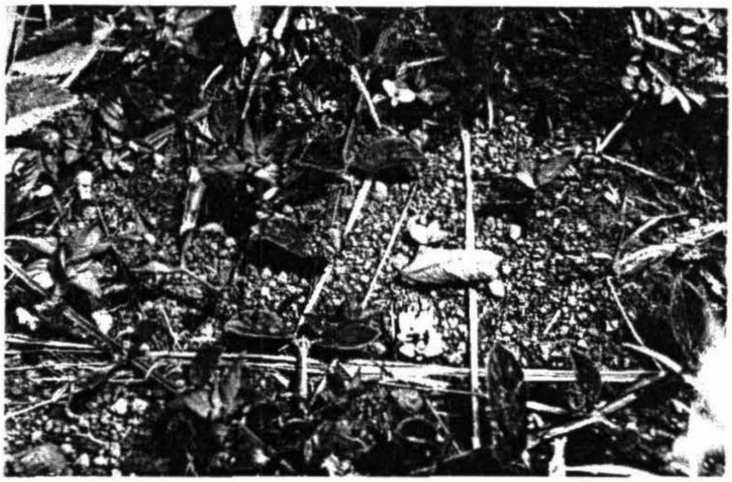
The functional significance of structures: By comparing the physico-chemical characteristics of the biogenic structures listed in this study with the surrounding soil, we could establish a classification, comprising three major groups:

- Structures more compact than the soil, enriched with organic C and mineral elements, and composed of large aggregates. This group corresponded, in our study, to the globular casts of the two earthworm species studied.
- Structures less compact than the soil, enriched with organic C and mineral elements, and composed of large aggregates. In our study, these were the epigeic termite domes.
- The least compact structures, built with soil from the deepest layers, granular, containing levels of organic C and mineral elements that are either equivalent or lower than those of the topsoil, and composed of highly stable but small aggregates. These structures were typified by anthills and epigeic termite slabs.

From this typology of biogenic structures we can deduce the impact produced by a given species on the soil. In fact, the nature of the respective biogenic structure could be considered as reflecting certain functional attributes of that species. Those species producing structures typical of groups 1 and 2 (termites and earthworms) accumulate organic C on the soil surface and probably influence dynamics of organic matter and the rate of release of mineral elements assimilable by plants.

Structures belonging to the first two groups are also characterized for their large size and the aggregates constituting them. In contrast, structures from group 3 (termite slabs and ant nests) are much smaller. The production of aggregates with diverse physico-chemical characteristics may result in the efficient regulation of soil structure. This mechanism has been described, for example, for the savannas of Côte d'Ivoire, where the smaller earthworm species break up the casts produced by larger species, thus preventing excessive accumulation on the soil surface. In Carimagua, termites (Nasutitermitinae) carry out a similar regulation—it visibly accelerates the kinetics of degradation of the large casts produced by *M. carimaguensis*. Recent studies carried out on Amazonian pastures showed that the presence of abundant earthworm populations could lead to considerable soil compaction because these populations are not associated with species able to break their casts up into much smaller aggregates.

Biogenic structures on the soil surface probably influence soil structure from the moment that these become disaggregated and the fragments are dispersed over the soil, into which they become progressively incorporated. In our study, the loose aggregates observed on the soil surface probably correspond, in essence, to fragments from biogenic structures that are being incorporated. This hypothesis is supported by the easy observation of the shape of these loose aggregates, most of which are either small casts of *Andiodrilus* sp. or recognizable fragments of *M. carimaguensis* casts (Picture 11) scattered across the soil surface.



Picture 11. Soil surface in the native savanna covered by free aggregates from biogenic structures (scale: length of photo = 40 cm).

Impact:

This study demonstrated the diversity of structures that ecological engineers build on the soil surface in a native savanna. We identified three types of structures on the basis of their physico-chemical properties: (1) compact structures, rich in organic matter (earthworm casts); (2) soft structures, rich in organic matter (termite mounds); and (3) soft granular structures, poor in organic matter (termite slabs and ant nests). The multivariate analysis reflected the wide diversity of structures and indicated both the possibility and complexity of a functional classification of engineer organisms that would simultaneously take into account the different functions reflected by these structures.

This study was limited to describing structures built by engineer organisms on the soil surface. Actually, the large number of structures built under the soil surface has not been taken into account for our typology. Numerous soil invertebrates can build endogeic structures (e.g., nests, galleries, and aggregates) that can influence soil processes in specific ways. For example, at Carimagua, an endogeic species of polyhumic earthworm (Ocnerodrilidae sp.) preferentially ingests the compact casts of *M. carimaguensis* and produces small granular casts below the soil surface. Another species, of medium size, *Glossodrilus* sp., sometimes behaves similarly. These species fall into the category of engineers that build soft granular structures. But because these earthworm casts may be richer in organic matter than the material used in ant nests and termite slabs, a new category must be created to correspond to those structures that are soft, granular, and rich in organic matter.

The definition of functional groups of ecological soil engineers is based on the typology of structures that they produce. A complete description of all biogenic structures built (including aggregates produced both on the soil surface and throughout the soil profile, galleries, and endogeic nests) is needed to precisely describe these organisms' functions. Such a description would also help establish accurately those characteristics of the structures that could be used to describe the functional attributes of a given engineer species. For example, do species building compact structures systematically produce a «compacting» effect on the soil? In contrast, do those that build soft structures have a «decompacting» effect on the soil? Do those that concentrate organic matter in their structures have an effect on the dynamics of organic matter and, if so, what sort of effect? And finally, what effects do these structures have on the living conditions of other soil organisms?

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Output 3. Improved decision making for combating soil degradation and greater agricultural productivity

Activity 3.1 Identify dynamic soil properties and test their suitability as soil quality indicators

3.1.1 Test the suitability of acid-ammonium oxalate extraction method to quantify the available soil phosphorus pool

Highlight:

- Showed that oxalate extracted P or the combined pools of resin + bicarbonate-P of the Hedley fractionation scheme may be better suited to determine soil P availability in oxisols that receive strategic application of lower amounts of fertilizer P.

Purpose:

To compare acid ammonium oxalate extraction method with Bray-II extraction, resin and bicarbinate extraction, and extraction with iron-impregnated paper strips for determining the available P in low-P supplying oxisol.

Rationale:

Phosphorus sorption capacity of highly weathered oxisols is due to P sorption capacity of various oxides, hydroxides, and oxyhydroxides of Fe and Al, and some of these components are active noncrystalline Fe and Al. These active and noncrystalline Fe and Al constituents are important in determining the availability of P in low P supplying oxisols because of their large surface areas and high reactivity with phosphates. Extraction with acid ammonium oxalate in the dark mainly dissolves active noncrystalline Fe and Al in the soil. Recently, Guo and Yost (1999) showed that P extracted with acid ammonium oxalate is a good predictor of the available P pool in the highly weathered soils. We compared the usefulness of this method as an indicator of P availability in soil compared with other methods of P availability such as resin and bicarbonate extraction of Hedley fractionation scheme, iron-impregnated paper strips, and the traditional Bray-II extraction method.

Materials and Methods:

We took advantage of Residual P experiment conducted at Carimagua to compare different methods. The residual effect of a soluble P fertilizer (triple super phosphate) was evaluated in a field experiment carried out at CORPOICA-CIAT research station at Carimagua. The soil is a well-drained Oxisol (tropeptic haplustox, *isohyperthermic*) with pH of 4.8. The study was carried out in a maize (first semester)-soybean (second semester) rotational crop system established in 1993. Treatments of P application and P rates were: residual P treatment with initial P application rates of 80, 120, and 200 kg P ha^{-1} (one time initial applications at the establishment of the field experiment); and annual P treatment with applications of 0, 20, 30, and 50 kg P ha^{-1} resulting in a total of 7 treatments. The system was evaluated for five years (1993 - 1997), with no P fertilizer application in 1997.

Soil samples (0-10 cm depth) from 1996 sampling were selected to test different methods of P extraction to determine available soil P pool and its relationship to grain yield of maize and soybean. We selected 4 treatments of P application: 0P and 20 kg P ha^{-1} (annual application) and 120 and 200 kg P ha^{-1} (one time initial applications at the establishment of the field experiment). Each treatment had samples from 4 replications.

To quantify the available soil P pool, soils were extracted using:

1) Bray-II (0.1 *M* HCl and 0.03 *M* NH_4F) (Bray and Kurtz, 1945);
2) FeO impregnated filter papers (Menon et al., 1990);

3) Resin strips: anion exchange membranes cut into strips, converted to bicarbonate form (Tiessen and Moir, 1993);
4) HCO_3 (0.5 M) (Hedley et al., 1982); and
5) Acid ammonium oxalate extraction (Guo and Yost, 1999).

Results and Discussion:

Results from the comparison of different methods to quantify the available soil phosphorus pool from either annual (20 kg P/ha) or residual P (120 or 200 kg P/ha) fertilizer applications are shown in Figure 29. The amount of available soil P determined using the acid ammonium oxalate method was significantly greater than that of the other 4 methods of P extraction. The differences among the methods of Bray-II, FeO impregnated filter paper and resin strips were not significant for each level of P application except at 200 kg P/ha. The values of Bray-II and resin-P were identical for each level of P application. When the values of resin-P were combined with the values of bicarbonate P extraction of Hedley sequential fractionation scheme, these combined values were closer to the values of acid ammonium oxalate extraction particularly at higher levels of P application. For annual application rate of 20 kg P/ha, the method of bicarbonate P extraction or the combined values of resin + bicarbonate extraction were more effective in detecting the available soil P level than the acid ammonium oxalate extraction

Results on the relationship between available soil P and grain yield of maize and soybean are shown in Figure 30. For testing these relationships, we selected 3 residual P treatments (0, 120 and 200 kg P/ha). The relationship of available soil P with grain yield was better with the method of Pi-Oxalate than the other methods, particularly for soybean. But resin + bicarbonate P extracted through sequential fractionation of Hedley also showed good relationship with grain yield of both crops.

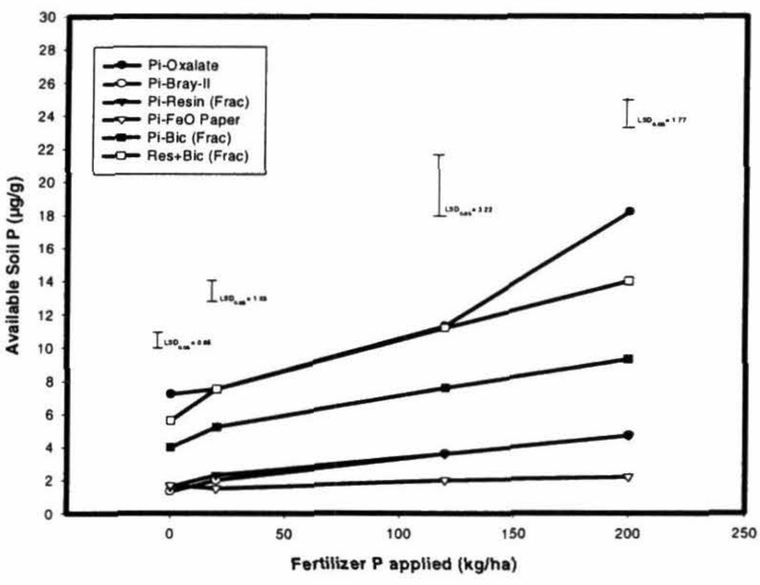

Figure 29. Comparison of acid ammonium oxalate extractable P method with other methods of P extraction to quantify the available soil phosphorus as influenced by fertilizer P application to an oxisol at Carimagua.

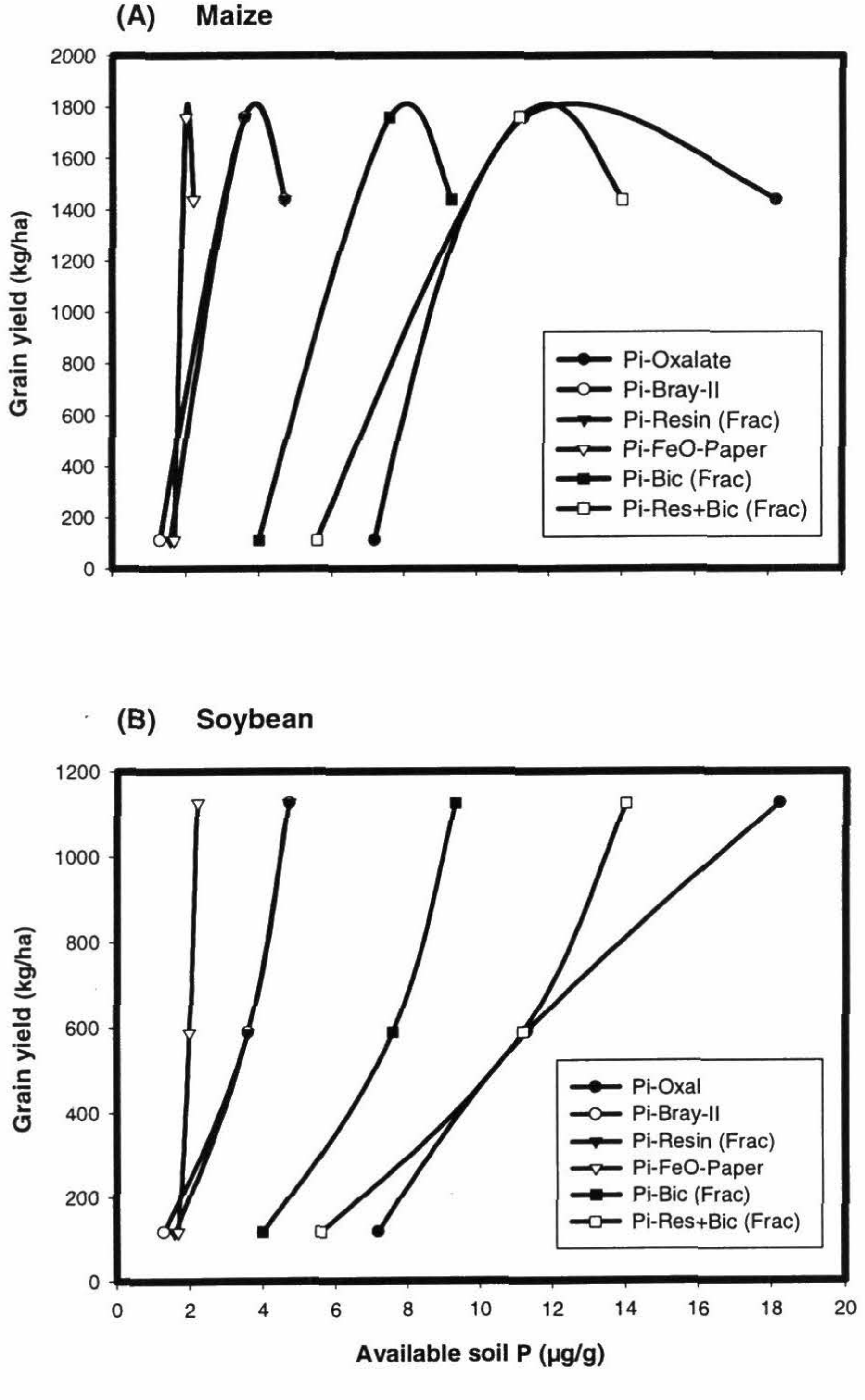

Figure 30. Relationship between available soil P and grain yield of maize (A) and soybean (B). Available soil P was determined with different methods using the residual P treatments of 0, 120 and 200 kg P/ha.

From these results it appears that either oxalate P extraction or the combined values of resin-P + bicarbonate P from the Hedley sequential fractionation scheme may be more suitable for the determination of available P in oxisols when strategic applications of lower levels of P were used. Further research work is needed to test the usefulness of -resin + bicarbonate sequential extraction method of Hedley compared with oxalate method to estimate available soil P and its relationship with grain yield in oxisols.

Impact:
This comparative study of P extraction methods indicated that use of either oxalate-P or resin-P + bicarbonate-P pools of Hedley sequential fractionation scheme are better suited to determine soil P availability in oxisols that receive strategic applications of lower amounts of fertilizer P.

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3.1.2 Adjustment of methods for the simultaneous evaluation of tropical legumes for animal feed and soil improvement

Highlights:
- Showed that differences in plant quality attributes could be more important than sample preparation in determining the extent and rate of decomposition of plant material in the soil and rumen.

Purpose:
To assess the effect of drying plant material on aerobic and anaerobic decomposition of legumes of contrasting quality

Rationale:
It is recognized that legume species are useful to enhance existing feed resources and to contribute to soil fertility in mixed livestock-cropping systems through their use in associated grass-legume pastures, as green manure or as mulch through prunings.

In mixed crop-livestock production systems legume quality is a key factor for obtaining maximum benefits in terms of rate and extent of N release in the rumen or soil. Consequently, Animal Nutritions and Soil Scientists have been interested in defining plant quality parameters that are correlated with release of nutrients from topical legumes. However, research in quality of legumes as it relates to ruminants or soil has been carried out in an independent manner and consequently there has been very little information sharing on methodological aspects.

Microbial populations mainly mediate the decomposition of plant material in the soil with lesser effects from soil macrofauna. Decomposition is often studied using the litterbag technique whereby plant material is placed in or on the soil in series of nylon litterbags. Decomposition is determined by sampling the bags over time of usually several weeks or months and relating the results (DM disappearance and N release) to initial compositional factors of the plant material. This method is resource -and time- consuming but provides valuable data for comparing plant species in terms of their relative decomposition and nutrient release patterns.

Ruminants also decompose plant material through microbes that degrade plant protein and cell wall constituents to ammonia, amino acids and energy for the host animal. To assess the extent and rate of nutrient release from plant material used as a feed resource, samples are incubated with rumen microbes using in vitro systems or alternatively using in situ techniques, which follow the same principle of the soil nylon litterbag method.

It is recognized that soil and rumen processes involved in plant degradation have fundamental differences namely an anaerobic aqueous environment in the rumen, higher number of microbes and much faster degradation rates in the rumen compared with soil. Despite these differences, the extent and rate of nutrient release from plants in the two processes is greatly affected by compositional factors of the plant (i.e. N level, lignin, condensed tannins).

Thus we tested the hypothesis that similar plant chemical entities control decomposition and the release on nutrients in the rumen and soil and that in vitro values on rates and extents of digestion by rumen microbes can be used for predicting decomposition values of legume plant material in the soil.

To test these hypotheses we setup a research program, which involves three phases:

a) Laboratory studies to determine rates and extent of aerobic and anaerobic degradation of plant material from legumes with contrasting quality subject to different drying treatments and using different methods.
b) Laboratory studies to determine relationships between plant chemical entities and aerobic and anaerobic decomposition and release of nutrients in a range of legumes of contrasting quality.
c) Field studies using selected legumes as green manures and indicator crops to validate predictions of equations of nutrient release and in vitro anaerobic and aerobic results.

We hope that through this research we can produce the following outputs:

a) Know applicability of *in vitro* methods used to assess feed value of forages to define potential decomposition and release of nutrients from legumes used as feed resource or to improve soil fertility.
b) Known chemical entities in plant material that controls the extent and rates of decomposition of tropical legumes in the rumen and soil.
c) Guidelines for quick and reliable assessment of the value of tropical legumes as feed resources and for soil improvement.

In this report we summarize results from the first series of laboratory studies in which measured anaerobic and aerobic decomposition of plant material from shrub legumes with contrasting quality and subject to different drying treatments.

Materials and Methods:
The following woody tropical legumes were selected for the initial studies: a) *Indigofera constricta* (low tannin content), b) *Cratylia argentea* (medium tannin content) and c) *Calliandra* sp (high tannin content).

Plant material from the three legumes growing in a hillside site (Pescador, Cauca) was harvested after 6 weeks of regrowth and cuttings (leaf + fine stem) were subjected to the following drying treatments prior to aerobic and anaerobic incubation: fresh, frozen, freeze-dried, oven-dried (60°C) and air-dried.

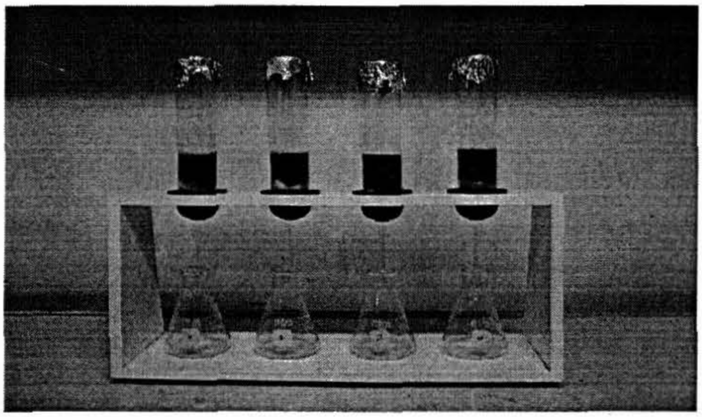
All samples were subjected to the following chemical analysis: N, C, P, fiber (NDF and ADF), lignin, soluble and bound condensed tannins and ash following standard protocols.

For measuring anaerobic degradation of DM we used two procedures:

a) **Tilley and Terry *In Vitro* method**, which comprises an incubation of the samples with rumen microorganisms followed by pepsin extraction; and
b) ***In Vitro* Gas Production**, which involves the incubation of samples with rumen microbes and measurement of gas produced at regular intervals using a transducer.

For measuring aerobic decomposition and nutrient release two procedures were used:

a) **Litterbag-Technique:** A greenhouse decomposition trial was carried out to observe decomposition and disappearance-rate of the legume prunings. Litterbags (10 cm x 10 cm, mesh size 1 mm) were filled with 5 g dry matter and placed on the soil surface. Soil from the upper layer obtained in Pescador was air-dried and filled in pots of 17 cm diameter. Pots were arranged in a randomized block design with 5 replicates. Moisture content of the soil was maintained at 60 % of water holding capacity. Sampling of litterbags was done after 1, 2, 4, 8 and 20 weeks. Bags were oven-dried (40°C) to constant weight with the plant material inside. Later plant material was manually cleaned from soil particles and weeds to determine dry weight and nutrient concentrations at different sample times.
b) **Leaching Tube Assay:** An aerobic leaching tube incubation method (see Picture 12) was used to measure N-release rates from legume pruning. Glass tubes (5 cm diameter and 20 cm length) with a funnel bottom were filled (from the bottom to the top) with a fine layer of glass fiber wool, 10g of acid-washed sand, 90 g of soil/sand mixture (1:1), and 200 mg of the different legume samples. Tubes were arranged in a randomized block design with 5 replicates and kept in a dark room at 26°C +/- 1°C. Leaching will be performed 8 times (1, 2, 4, 6, 8, 12, 16 and 20 weeks) with 100 ml of leaching solution (1mM $CaCl_2$, 1mM $MgSO_4$ and 1mM $KHPO_4$). Leachates will be analyzed for NO_3^-, NH_4^+ and condensed tannin content. Results of this experiment will show amount and period of N-release of the different legumes during degradation.



Picture 12. Leaching Tube Setup.

Results on gas production and DM decomposition over time were fitted to appropriate regression models to estimate rates, which were then subject to an analysis of variance with drying treatment and legume species as sources of variation.

Results and Discussion

The effect of drying method on chemical composition of the three legumes used in the study is shown in Table 42. As expected, there were large differences among legumes in cell wall content, lignin and N, which could results in different decomposition rates when exposed to rumen and soil microorganism.

The legume with the highest quality was *Indigofera constricta* (no condensed tannins) given its lower fiber and lignin concentration and higher N level when compared to the other two species. In the case of *Cratylia argentea* with low levels of condensed tannins, the main factor affecting its quality would seem to be the high and lignified cell wall fraction. In contrast, degradation of *Calliandra sp* could be more related to its high tannin content than to fiber and lignin.

Also as expected, drying treatment had a significant effect on the chemical composition of the three legumes included in the test. Results shown in Table 42 indicate that in all legume species, oven drying resulted in more fiber and lignin than freeze-drying or air-drying possibly as a result of artifacts formed by heat damage (Maillard reaction). However, this effect did not result in consistent reduction in the soil or rumen of DM degradation of the legumes under test as we had expected based on results in the literature.

The extent of DM decomposition of the three legumes by rumen microbes using two methods was highly correlated ($r = 98$; $P<0.01$) as has been shown in other studies. We also found a high correlation ($r = 0.87$; $P<0.0001$) between anaerobic in vitro DM loss and aerobic decomposition of DM in the soil, which had been shown in previous studies carried out in CIAT.

One important finding was that in vitro DM degradation by rumen microbes was more affected by legume specie than by drying method, regardless of the *in vitro* method used. The extent of degradation of *I. constricta* was 1.5 times greater than *C. argentea* and almost 3 times greater than *Calliandra* sp, which is a reflection of the different chemical composition of the plant material used in the experiments.

Another parameter measured in the *in vitro* fermentation and litterbag trials was the rate of degradation of the three legumes subject to different drying treatments. Results indicated a positive correlation ($r = 0.49$; $P<0.05$) between anaerobic rate of *in vitro* gas production and aerobic rate of DM disappearance using the litterbag technique.

Results also showed that rates of aerobic and anaerobic rates of degradation were significantly influenced by legume species as shown in Table 43. However, the effect of legume species on rates of degradation was greater when samples were incubated under aerobic than under anaerobic conditions. The rate of DM disappearance of *I. constricta* under aerobic conditions was 4 times greater than *C. argentea* and 7 times greater than with *Calliandra* sp. However, under anaerobic conditions the rate of gas production of *I. constricta* when averaged across drying treatments was only1.4 times greater than with *C. argentea* and 3.5 times greater than with *Calliandra* sp.

One of the objectives of this work is to establish functional relationships between plant chemical components and decomposition and release of nutrients from legumes with contrasting quality in an anaerobic rumen system and in an aerobic soil system. Initial results indicate that cell wall content (ADF) was poorly correlated to DM loss in the anaerobic in rumen *in vitro* system and in the aerobic soil litterbag system, but that negative and significant correlations were observed with ADF (cellulose + lignin) and lignin content (Table 44). By correcting the lignin fraction with condensed tannins and with N the correlations with observed DM decomposition under aerobic and anaerobic conditions significantly improved.

Table 42. Chemical composition of three tropical legumes subject to different drying treatments prior to aerobic and anaerobic incubation

Treatment	NDF (%)	Lignin (%)	N (%)
*Indigofera constricta**			
Freeze-dried	27	5.0	4.6
Oven-Dried (60 °C)	**43**	**5.4**	5.0
Air-dried	30	4.5	5.3
*Cratylia argentea***			
Freeze–dried	57	12.0	3.7
Oven-Dried (60 °C)	**77**	**13.4**	3.8
Air-dried	67	12.6	3.9
*Calliandra sp.****			
Freeze-dried	36	10.3	2.0
Oven-dried (60 °C)	**43**	**13.3**	2.7
Air-dried	35	8.5	2.3

*No tannins
**Low tannins (1- 2 %)
***High tannins (17 to 22 %)

Table 43. Rates of anaerobic (gas production with rumen microbes) and aerobic (DM disappearance in litter bags) rates of degradation of three legumes (Data presented are means across drying treatments)

Legume Species	Anaerobic Conditions- Rumen Microorganisms Rate of in vitro gas production (% / h)	Aerobic Conditions- Soil Microorganisms Rate of DM disappearance (% /d)
Indigofera constricta	8.57 a	1.35 a
Cratylia argentea	6.16 b	0.33 b
Calliandra sp	2.51 c	0.19 c

In general, these results confirm that decomposition of legume plant material in the soil using the litterbag technique is highly correlated with DM disappearance using *in vitro* anaerobic methods. The advantage of this finding is in terms of time and cost savings. While with the litterbag it takes 20 weeks to determine the extent and rate of decomposition of plant material in the soil with the *in vitro* anaerobic system it only takes 48 h to determine extent and rate of degradations of DM from plant material.

Finally, our results suggest that differences in plant quality attributes could be more important than sample preparation in determining the extent and rate of decomposition of plant material in the soil and rumen. Initial results indicate that decomposition of legumes in the soil and rumen is not a function of total cell wall in the plant but rather it is a function of indigestible fractions of the cell wall such as lignin alone or corrected for presence of condensed tannins.

Table 44. Correlation coefficient r-values between different plant chemical components and dry matter (DM) loss in an anaerobic *in vitro* gas production system and an aerobic soil litterbag system

Plant Chemical Components	Anaerobic Conditions- Rumen Microorganisms DM loss (%) r	Aerobic Conditions- Soil Microorganisms DM loss (%) r
NDF	- 0.13 (NS)	- 0.28 (NS)
ADF	- 0.64 (P< 0. 0045)	- 0.66 (P < 0.0014)
Lignin	- 0.74 (P< 0.0014)	- 0.78 (P < 0.0002)
Lignin + Total Condensed Tannins	- 0.95 (P < 0.0001)	- 0.91 (P < 0.0001)
Lignin: N	- 0.98 (P < 0.0001)	- 0.96 (P < 0.0001)

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Activity 3.2 Develop and test a soil quality monitoring system (including indigenous knowledge) for use by farmers and extensionists in hillsides and savannas

3.2.1 Integration of local soil knowledge for improved soil management strategies

Highlight:

- Developed a methodological guide through a participatory approach, to identify and classify local indicators of soil quality related to to permanent and modifiable soil properties. This guide is being used in Latin America and the Caribbean (Colombia, Honduras, Nicaragua, Peru, Venezuela, Dominican Republic) and Africa (Uganda, Tanzania).

Purpose:
To construct the local knowledge platform needed to develop local soil quality monitoring systems.

Rationale:
Current estimates of degradation of the soil resource indicate that we cannot afford to adopt a grow-now and-clean-up-later approach to agriculture. Farmers need early warning signals and monitoring tools to help them assess the status of their soils, since by the time degradation is visible, it is either too late or too expensive to reverse it. Furthermore, the costs of preventing degradation are often several times less than costs of remedial actions. Technical solutions to soil degradation abound but are often left on the scientists's shelves, because they are developed without the participation of the land user or do not build on local knowledge of soil management. A common language is required to link local and technical knowledge so that acceptable, cost-effective solutions to soil degradation can be developed.

There is increasing recognition that local soil knowledge can offer many insights into the sustainable management of tropical soils. A participatory approach in the form of a methodological guide has been developed to empower local communities to better manage their soil resource through better decission making and local monitoring of their environment. It is also designed to steer soil management towards developing practical solutions to identified soil constrains, as well as, to monitor the impact of management strategies implemented to address such constraints. The methodological approach presented here constitutes one tool to capture local demands and perceptions of soil constraints as an essential guide to relevant research and development activities. A considerable component of this approach involves the improvement of the communication between the technical officers and farmers and *vice versa* by jointly constructing an effective communication channel. 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 resulting in the adoption of improved soil management strategies at the landscape scale.

A considerable proportion of soil degradation induced by human-related activities is a result of deforestation, overgrazing and improper agricultural practices. Eighty five percent (85%) of agricultural land is estimated to have some dregree of degradation. The mounting evidence of land degradation induced by agriculture is resulting in a gradual shift from a high input agriculture paradigm, based on overcoming soil constraints to fit plant requirements by amending soils with fertilizers, lime, biocides and tillage, to a paradigm with more reliance on biological processes. This paradigm invokes a more ecological approach based on the adaptation of germplasm to adverse conditions, the enhancement of biological activity of the soil and the optimization of nutrient cycling to minimize external inputs and maximize the efficiency of their use. This new paradigm focuses on the need to improve agricultural production in more benign ways compared with traditional agricultural improvement that is based on high inputs with subsequent detrimental environmental impacts that result in soil degradation. Nevertheless, while this paradigm shift is a good sign its beneficial impact, in terms of improved soil management options for healthier landscapes, will be limited if there is little adoption by local land managers. 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. It is thus argued that research efforts should further explore a suitable balance between scientific precision and local relevance resulting in an improved knowledge base as indicated in Activity 1.3.1.

Materials and Methods:
A participatory approach for integration of local and technical knowledge systems: A common language is required to link local and technical knowledge about soils and their management so that acceptable, cost-effective strategies for improved soil management can be developed. For this purpose a methodological guide has been developed and used in Latin America and the Caribbean (Trejo et al., 1999) and Africa (Barrios et al., 2001) in order to help stakeholders identify and classify local indicators of soil quality (SQI) related to permanent and modifiable soil properties as this is the first step in the development of local soil quality monitoring systems (Figure 31).

Selecting a suitable set of SQI, and developing its use as a monitoring system (Soil Quality Monitoring System, SQMS), can be captured in the following Figure:

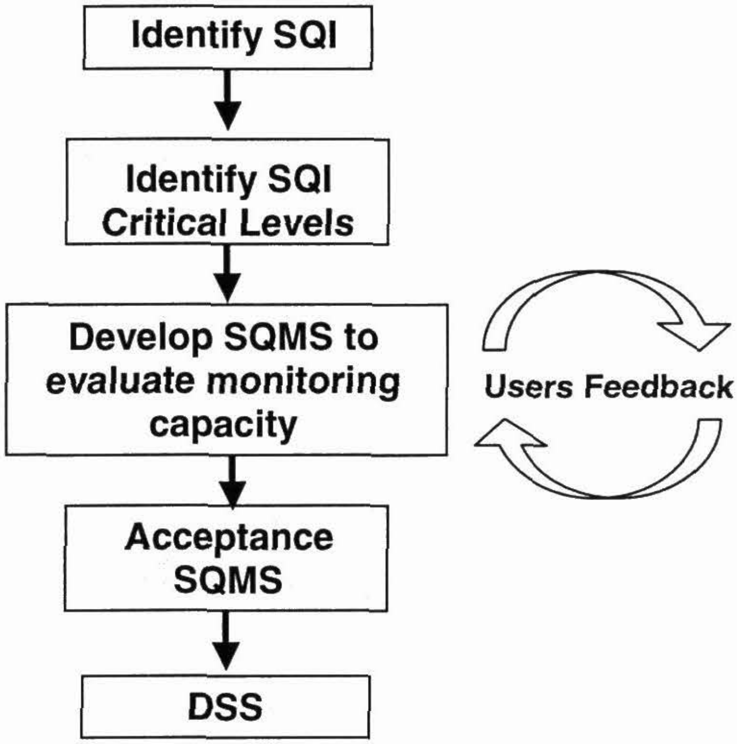

Figure 31. Process leading to the development of Soil Quality Monitoring Systems (SQMS) as Decision Support Systems (DSS).

Results and Discussion:
Suitable SQI are identified from the local and technical knowledge base and critical levels defined. This phase is followed by the definition of guidelines to establish a Soil Quality Monitoring System (SQMS) along with interpretation information as well as reaching an agreement about the suitable SQI for the relevant conditions. User feedback is very important at this stage as it will provide the grounds for acceptance of the SQMS for soil quality diagnosis and monitoring. Once the SQMS is fully accepted by users it becomes part of the Decision Support System for Natural Resource Management

This methodological guide is mainly focused on the first phase of this process; i.e.: identifying soil quality indicators that can be used by farmers, extension officers, NGO's, technicians, researchers and educators. The SQI will help in identifying the main soil biophysical limitations of the agricultural system under study. The most sensitive and robust SQIs selected for the soil constraints identified can then be incorporated into a Soil Quality Monitoring System (SQMS), and should include basic parameters such as bulk density, pH, effective rooting depth, water content, soil temperature, total C and electrical conductivity. Since our objective is to develop a SQMS for the land users, local indicators of soil quality must be included in the monitoring system. The mix of native and scientific parameters varies according to the monitoring objectives; e.g.: if they are farmers, extension agents or policy makers. It is likely that integrative SQI might be more useful to land users, than a measurement, for example, soil available P, since many indicators used by the farmers are also of the integrative type; for instance, soil color, soil structure, crop yield, presence of specific weed species. Attention should be paid to the inclusion of indicators that can be used while progressively increasing the scale at which results are applied (e.g. from plot to field and farm level, up to watershed, region and nation level). Some examples of such indicators might be crop yield and yield trends, land cover, land use intensity and nutrient balances. More recently, the use of resource and nutrient flows at farm scale has been proposed to assess land use sustainability and local variation usually missed in studies at higher levels of aggregation (i.e. region, country).

The methodological approach proposed by Trejo et al. (1999) and Barrios et al. (2001) rests on the belief 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 in Figure 32 shows the different sections of the methodological guide for Africa.

This methodological guide aims to empower local communities to better manage their soil resource through better decission making and local monitoring of their environment. It is also designed to steer management towards solutions to the soil constrains identified as well as to monitor the impact of management strategies implemented to address such constraints.

This methodological guide is made up of six sections: Section 1 provides a general introduction about the management of the soil resource in the African context and the ISQ. Section 2 presents a technical conception of the soil through a Simplified Model of Soil Formation (SMSF) based on Jenny's seminal work in order to bring participants to a common starting point. It also introduces the technical indicators of soil quality (TISQ) with the participation of professionals from National Research and Extension Organizations (NARES), NGO's, universities and International Agricultural Research Centers. Section 3 deals with participatory techniques that help gather, organize and classify local indicators of soil quality (LISQ) through consensus building and this is conducted with local farming communities. The process to elicit information about local indicators of soil quality starts with a brainstorming session guided by trainers where local farmers explain, in their own words, how they define and classify the quality of their soils. Once local indicators have been collected a ranking session is initiated where the original group of farmers is split into smaller groups of 3 or 4 in order to carry out several ranking exercises for the same information and thus obtain a more representative mean value. All results obtained from each group conducting the ranking exercise are put together in a ranking matrix where rows represent all local indicators identified during brainstorming and the columns represent the ranking assigned by different small groups of farmers.

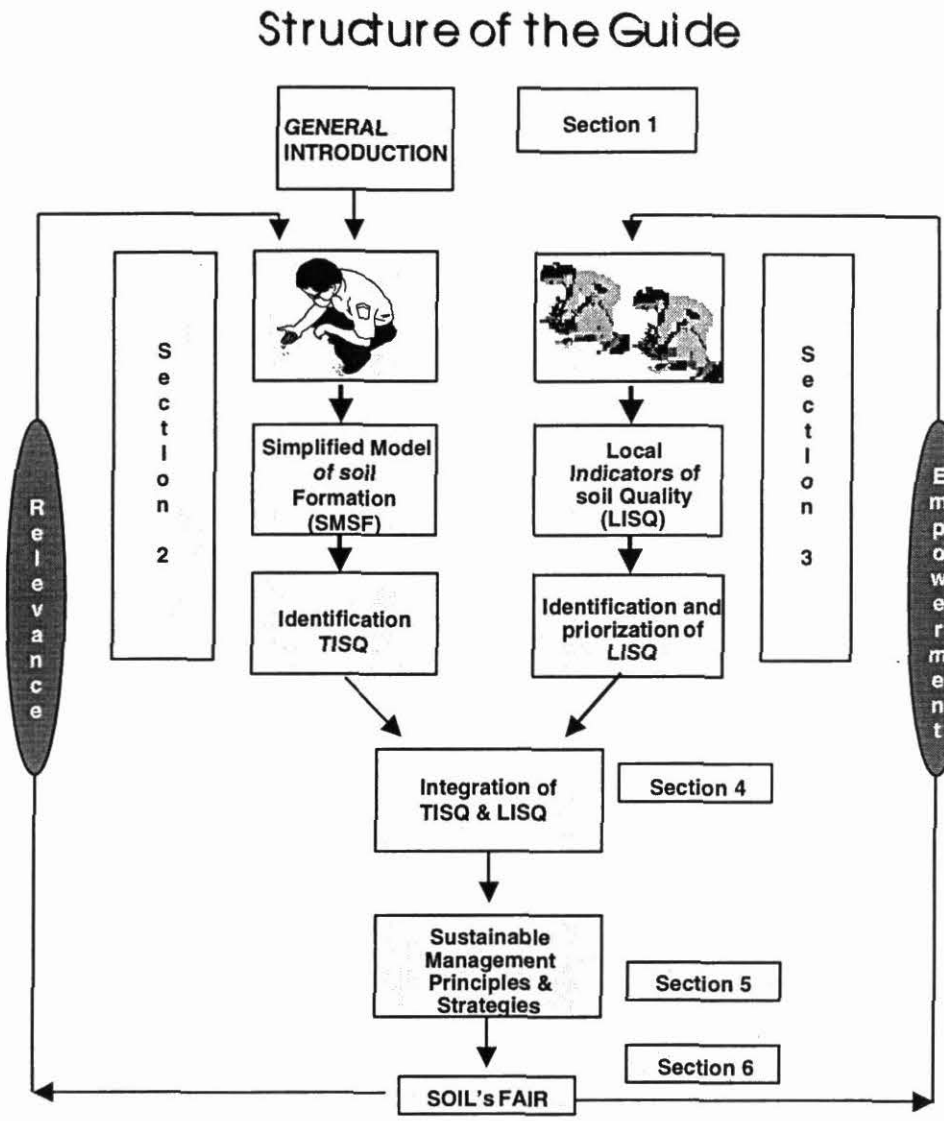

Figure 32. Structure of the methodological guide for Africa.

Section 4 provides a methodology to construct an effective channel of communication by finding correspondence between TISQ and LISQ that permit a better Extension/NGO officier – farmer communication. This is carried out in a plennary 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 (Table 45). 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 alternative soil management practices.

Table 45. Integration of LISQ identified and ranked by farmers of Jalapa village, Yoro, Honduras with TISQ and their association with permanent or modifiable soil properties.

	Knowledge integration		Property	
Ranking[a/]	Local	Technical	P[b/]	M[c/]
1	Thick soil layer/thin soil layer	Effective soil depth	X	
2	'Opulento', no need of chemical fertilizer/ needs fertilization	Soil fertility		X
3	Presence of earthworms/ lack of earthworms	Biological activity		X
4	Soils with gentle slopes, uniform/ soils with high slopes	Slope	X	
5	Soil macroaggregates can be broken into pieces, lose soil/ Macroaggregates can not be broken, tied soil	Structure	X	
6	Soil keeps water for longer time/ soil does not keep water	Texture / water holding capacity	X	
7	No burnings have occurred in the last 5 years/ Lands have been burned in the last 5 years	Soil burning		X
8	Black / various soil colors	Color	X	
9	Fast water absorption/ slow water absorption	Texture / infiltration	X	
10	Loamy soils, little clay/ 'Barrialosa' or "muddy", sandy	Texture	X	
11	'Zaléa', 'Chichiguaste'/ 'Chichiguaste' does not grow, weeds do not develop, 'zacate de gallina'	Indicator plants		X
12	Easy tillage/ difficult tillage, 'Tronconosa'	Physical barriers	X	
13	Greater yields/ Lower yields, more work to produce	Productivity		X
14	No stones present / 'Balastrosa', stony, gravely	Stoniness	X	
15	Soil does not flood, no 'aguachina'/ 'aguachina', soil sweats	Drainage	X	
16	Non washed soils/ washed soils	Erosion	X	

a/ Degree of importance given by farmers
b/ P: permanent property
c/ M: modifiable property

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.

Results to date indicate that biological indicators like native flora (see activity 1.3.1) and soil macrofauna (see activity 3.2.2) are important components of local indicators of soil quality. This is not surprising as biological indicators have the potential to capture subtle changes in soil quality because of their integrative nature. They simultaneously reflect changes in the physical, chemical and biological characteristics of the soil. There is considerable scope, therefore, to further explore the use of local knowledge about biological indicators of soil quality and as a tool guiding soil management decisions.

Section 5 is concerned with management principles behind potential strategies to address constraints modifiable in the short (< 2 yrs), medium (2-6 yrs) and long (> 6 yrs) term. Modifiable constraints are those that can be overcome through management. Examples include low nutrient and water availability, low and high pH, soil compaction and low soil organic matter content. The discrimination between short, medium and long term is necessary to enable ranking of management strategies, which is mainly dictated by resource endowment.

Section 6 is devoted to the Soils Fair which is designed 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. Here farmers and scientists communicate through a commonly developed language and simple demonstrations on how to measure soil quality *in situ* to solve local soil management and land degradation problems.

The result of this two-way exchange process is that it has a positive impact on the technical knowledge by nurturing it with local perceptions and demands. The number of improved soil management experiences will likely increase because of the solid basis provided by local relevance. Positive impacts are also envisioned on the local knowledge base as it provides with a way for this tacit knowledge to be widely understood, assessed and utilized. Besides, 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 this methodological approach for consensus building that precede collective actions resulting in the adoption of improved soil management strategies at the landscape scale.

Action plans: Finally, participants in the training event associated with the guide are encouraged to develop "action plans". These action plans show the institutional commitment made by participants to apply the guide and gained insights in their own work plans and environments. To date more than 23 action plans have been initiated in Latin America and Africa. Follow up of these action plans in the coming years will provide a measure of the impact of this participatory approach in better natural resource management through improved soil management strategies.

Participatory approaches involving group dynamics and consensus building are likely to be key to adoption of improved soil management strategies beyond the farm-plot scale to the landscape scale through the required collective action process. Action plans developed by local actors as a result of consensus building and new insights derived from the training exercise become a vehicle by which profitable and resource conserving land management is locally promoted and widely adopted. Taking advantage of the complementary nature of local and scientific knowledge is highlighted as an overall strategy for sustainable soil management.

Impact:

The approach summarized in this activity provides the tools to conduct a technical-local classification of the soil, based on modifiable and permanent soil properties, which has the flexibility to work in the spatial scale continuum plot/farm/landscape (watershed) while also having the potential to take the stakeholder groups and gender issues dimensions into consideration. This guide then provides a valuable tool to evaluate the impact of the land use change across various spatial scales and social actors.

The development of these methodological guides has been a good example of 'South – South' cooperation where experiences from Latin America were brought and adapted to the African context, and feedback from Africa has helped further improvement of the Latin American guide.

References:

Barrios E., Bekunda M., Delve R., Esilaba A. and Mowo J. 2001. Identifying and classifying local indicators of soil quality. Eastern Africa Version. Participatory Methods for Decision Making in Natural Resource Management. CIAT-SWNM-TSBF-AHI.

Trejo M.T., Barrios E., Turcios W. and Barreto H. (1999) Método Participativo para identificar y clasificar Indicadores Locales de Calidad del Suelo a nivel de Microcuenca. Instrumentos Metodológicos para la Toma de Decisiones en el Manejo de los Recursos Naturales. CIAT-CIID-BID-COSUDE.

Contributors:

E. Barrios, R. Thomas (PE-2), R. Delve (CIAT, TSBF), M.Trejo (PE-3), M.Ayarza (PE-2, PE-3).

3.2.2 Local knowledge about natural resources at watershed scale: the case of land use classification and soil fauna

Highlights:

- Showed that distribution and abundance of soil macrofauna appears to be related to local land calssification units.

Purpose:

To generate information about local knowledge of the soil and land resources in hillside agro-ecosystems.

Rationale:

In 2000, a local land use classification was investigated in the CIAT benchmark site in Pescador, Cauca. The local classification contains eight major categories that are based on physical, chemical and topographical characteristics of the Potrerillo microwatershed. To determine meaning behind this local classification we investigated occurrence of soil fauna and vegetation within these categories. The produced results will directly help to implement the project work on harmonizing scientific rigor and local relevance for improved management of natural resources as described in Output 4 (Complementary and special projects).

Results:

Preliminary findings are capture in Figure 4. It is for example clear that earthworms as a soil quality indicator dominate in the soils considered fertile by local farmers as reported in earlier studies for the Cabuyal watershed. Interesting are findings that illustrate the role of ants in infertile soils, or the role of beetles in soils that have been exhausted by nutrient mining. These and other findings warrant further investigation.

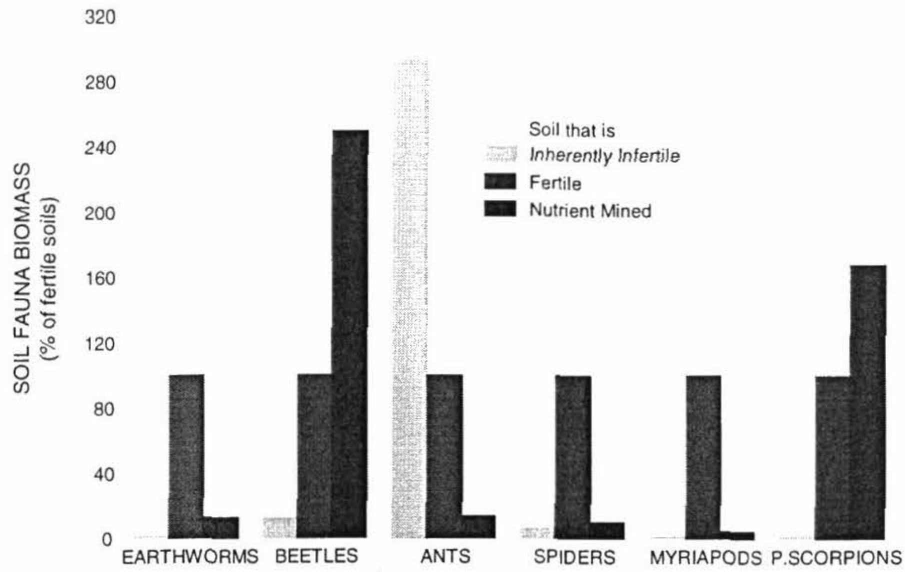

Figure 33. Biomass of functional soil fauna groups including earthworms, beetles, ants, spiders, myriapods and pseudo scorpions determined for three categories of a local land use classification (fertile soils FS, inherently infertile soils IS and soils that have been exhausted by nutrient mining ES). Biomass found in IS and ES was plotted relative to biomass in FS that was set to 100%.

Impact:
Measurable impact will be generated when these results are used to modify and improve land management strategies that explicitly integrate soil fauna.

Contributors:
F. Sevilla (Univ. Nacional), T. Oberthür (PE-4), J.J. Jiménez, E. Barrios (PE-2), H. Usma, G. Escobar (PE-4), J.G. Cobo (PE-2)

Activity 3.3 Compile databases to feed into simulation models and decision support systems

3.3.1 Creating a database for the long-term field experiments carried out in savannas and hillsides agroecosystems

Highlight:
- Created a database for the past and present field experiments in savannas and hillsides agroecosystems to facilitate further analysis and use by PE-2 and other CIAT projects.

Purpose:
To organize and create a database for the long-term field experiments carried out in savannas and hillsides agroecosystems.

Rationale:
Over the past few years, the soils project (PE-2) of CIAT has several field experiments either completed or in progress in both tropical savannas and hillsides agroecosystems. The data collected from these field studies need to be organized systematically. The organized database can facilitate not only further analysis

and interpretation of data by soils project staff but also can be extremely useful to different projects of CIAT.

Results and Discussion

More than 200 files (Lotus, Excel and SAS documents) were used to create the database (Figure 1). They contained data from measurements carried out during the last few years. Most of these data were in different formats. This information was organized and at present stored in the Oracle institutional database of CIAT.

To organize the data, three big blocks were established: one block for hillsides agroecosystem and two blocks (Culticore and Plains (Altillanura)) for savannas agroecosystem. For hillsides agroecosystem, data from 1995 to 2000 were organized systematically. For savannas, organization of data files from Culticore experiment from 1993 to 1999 was completed while the data of Altillanura are still being organized.

A standard format is developed in Excel for adding new data to this database (Figure 2). The criteria for using this format are developed so that data collection system used within the project by research and support staff is uniform across sites and experiments. The process for adding data to the database is very simple. There are three steps: first to create the Excel files for the new samples/observations; second to have the privilege of adding information to the database by pressing the finish button in the Excel format to create the files, then load those files to the database in Oracle and enter the new sites, trials or treatments, and third to have easy access for users to consult the information from the database

The soils project was allocated space in the CIAT documentation center for the publication of documents that can be shared with other units internally within CIAT. There are about 70 files (word, power point, pdf, etc.) as articles, posters and presentations. These can be accessed through CIAT intranet (Figure 1).

In addition to database, information on the CIAT collection of arbuscular-mycorrhizae was organized as a catalog that can be accessed by CIAT staff through intranet.

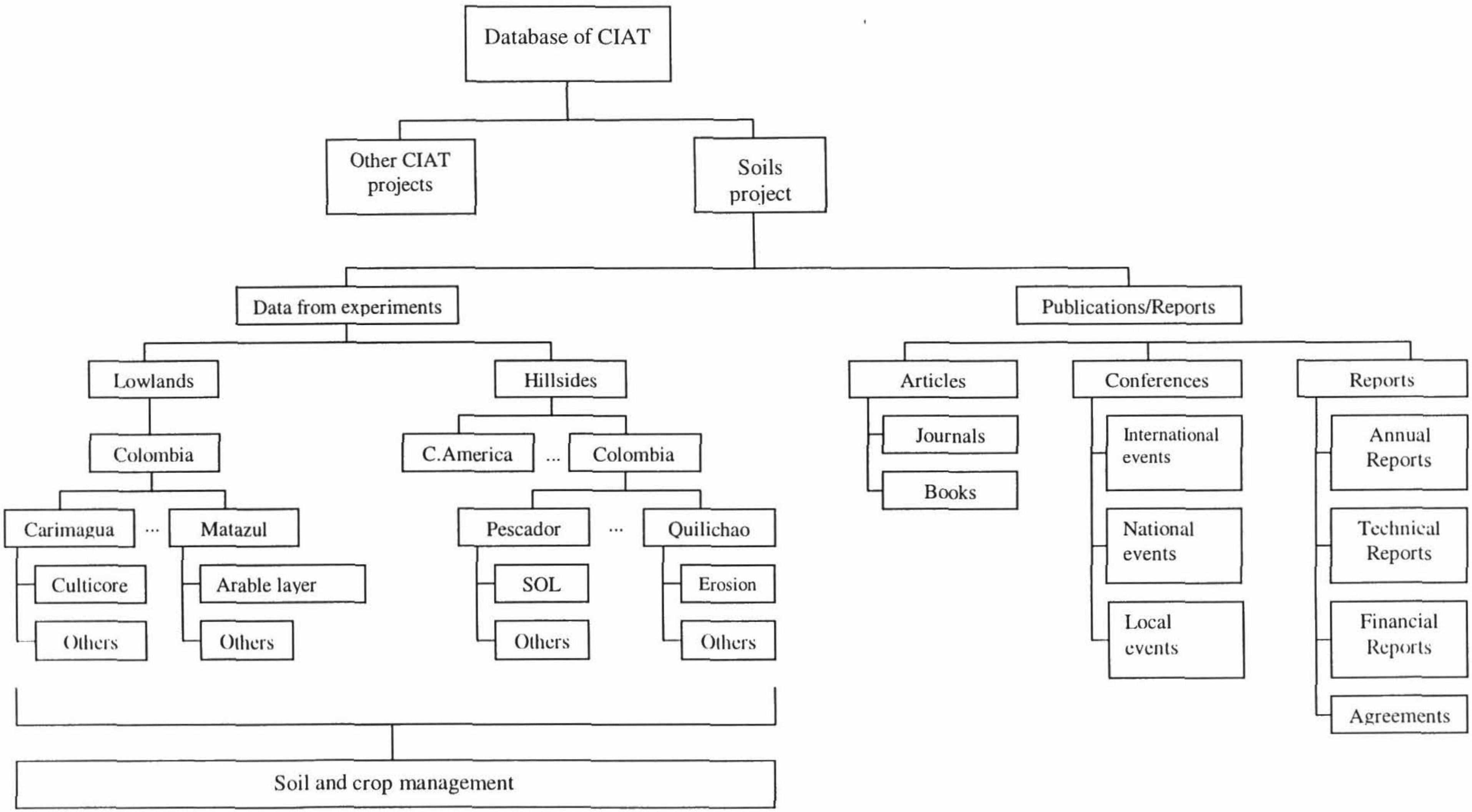

Figure 34. Descriptions of the structure of the database of Soils project (PE-2).

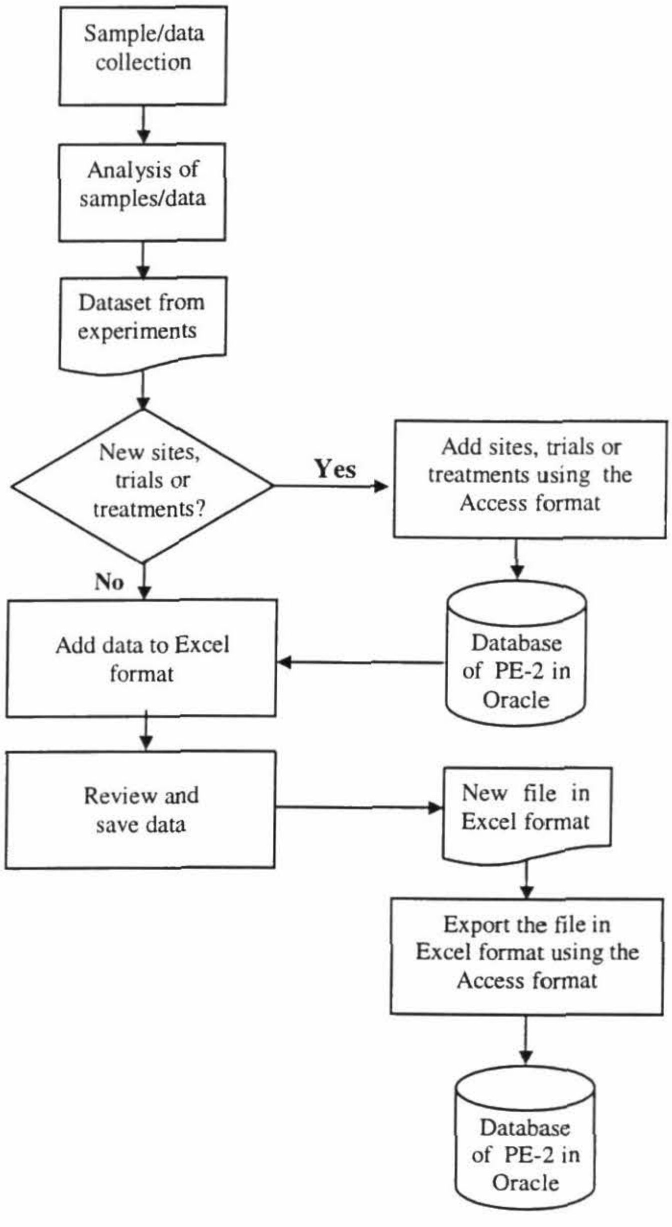

Figure 35. The process of compilation and storage of data for each sample/ observation from Soils project (PE-2).

Impact:
A database was created for the past and present field experiments of savannas and hillsides agroecosystems to facilitate further analysis and use for soils project and other projects of CIAT. This database contains valuable information on soil and crop management strategies for sustainable production in both hillsides and savannas agroecosystems.

Contributors:
C. García, A. Franco, E. Amézquita, I. M. Rao, R. Thomas, E. Barrios, J. Jimenez, L. Chávez, M. Rivera, J. Galvis, J. Ricaurte, J. Cobo, N. Asakawa, I. Corrales, D. Molina and P. Hoyos.

Activity 3.4 Develop decision support tools for improved soil, water and crop management

Progress on this activity will be reported next year.

Activity 3.5 Develop and test a decision support systems for organic materials

Activities conducted in Colombia and currently in Centroamerica will be presented together next year.

Activity 3.6 Develop soil degradation risk assessment maps

3.6.1 Develop a georeferenced soil data bank to generate soil maps and to plan land use in the Easter plains of Colombia

Highlight:
- Developed soil maps for the municipality of Puerto López, Colombia, using a georeferenced soil data bank (GEOSOIL) to facilitate land use-planning and site-specific soil management recommendations .

Purpose:
To develop a GIS based soil mapping tool to support the decision-makers in land use planning and agronomists for improved soil management.

Rationale:
The development of tools and techniques of Geographical Information Systems (GIS) has contributed to different disciplines such as agronomy, geography, digital cartography, and remote sensing. During the last few years, CIAT researchers have focused their activities in GIS to improve land use planning for better management of natural resources and to support decision-makers. The main objective of this work is to link GIS with data on soil properties in order to generate maps of soil quality. These maps are useful to improve land use planning and soil management for improved and sustained agricultural productivity while conserving natural resources.

Materials and Methods:
Field Work. An intensive soil sampling was carried out over an area of 20,000 ha covering the municipality of Puerto López (Altillanura plana). Seventy two field sites were identified for data collection on soil properties. Soil pits were dug for profile descriptions and for sampling at different soil depths (0-5, 5-10, 10-20 y 20-40 cm). In addition to the above soil pits, four representative model profiles were selected for taxonomic verification. The following parameters were considered for measurement and analysis:
Site description (georeference)

Identification of horizons
Descriptions of color (Munssel table)
Texture (organoleptic method)
Texture modifiers (% gravel)
Structure (type, class, degree)
Presence of cutans
Presence of concretions
Consistence (dry, wet)
Soil strength (3 measurements at depth, Torvane)
Resistance to penetration (3 measurements per pit using a penetrographer)
Effective soil depth
Drainage
Soil moisture

Soil Sampling. Nested analysis of variance requires a hierarchical dataset and the hierarchical levels in the data are based on sampling distance. Four levels were chosen corresponding to sampling distances of 5, 50, 1000 and 4000 m. The distances are arbitrary but were chosen on the presumption that a sampling interval of 5 m would encompass almost all of the spatial variation. Variation due to large (e.g. geological) structures would be accounted for in the 4000 m interval. The number of replicates at the first level of 4000 m sampling distance was 8. The remaining levels were subdivided two at a time, resulting in 8 x 2 x 2 x 2 = 64 replicates at the fourth level, equal to the total number at sampling points. To cover more area and to be more precise in the understanding of spatial variability an additional point was taken, thereby increasing the replicates from 64 to 72 points. In each point, a soil pit (50 x 50 x 50 cm) was dug and samples were collected for the determination of the following soil properties at different depths:
Soil water content
Bulk Density
Macroporosity and residual porosity
Texture (Boyucos)
Sand fractions
Hydraulic conductivity
Air permeability
Organic carbon
pH
Elemental analysis (Ca, Mg, K, P, Al, Zn, CEC)

Geostatistical Analysis. The soil data are being analyzed using multivariate analysis with the purpose of determining whether there are correlations among measured variables. This preliminary analysis will permit to identify more sensible soil parameters to change with land use. This geoestatistical analysis is being carried out using the following software: Surfer16 and GIS-Spring to generate maps of isolines for each soil property. So far, we have completed generation of maps of soil pH and resistance to penetration.

Results and Discussion:
Using data collected from field and analysis from laboratory, it was possible to generate maps as shown in Figures 1 and 2. Figure 1 shows a preliminary map of soil pH distribution for the study area of 20000 ha. To construct the map, Surfer-16 software was used. The intensity of color from yellow to red indicates the increase in values of pH. The dark red color indicates the higher values and the yellow color indicates the lower values. The soil pH values in the study area varied from less than 3.9 to more than 4.4. Based on these soil pH values, it is possible to develop site-specific recommendations for lime application to different crop and pasture systems. Therefore, these type of soil maps are extremely useful to plan land use and also to develop site-specific soil management recommendations.

Resistance to penetration is a key soil physical property that affects root penetration and thereby crop or forage adaptation to infertile, Al-toxic acid soils of the Altillanura. Figure 2 shows the spatial variability in resistance to penetration at three soil depths (5, 10 and 20 cm) in the study area. The light color of yellow indicates lower values of resistance to penetration while the dark color of red indicates higher values. There are is a good correlation of values among the three soil depths.

Impact:

Results from this study indicate the importance of integrating GIS tools with soils data to generate soil maps. These soil maps are extremely useful for: (i) planning land use changes; (ii) developing site-specific recommendations for better soil management; and (iii) targeting crop and forage cultivars to specific ecological niches

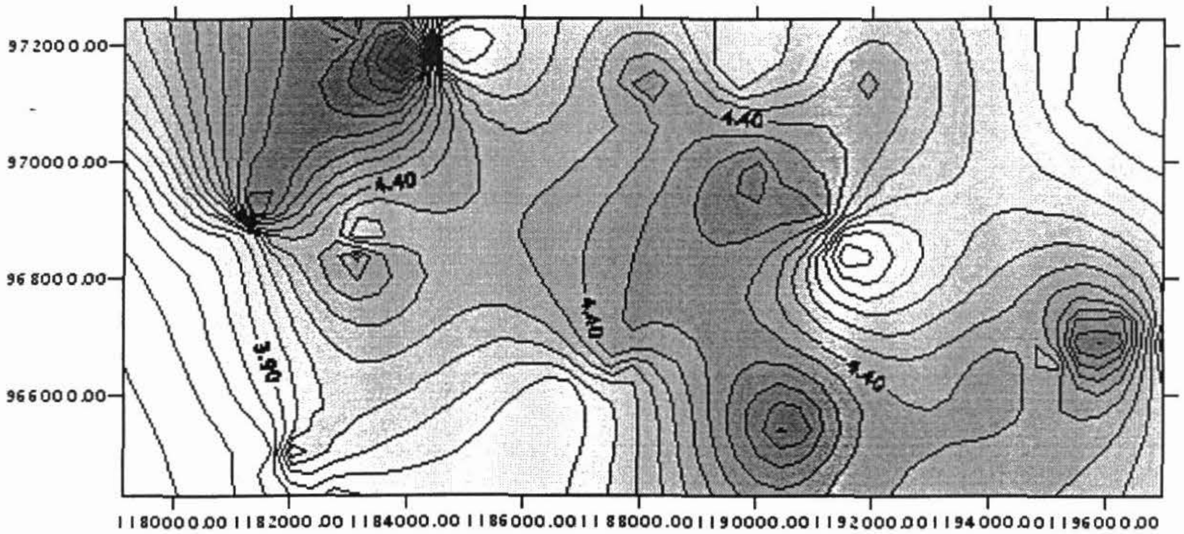

Figure 36. A preliminary soil map showing spatial variability of soil pH in the study area of Puerto Lopez. Software Surfer-16 was used to generate the soil map. The intensity of color from yellow to red indicates the increase in values of pH.

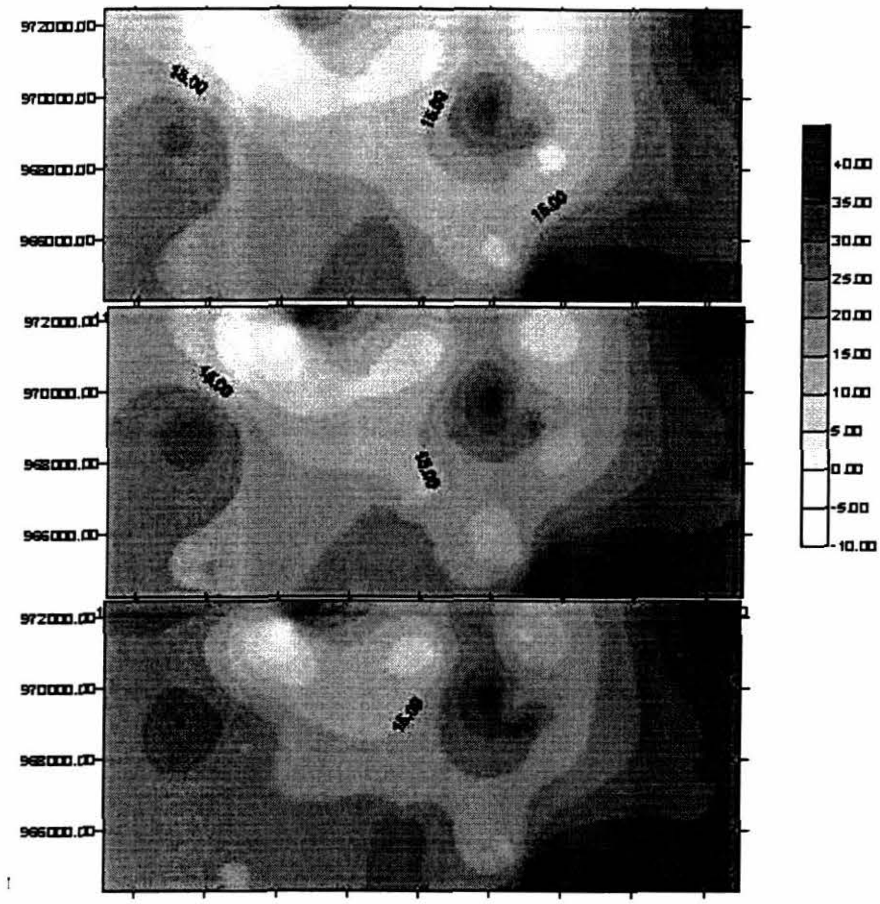

Figure 37. A soil map showing spatial variability in resistance to penetration in the study area of Puerto Lopez. Software Surfer-16 was used to generate the soil map. The intensity of color from yellow to red indicates the increase in values of resistance to penetration.

Contributors:
Y. Rubiano (PE-2, PE-4), E. Amézquita (PE-2), N. Beaulieu (PE-4), A. Franco (PE-2, PE-4), D. Malagón (IGAC, Colombia), R. Thomas (PE-2), M. Romero (CORPOICA, Colombia)

Output 4. Institutional capacity for SWNM enhanced through the dissemination of concepts, methods, tools and training

Activity 4.1 Organize and coordinate field days and workshops

Highlight:

- Nine Field days were held in Pescador (October 2000 – October 2001), Cauca, Colombia with the participation of 212 visitors mainly farmers, extensionists and students from universities and schools.
- Coordinated field day and workshop entitled: "Nuevos conceptos para el manejo de suelos en los Llanos Orientales de Colombia" (New concepts for soil management in the Eastern Plains of Colombia), Villavicencio, Colombia, July 10-13, 2001. This course was attended by 120 persons and was financed by MADR of Colombia.

Activity 4.2 Prepare guidelines/pamphlets on soil, water and nutrient management concepts

Highlight:

- The new pamphlet series **Agroecology Highlights** has been launched with four contributions from team members: 1) Farm nutrient recycling through double purpose live barriers, 2) Improved fallows: an alternative for rapid restoration of degraded soils, 3) Opportunities for increasing the efficiency of phosphorus use in tropical agroecosystems and 4) Harnessing the biological plows of the soil: soil macrofauna communities. The objective of this series is to provide in a compact (single two-side page) and graphic form summarized user-friendly information about important new approaches taken by PE-2 towards improved agroecosystem management and soil health.

Activity 4.3 Promote and participate in specialized training courses, prepare training materials

Highlight:

- Coordinated training course entitled: "Local Indicators of Soil Quality", held in Arusha, Tanzania and sponsored by CIAT, SWNM, TSBF and AHI

Activity 4.4 Publish research results in refereed journals and other publications

Highlight:

- Published 28 refereed journal articles, 5 refereed book chapters, 3 edited books, 9 non-refereed book chapters and 1 article in conference proceedings.

Activity 4.5: Supervise postdoctoral research, graduate and undergraduate theses

Highlight:

- The following is a list of undergraduate and graduate students who received training with the project scientists (Table 46).

Table 46. Training supported by PE-2 and MAS/MIS consortia of SWNM Program

Name	Nationality	Education	Institution	Research theme
Axel Schmidt	German	Post-Doc	Univ.Hohenheim	Utilizing multipurpose legumes to improve soil and feed quality
Armando Torrente	Colombia	Ph.D.	U.Nacional, Palmira	Soil-water movement in Magnesic soils
Karen Tscherning	Germany	PhD	Univ.Hohenheim	Simultaneous evaluation of tropical forage legumes for feed value and soil enhancement
Brigit Krucera	Germany	Ph. D.	University of Freiburg	Characterization of bean genotypes for abiotic stress adaptation
Christian Thierfelder	Germany	Ph.D.	Univ.Hohenheim	Development of soil preserving land use systems in the tropics
Nelson Castañeda	Colombia	Ph.D.	University of Gottingen	Genotypic variation in P acquisition & utilization in *A. pintoi*
Susan Buehler	Switzerland	Ph.D.	ETH, Zurich	Phosphorus acquisition/cycling
Twaha Atenyi	Uganda	Ph. D.	Agric. University of Norway	Soil phosphorus transformations and organic matter dynamics
Yolanda Rubiano	Colombia	Ph.D.	U.Nacional, Palmira	Soil degradation indicators for the Llanos
Lucero Mariani	France	Ph.D.	IRD	Impact of biogenic structures of *M. carimaguensis* (Oligochaeta, Glossoscolecidae) on soil functioning in savanna soils from Colombia
Elena Velásquez	Colombia	Ph.D.	University Nacional, Palmira	Soil quality indicators based on macroinvertebrate communities and functional parameters
Patricia Cerón	Colombia	M.Sc.	U.Nacional, Palmira	Local knowledge about soils and their management
José T. Reyes	Honduran	M.Sc.	U.Nacional, Palmira	Biological indicators of soil quality
Lina A. García	Colombia	M.Sc.	CATIE	Local indicators of water quality
Ivonne Valenzuela	Colombia	M.Sc.	U.Nacional, Palmira	Relationship between free soil water and its composition in Vertisols
Mariela Rivera Peña	Colombia	M.Sc.	U.Nacional, Palmira	Chemistry of tropical soil
Jaime Lozano Fernández	Colombia	M.Sc.	U.Nacional, Palmira	Variability of soil physical properties in CIAT Experimental Station
Aleyda Suárez	Colombia	B.Sc.	U. del Llano, Villavicencio	Influence of depth of compaction in maize yields
Alveiro Salamanca	Colombia	B.Sc.	U.Nacional, Palmira	Soil physical characterization under Desmodium
Carlos Alberto Cabrera	Colombia	B.Sc.	U. del Llano, Villavicencio	Characterization of degraded and non-degraded pastures in Altillanura
Carolina Becerra	Colombia	B.Sc.	U.Nacional, Palmira	Variability of soil physical properties in CIAT Experimental Station
Elio Enrique Ruiz	Colombia	B.Sc.	Univ. del Valle, Cali	Relationship between compaction and electrical conductivity
Enna Diaz Betancourt	Colombia	B.Sc.	Fundación Univ. de Popayán	Soil physical characterization in Cauca Paramo soils
Jairo Barragán	Colombia	B.Sc.	U. del Llano, Villavicencio	Influence of depth of compaction in maize yields
José Manuel Campo	Colombia	B.Sc.	U.Nacional, Palmira	Evaluation of some crop systems in relation to erosion in Volcanic Ash Soils (Pescador)

Name	Nationality	Education	Institution	Research theme
Leando Brejarano	Colombia	B.Sc.	U.Nacional, Palmira	Erodability in hillsides (Santander de Quilichao)
Liliana Paz Betancourt	Colombia	B.Sc.	Fundación Universitaria de Popayán	Soil physical characterization in Cauca Paramo soils
Lorena Parra Lopez	Colombia	B.S.	University of Valle	Screening methods for aluminum resistance in common bean
Paola Andrea Pinto	Colombia	B.Sc.	ITA, Buga	Technician, working on soil physical determinations
Robinson Parrado	Colombia	B.Sc.	U. del Llano, Villavicencio	Characterization of degraded and non-degraded pastures in Altillanura
Ximena Pernett Medina	Colombia	B.Sc.	U.del Valle-Cali/ Nacional-Palmira	Climatic studies in the Llanos
Fernando Sevilla	Colombia	B.Sc.	U.Nacional, Palmira	Soil macrofauna and farmer perception in Potrerillo watershed (Cauca)
Lina María Gaviria	Colombia	B.Sc.	University Suramericana, Neiva	Characterization of surface biogenic structures under different cassava treatments in Santander de Quilichao
Elías Claros	Colombia	B.Sc.	U.Nacional, Palmira	Agronomic evaluation sugarcane live barriers
Juliana Rizo	Colombia	B.Sc.	U.San Buenaventura	Economic analysis of sugarcane live barrier systems
Judith Cruz	Nicaragua	B.Sc.	U. Centroamericana	Ethnobotanical studies at San Dionisio reference site.
Ligia González	Nicaragua	B.Sc.	U. Centroamericana	Ethnobotanical studies at San Dionisio reference site.

Activity 4.6 Foster linkage with institutions in the region and advanced research organizations

Highlight:

- Established and maintained collaborative links with 87 institutional partners

NARS:

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Specialized Institutions:
University of Gottingen, Germany: N. Claassen
University of Hohenheim, Germany: R. Schulze-Kraft, D. Leihner
University of Freiburg: Germany: E. Wellmann
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Universidad del Valle: Patricia Chacón
Universidad del Cauca: Patricia Cerón
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Complementary and Special Projects

Research activities reported have been supported from a number of donors (Table 47).

Table 47. List of donors of Complementary and Special Projects

Donor/Project	Duration	Total Pledge (US$)
ACIAR Integrated nutrient management in tropical cropping systems: Improved capabilities in modelling and recommendations.	1999-2002	434,130
BMZ-GTZ, Bonn, Germany An integrated approach for genetic improvement of aluminum resistance of crops on low-fertility acid soils.	2001–2003	690,244 (Euros)
ETHZ, Zurich, Switzerland Assessing the impact of adapted germplasm on the phosphorus fertility of low phosphorus –supplying tropical soils.	1998–2001	140,000
European Commission (EC), Brussel, Belgium Characterization of South American genotypes of bean for optimal use of light under abiotic stress.	2001-2004	831,261 (Euros)
PRONATTA, Colombia Strategies for building up productive arable layer in Altillanura soils/	2001-2004	153,000
DFID, United Kingdom Integrated Resource Management in Crop-Livestock Farming Systems of Sub-Saharan Africa.	2000-2003	602,916
SWNM Integrated Soil Management (MIS): Sustainable agricultural development. A consortium of research organizations for development.	1999-2002	370,764

Preparation of a concept note and proposal entitled 'Learning to communicate: harmonizing spatial perceptions of farmers and scientists for landscape-based agro-ecosystem management'.

Highlight:

- Concept note developed and submitted to BMZ in October 2001

Purpose:

Develop a new framework that provides for the identification of relevant information needed for specific natural resource management issues

Rationale:

The project develops a process that strengthens farmers' understanding of natural resources with formal analysis of land resources. The objective is to outline processes that allow identifying and structuring spatial information of farmers and scientists in a way that is relevant to farmers, and complements their awareness of risky land management to remove uncertainty that impedes implementation of improved land use options (Figure 38).

These processes will be investigated in watersheds in different agro-ecological hillside regions of Central America, East Africa and Southeast Asia using natural resource management (NRM) themes that may include soil and water management, diversification of agricultural systems, and impacts of tenure systems on sustainable use of forest resources. Different geographical regions and different NRM themes are considered essential to provide the bases to identify [a] general and [b] site-specific principles on harmonizing spatial perceptions of farmers and scientists.

The project explores congruencies/inconsistencies between participatory research and modeling approaches to address agro-ecosystem management issues at the landscape scale. It aims to improve interaction of scientists with the land managers by incorporating farmer perceptions in the conceptualization of problems, definition of parameters and generation of data in an iterative process of learning and action.

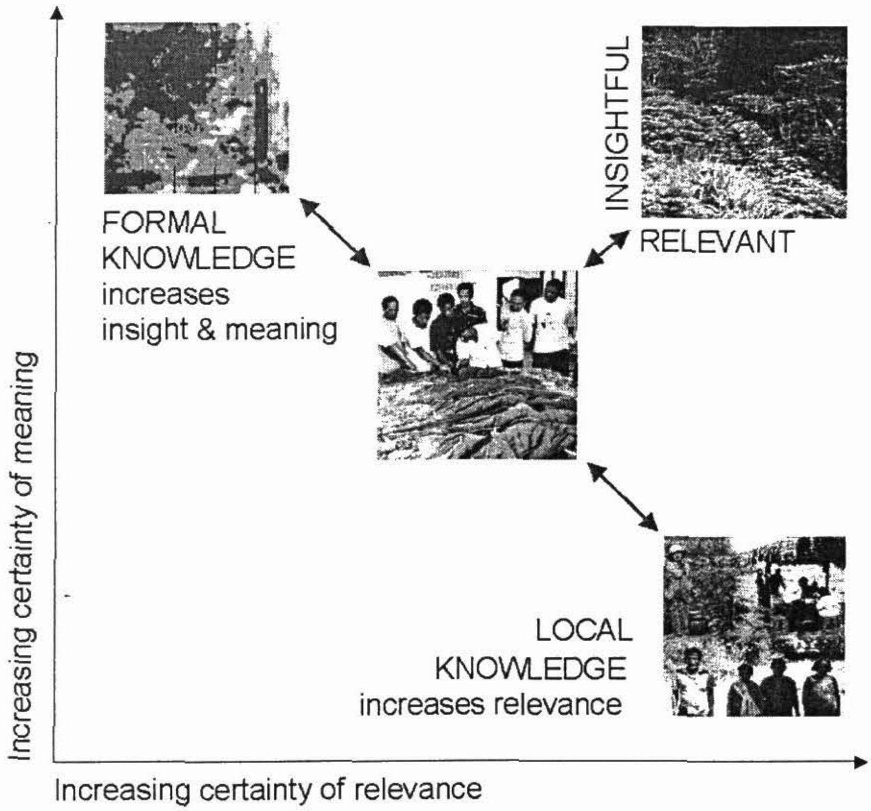

Figure 38. The integration of the local and scientific systems of knowledge: Spatial perceptions of local people are formalized and transferred into the geo-referenced and scaled spatial integrator (here a participatory 3D model) where it can be analyzed jointly with scientific outputs from models and geographical information systems. Feedback loops are hoped for and technically easily feasible. The joint analysis will produce information for NRM that is more relevant than scientific knowledge and more insightful than local knowledge on its own.

Information theory is envisioned as a framework to help identifying those principles that ultimately may lead to environmentally safe options for improved management of resource variability at the landscape scale. The project will develop this framework that filters and brings to use farmers' appreciation of land resource behavior together with conventional scientific understanding. The framework will enable us to see in which cases certain pieces of information are appropriate and can realistically be considered to generate useful information for identification and management of 'hot spots' as part of Landscape-Based Agro-Ecosystem Management (LBAM).

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LIST OF PUBLICATIONS

Refereed journal articles:

1. Amézquita E., Thomas R.J., Rao I.M., Molina D.L., Hoyos P. 2001. The influence of pastures on soil physical characteristics of an Oxisol in the Eastern Plains (Llanos Orientales) of Colombia. Agriculture, Ecosystems and Environment (in review).
2. Barrios E., Trejo M.T. 2001. Implications of local soil knowledge for integrated soil fertility management in Latin America. Geoderma (in press).
3. Barrios E., Cobo J.G., Rao I.M., Thomas R.J., Amézquita E., Jiménez J.J. 2001. Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia. Agriculture, Ecosystems and Environment (in review).
4. Blanchart, E., Albrecht, A., Decaëns, T., Duboisset, A., Lavelle, P., Mariani, L., Roos, E. 2001. The potential of soil macrofauna activities in reducing soil erosion: the case of endogeic earthworms. Agriculture, Ecosystems and Environment (in press).
5. Buehler, S., Oberson, A., Rao, I.M., Frossard, E. and Friesen, D.K. 2001. Sequential phosphorus extraction of a 33P-labeled Oxisol under contrasting agricultural systems. Soil Sci. Soc. Am. J. (in press).
6. Cobo J.G., Barrios E., Kass D.L, Thomas R.J. 2001. Nitrogen mineralization and crop uptake from green manure applications to a tropical volcanic-ash soil. Biology and Fertility of Soils (in press).
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10. Decaëns T., Galvis J.H., Amézquita E. 2001. Propriétés des structures produites par les ingénieurs écologiques à la surface du sol d'une savane colombienne. Comptes Rendus de l'Acad. Sci. Paris, Sciences de la vie/Life Sciences 324: 465-478.
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12. Decaëns T., Asakawa N., Galvis J.H., Thomas R.J., Amézquita E. 2001. Surface activity of ecosystem engineers and soil structure in contrasting land use systems of Colombia. European Journal of Soil Biology (in press).
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14. Jiménez, J.J., Decaëns, T. The impact of soil organisms on soil functioning under neotropical pastures. A case study of a native anecic earthworm species. Agriculture, Ecosystems and Environment (in press)
15. Jiménez, J.J., Rossi J.P., Lavelle, P., 2001. Spatial distribution of earthworms in natural and disturbed savannas of the Eastern Plains of Colombia. Applied Soil Ecology, 17(3): 267-278.
16. Jiménez, J.J., Cepeda, J.A., Decaëns, T., Oberson, A., Friesen, D.K. 2001. Phosphorous fractions and dynamics in surface earthworm casts under native and improved grasslands in a Colombian savanna Oxisol. Soil Biology and Biochemistry (in review).
17. Lavelle P., Barros E., Blanchart E., Brown G., Desjardin T., Mariani L., Rossi J.-P. 2001. SOM management in the tropics: why feeding the soil macrofauna? Nutrient Cycling in Agroecosystems 62(1-2), (in press.).

18. Mariani, L., Bernier, N., Jiménez, J.J., Decaëns, T. 2001. Régime alimentarie d'un ver de terre des savanes colombiennes. Une remise en question des types écologiques. Comptes Rendus de l'Académie des Sciences Paris, Sciences de la Vie, 324(8): 733-742.
19. Mariani L., Decaëns T., Jiménez J.J., Torres E.A., Amézquita E. 2001. Rainfall impact on casts of various ages of the anecic earthworm *Martiodrilus carimaguensis* (Glossoscolecidae). Geoderma (in review).
20. Oberson, A, Friesen D. K., Rao, I. M.,. Buehler, S. and Frossard, E.. 2001. Phosphorus transformations in an oxisol under contrasting land-use systems: The role of the soil microbial biomass. Plant and Soil (in press).
21. Phiri S., Amézquita E., Rao I.M., Singh, B.R. 2001. Constructing an arable layer through vertical tillage (chisel) and agropastoral systems in tropical savanna soils of the Llanos of Colombia. Nutrient Cycling in Agroecosystems (in review).
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23. Phiri, S., Rao I. M., Barrios, E. and B.R. Singh. 2001. Plant growth, mycorrhizal association, nutrient uptake and phosphorus dynamics in a volcanic-ash soil in Colombia as affected by the establishment of *Tithonia diversifolia*. Journal of Sustainable Agriculture (in review).
24. Phiri, S., Amezquita, E., Rao I.M. and Singh, B.R. 2001. Disc harrowing intensity and its impact on soil properties and plant growth of agropastoral systems in the Llanos of Colombia. Soil and Tillage Research 62: 131-143.
25. Ruiz, H., Legarda B. E.L., Amézquita E. 2000. Evaluación de algunos parámetros físicos bajo un suelo vertisol sometido a uso intensivo. *Revista de Ciencias Agrícolas* 27(2):107-115.
26. Wenzl, P., Chaves, A.L., Patiño, G.M., Mayer, J.E. and Rao, I. M.. 2001. Accumulation of Al-Complexing Organic Acids in Root Apices of *Brachiaria* Species under Alumminium Stress. J. Plant Nutrition and Soil Science (in review).
27. Wenzl, P., Patiño, G.M., Chaves, A.L , Mayer, J. E. and Rao, I.M.. 2001. The high level of aluminum resistance in signalgrass is not associated with known mechanisms of external detoxification in root apices. Plant Physiology 125: 1473-1484.
28. Wenzl, P., Mayer, J.E. and Rao, I.M.. 2001. Inhibition of phosphorus accumulation in root apices is associated with aluminum sensitivity in *Brachiaria*. Journal of Plant Nutrition (in press).

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1. Barrios E., Schroth G. (2001) Measuring/predicting the availability of N for trees and crops. Chapter 2.2. Maintenance and replenishment of soil fertility. In IUFRO Agroforestry Working Group Manual of Research Methodologies (in press).
2. Lavelle, P., Barois, I., Blanchart, E., Brown, G. G., Brussaard, L., Decaëns, T., Fragoso, C., Jiménez, J. J., Kajondo, K. K., Martínez, M. A., Moreno, A., Pashanasi, B., Senapati, B., Villenave, C. 2001. Earthworms as a resource in tropical agroecosystems. In: Subba Rao, N. S. and Dommergues, Y. R. (eds.). *Microbial Interactions in Agriculture and Forestry*. Science Publishers, Inc., Enfield, USA; Plymouth, UK. p 163-181.
3. Miles, J.W., do Valle, C.B., Rao, I.M. and Euclides, V.P.B.. 2001. *Brachiaria* grasses. In: L. E. Sollenberger, L. Moser and B. Burson (eds) Warm-season grasses. ASA-CSSA-SSSA, Madison, WI, USA (in press).
4. Rao, I.M. 2001. Role of physiology in improving crop adaptation to abiotic stresses in the tropics: The case of common bean and tropical forages. In: M. Pessarakli (ed). *Handbook of Plant and Crop Physiology*. pp. 583-613. Marcel Dekker, Inc., New York, USA

5. Rao, I.M. and Cramer, G. 2001. Nutrition from the soil and crop improvement to utilize soil resources. In: M. Chrispeels and D. Sadava (eds). *Plants, Genes, and Agriculture*. American Society of Plant Physiologists, USA (in press).

Non-refereed book chapters:

1. Amézquita E. 2001. Las propiedades físicas y el manejo productivo de los suelos. In: A.Garcia O., I.G. Velenzuela B. (eds). *Manejo Productivo de Suelos para Cultivos de Alto Rendimiento*. Sociedad Colombiana de la Ciencia del Suelo, Comité Regional del Valle del Cauca/CORPOICA, Palmira, Colombia. pp.11-30.
2. Amézquita E., Rubiano Y. 2001. Aplicabilidad de la agricultura de precisión en el trópico. In: A. Garcia O., I.G. Velenzuela B. (eds). *Manejo Productivo de Suelos para Cultivos de Alto Rendimiento*. Sociedad Colombiana de la Ciencia del Suelo, Comité Regional del Valle del Cauca/CORPOICA, Palmira, Colombia. pp.77-93.
3. Decaëns, T., Jiménez, J.J., Rangel, A.F., Cepeda, A., Lavelle, P., 2001. La macrofauna del suelo en la sabana bien drenada de los Llanos Orientales. In: G. Rippstein, G. Escobar, F. Motta, (eds) *Agroecología y Biodiversidad de las Sabanas en los Llanos Orientales de Colombia*, CIAT / CIRAD, Cali, Colombia. p. 109-135.
4. Gómez-Carabalí, A., Rao, I. M., Beck, R.F. and. Ortiz, M. 2001. Rooting ability and nutrient uptake by tropical forage species that are adapted to degraded andisols of hillsides agroecosystem. In: N. Gaborcik (ed.) Grassland Ecology V, Slovakia (in press).
5. Jiménez, J.J., Decaëns, T., Thomas, R.J., Lavelle, P. 2001. Soil macrofauna: an available but little known natural resource. In: J.J. Jiménez and R.J. Thomas (eds). Nature's Plow: Soil microinvertebrate Communities in the Neotropical Savannas of Colombia. CIAT, Cali, Colombia. p. 1-16.
6. Jiménez, J.J., Decaëns, T., Thomas, R.J., Mariani, L., Lavelle, P. 2001. General conclusions highlights and future needs. In: J.J. Jiménez and R.J. Thomas (eds). Nature's Plow: Soil microinvertebrate Communities in the Neotropical Savannas of Colombia. CIAT, Cali, Colombia. p. 361-386.
7. Rao, I.M., Ayarza, M.A.,. Herrera, P. and Ricaurte, J.. 2001. El papel de las raíces de especies forrajeras en la adquisición, reciclje y almacenamiento de nutrientes en el suelo. Memorias de Curso Internacional "Investigación y Desarrollo de Systemas de Producción Forrajera en el Tropico". CIAT, Cali, Colombia (in press).
8. Rao, I.M, Rippstein,. Escobar, G.G and. Ricaurte, J. 2001. Producción de biomasa vegetal epígea e hipógea en las sabanas natives. In: G. Rippstein, G. Escobar and F. Motta (eds.) *Agroecología y Biodiversidad de las Sabanas en los Llanos Orientales de Colombia*. CIAT, Cali, Colombia. pp.198-222.
9. Rippstein, G., Amézquita E., Escobar G., Grollier C. 2001. Condiciones naturales de la sabana. In: Rippstein G., Escobar G. and Motta F. (eds.) *Agroecología y Biodiversidad de las Sabanas en los Llanos Orientales de Colombia*. CIAT, Cali, Colombia. pp.1-21.

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1. Barrios E., Bekunda M., Delve R., Esilaba A., Mowo J. 2001. Identifying and classifying Local Indicators of Soil Quality – East African Edition. Participatory Methods for Decision Making in Natural Resource Management. CIAT, SWNM, TSBF, AHI. 154 p.
2. Jiménez, J. J., Thomas, R. J. (Eds.) 2001. *Nature's plow: Soil Macroinvertebrate Communities in the Neotropical Savannas of Colombia*. CIAT, Cali, Colombia. May 2001. 389 p.
3. Jiménez, J. J., Thomas, R. J. (Eds.) *El Arado Natural: Las Comunidades de Macroinvertebrados del Suelo en las Sabanas Neotropicales de* Colombia. (Spanish edition in press).

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1. Kelemu, S., J. F. White and I. M. Rao. 2001. The role of endophytic fungi in Brachiaria, a tropical forage grass. pp. 605-607. Proceedings of XIX International Grassland Congress, Brazilian Society of Animal Husbandry, Piracicaba, Brazil.
2. Rao, I. M. 2001. Adapting tropical forages to low-fertility soils. Proceedings of XIX International Grassland Congress, pp. 247-254. Brazilian Society of Animal Husbandry, Piracicaba, Brazil.
3. Rao, I. M. 2001. Limitaciones edaficas climáticas para la producción de frijol común. Proceedings of the conference on "Manejo productivo de suelos para cultivos de alto rendimiento. Palmira, September 27-28.

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1. Rao, I.M., Plazas, C. and Ricaurte, J. 2001. Root turnover and nutrient cycling in native and introduced pastures in tropical savannas. pp. 976-977. In: W. J. Horst, M. K. Schenk, A. Burkert, N. Claassen, H. Flessa, W. B. Frommer, H. Goldbach, H. –W. Olfs, V. Romheld, B. Sattelmacher, U. Schmidhalter, S. Schubert, N. v. Wiren and L. Wittenmayer (eds.) Plant Nutrition: Food security and sustainability of agro-ecosystems through basic and applied research. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Non-refereed conference presentations:

1. Amézquita, E. 2001. Conference presented at the VII Seminario de Pastos y Forrajes "Manejo y Utilización de Pastos y Forrajes en Sistemas de Producción Animal". Guanare (Barinas), Venezuela, March 14-17.
2. Amézquita, E. 2001. El concepto de la capa arable. Conference presented at the Curso "Nuevos conceptos para el manejo de suelos en los Llanos Orientales de Colombia". Villavicencio, Colombia. July 10-13.
3. Amézquita, E. 2001. Impacto de los sistemas de labranza en las características de suelos volcánicos, and Condiciones de suelo para lo no labranza. Conferences presented at the Seminario-Taller "Labranza de Conservación en Suelos de Ladera", CORPOICA C.I.-Obonuco, June 21-22. Pasto, Colombia.
4. Amézquita, E. 2001. Soil physical characteristics and land degradation in savanna Oxisols of Colombia. Poster presented at 3rd International Conference of Land Degradation ICLD and Meeting of the IUSS Subcommission C Soil and Water Conservation. Rio de Janeiro, Brazil, September 14-22.
5. Araya, R. and I. Rao. 2001. Evaluación de fuentes de resistencia baja fertilidad en frijol común. Paper presented at XLVII Annual Meeting of PCCMCA, San Jose, Costa Rica.
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8. Beebe, S., Téran, H. and Rao, I.M. 2001. Progreso en el desarrollo de líneas de frijol resistentes a sequía con grano rojo y negro en CIAT, Cali, Colombia. Paper presented at XLVII Annual Meeting of PCCMCA, San Jose, Costa Rica.
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10. Chávez, L.F. 2001. Experiencia en siembra directa en los Cerrados del Brasil. Conference presented at the Curso "Nuevos conceptos para el manejo de suelos en los Llanos Orientales de Colombia". Villavicencio, Colombia. July 10-13.
11. Jiménez, J.J. 2001. Caracterización de la biodiversidad del suelo y el desarrollo de estrategias para favorecer los procesos biológicos en el suelo. Taller de Planificación de Actividades. Consorcio Manejo Integrado de Suelos Frágiles en Centro Amércia (MIS), Playa Negra, Amapala, Honduras, 14 –17 February.
12. Jiménez, J.J. 2001. La Biodiversidad en el suelo y papel funcional de la macrofauna. Ejemplos de la sabana colombiana. Taller sobre Manajeo de Indicadores Biológicos del Suelo. CORPOICA, Tibaitatá, Bogotá, Colombia, 21-22 June, 2001.
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14. Rao, I.M., Beebe, S., Ricaurte, J., Téran, H. and Singh, S.P. 2001. Frijol común (*Phaseolus vulgaris* L.) con mejor adaptación a toxicidad de aluminio. Paper presented at XLVII Annual Meeting of PCCMCA, San Jose, Costa Rica.
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16. Rubiano, Y. 2001. Distribución de los suelos en los diferentes paisajes de la Orinoquía. Conference presented at the Curso "Nuevos conceptos para el manejo de suelos en los Llanos Orientales de Colombia. Villavicencio, Colombia. July 10-13.

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List of Acronyms

ACIAR	Ausralian Centre for International Agricultural Research, Australia
AUN	Agricultural University of Norway, Norway.
BMZ	Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung
CATIE	Centro Agronómico Tropical de Investigación y Enseñanza (para América Central), Costa Rica.
CENICAFE	Centro Nacional de Investigaciones en Café, Chinchiná, Colombia
CENIPALMA	Centro de Investigación en Palma de Aceite, Colombia
CIAT	Centro Internacional de Agricultura Tropical, Colombia
CIDIAT	Centro Internacional de Desarrollo Integral de Aguas y Tierras, Venezuela.
CIELAT	Centro de Investigaciones Ecológicas de los Andes Tropicales, Venezuela.
CIPASLA	Consorcio Interinstitucional para la Agricultura Sostenible en Laderas, Colombia.
CIRAD	Centre de Coopération Internationale en Recherche Agronomique poour le Depeloppement, France
CNPAB	Centro Nacional de Pesquisa de Agrobiologia, Brazil
COLCIENCIAS	Instituto Colombiano para el Desarrollo de la Ciencia y la Tecnología "Francisco José de Caldas", Colombia
CORPOICA	Corporación Colombiana de Investigación Agropecuaria, Colombia.
CPAC	Centro de Pesquisa Agropecuaria dos Cerrados (of EMBRAPA)
CSIRO	Commonwealth Scientific and Industrial Research Organization, Australia
DFID	Department for International Development
EC	European Comisión, Belgium
ENA	Escuela Nacional de Agricultura
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuaria, Brazil
ETH	Institut for Plant Science, Zurich
FAO	Food and Agriculture Organization of the United Nations, Italy
FEDEARROZ	Federación Nacional de Arroceros, Colombia
GTZ	Technical Cooperation, Germany
IAEA	International Atomic Energy Agency, Vienna, Austria
IBSRAM	International Board for Soil Research and Managment
ICRAF	International Centre for Research in Agroforestry, Nairobi, Kenya
ICRISAT	International Crops Research Insttitute for the Semi-Arid Tropics, India
IFDC	International Fertilizer Development, USA
IRD	Institut Français de Recherche sicentifique pour le Developpement et Coopération, France.
IRRI	International Research Institute
LAC	Latin American and the Caribbean
MAS	Management of Acid Soils (of SWNM of the CGIAR), CIAT Colombia.
MIS	Integrated Soil Management (of SWNM of the CGIAR), CIAT Honduras
NARS	National Agricultural Research Systems
NGO	Non-Governmental Organization
PRONATTA	Programa Nacional de Transferencia de Tecnología, Colombia
SLU	Swedish Agricultural University
SOL	Supermercado de Opciones para Laderas
SWNM	Soil, Water and Nutrient Management (systemwide program of the CGIAR), CIAT Colombia.
TSBF	Tropical Soil Biology and Fertility Program, Nairobi, Kenya
UNA	Universidad Nacional Agraria, Nicaragua