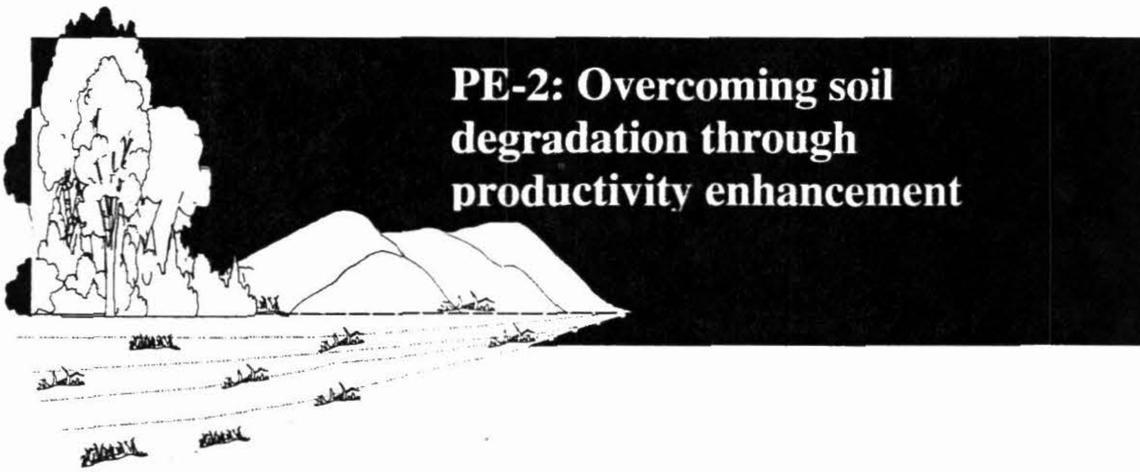

PE-2: Overcoming soil degradation through productivity enhancement

Annual Report
2000

CIAT
Centro Internacional de Agricultura Tropical
International Center for Tropical Agriculture

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PE-2: Overcoming soil degradation through productivity enhancement and natural resource management

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, macrofauna, 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 and extensionists 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:

1998 Nutrient release rates of maize, rice, forage legume residues and green manures quantified; soil physical properties susceptible to degradation identified; soil N and P fluxes quantified in rice and maize monocultures, rice-green manure, maize-green manure rotation systems in the Colombian savannas.

1999 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.

2000 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.

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;

Universities: Uberlandia (Brazil), Nacional (Colombia), Paris (France), Bayreuth (Germany), Bangor (Wales, U.K.), Complutense de Madrid (Spain), Cornell, Michigan State, Ohio State (USA), ETH (Switzerland.); International Research Institutes: Macaulay Land Use Research Institute (U.K.), IFDC (USA); ORSTOM, CIRAD (France); CATIE (Costa Rica).

CG system linkages: Enhancement & breeding - 15%; Crop Production Systems - 60%; Biodiversity - 5%; Stengthening NARS- 20%; Co-convenor Systemwide Program on soil-water-nutrient management (SWNM) and lead institute for the Managing Acid Soils consortium, and contributes to Tropical America Ecoregional Program.

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), strategies to mitigate soil degradation (PE-3 to PE-5), strengthening 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 and natural resource management

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 and forage 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 (with PE-4).	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 2000

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 to 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, three 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.

Figures 1 and 2 show the conceptual frameworks for the project and the projected pathways to achieving impact. Diagnosis and identification of major soil constraints is the main focus of output 1 (Figure 1). Process-based research on various aspects of soil function and quality are concentrated in output 2. From a better understanding of fundamental processes in soils we develop strategies targeted to reversing soil degradation. These strategies and concepts are then put into practice via the development, testing and validation of decision support tools (Output 3). Data is also incorporated into biophysical and socio-economic models mainly via collaborative arrangements. Finally our products are disseminated via training and other capacity building activities such as farmer field days, workshops, conference papers, referred journals and other articles (Output 4).

Figure 1. Schematic framework for PE-2 outputs

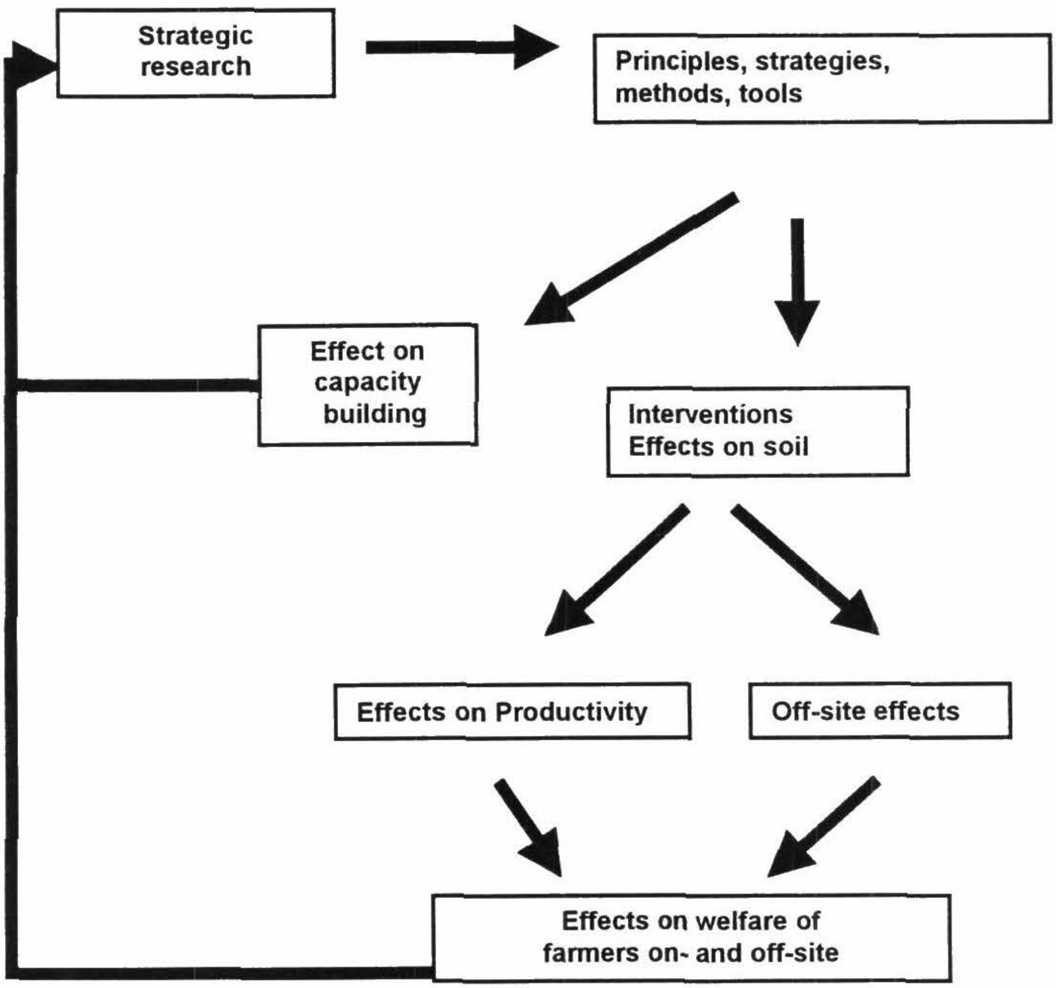


Figure 2. Pathways to impact of project PE-2

Research progress made this year for each output is summarized below.

Main highlights of research progress in 2000

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

This output represents the diagnostic phase of the research process. We gather information from scientific and local knowledge to determine the major soil, water and nutrient management constraints and from these prioritize research areas and, where necessary, conduct research to determine constraining factors.

This output contributes to our efforts to better match crops to the prevailing constraints under conditions where farmers generally cannot afford the investments for the amelioration of soil constraints (i.e. with fertilizers, lime etc.). Where agrochemicals and other inputs such as organic manures are available they are often used inappropriately and can contribute to environmental degradation. Phosphorus is frequently the limiting nutrient for plant growth and either needs to be supplied by external inputs or we can exploit the natural variation in the ability of plants to access less-available P-sources in the soil.

Highlights include:
1. We have shown that excessive applications of chicken manure (a common farmer practice) on inceptisols of Andean hillsides can result in the deterioration of the soil structure and a reduction in water holding capacity thereby hastening soil degradation and reducing productivity. Management practices to alleviate or prevent this include the use of minimum tillage, surface mulches and rotations with pastures in cassava-based systems. These results will be fed into the decision support system developed for the management of organic nutrient resources (output 3.2) in order to refine the guidelines for the management of organic resources.

2. Using new isotopic methods we have shown that the forage legume *Arachis pintoi* and the grass *Brachiaria decumbens* can access soil P pools not normally available to plants. However most (>80%) of the P taken up by the plants is from recently added fertilizer P.

Output 2 Strategies developed to protect and improve soil quality

To prevent soil degradation and loss of organic matter land users need simple, easily understandable guidelines and options that they can apply and adapt themselves to their particular circumstances. The development of such guidelines and options requires an understanding of the underlying processes of soil functions. Most of the project's process-based research is included in this output. This output focuses on the development of concepts and strategies to improve soil quality and health including options for maintaining levels of soil organic matter in different agroecosystems. The loss of soil organic matter and the functional attributes associated with it such as water holding and ion exchange capacity, nutrient supply, biological activity etc., are of particular concern in the tropics because of the rapid oxidation of organic mater and accompanying deterioration of the soil structure. As we focus on resource-poor farmers we are adopting the overall goal of the so-called "second paradigm of soil fertility". In this concept plant production is maintained by focusing on the use of adapted germplasm and a reliance on the biological activity of the soil for more efficient nutrient cycling rather than ameliorating soil constraints by inputs such as agrochemicals and heavy tillage.

This year has seen significant progress in synthesizing our process-based research activities.
1. For the llanos of Colombia critical values have been determined for a number of soil parameters (see output 3.4.2). These feed into the development of a soil quality monitoring system (Output 3.2). We have advanced the concept of the need for "an arable soil layer" which is essentially a layer free from

chemical, physical and biological constraints as applied to for the acid infertile soils of the Colombian llanos. Deep rooting plants, minimum tillage systems and the judicious use of chemical inputs form the basis of the implementation of this concept. A brochure on this is in preparation for dissemination to clients.

2. In the Andean hillsides we have shown that an improved fallow with species such as *Tithonia diversifolia* in a slash and mulch system can contribute to the rapid restoration of soil fertility that has been exhausted after years of cropping with little or no inputs. Increased biomass production, greater accumulation and recycling of plant nutrients, especially phosphorus, with introduced fallow species are the reasons for the observed increases in soil fertility and biological activity. *Tithonia* has been shown to increase the pool of plant-available phosphorus. The identification of genetic variation in nutrient contents amongst *Tithonia* accessions collected worldwide as part of an international collaborative project represents an important advance in this area.
3. In a unique study for tropical savannas we have shown that the introduction of improved pasture species with deep rooting capacities can convert the agroecosystems of the savannas from a net source of global warming potential (total greenhouse gas emissions of carbon dioxide, nitrous oxide and methane) into a net negative potential or sink. The study is the first to collect data on all greenhouse gas emissions from different land management practices (cropping and pastures) and develop an overall global warming potential based on current and projected land use.
4. The first study of the ecology and biology of soil macrofauna in the Colombian savannas has resulted in a wealth of new information, including the identification of 7 earthworm species new to science. We have determined the functional role of ecological engineering macrofauna species and suggest that a target beneficial population of earthworms should consist of one or more epigeic species, one or more anecic species that construct vertical galleries and that produce biogenic structures on the soil surface and mix plant residues with the mineral soil substrate. Management guidelines to encourage such a population include the adjacent spatial arrangements of crops and pastures and agropastoral systems. A book compiling 24 refereed research publications is currently being prepared for a CIAT publication.

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

This output attempts to collate our research findings and develop them into decision support tools and improved biophysical and socio-economic models for use by a range of stakeholders including farmers, extension workers, other researchers and policy makers. It represents one of our main pathways for interactions with stakeholders and other partners including those within CIAT. Some of the guidelines are being developed, tested and validated with the direct involvement of land users. These are being fed into the system-wide program on Soil, Water and Nutrient Management (SW-2) for global impact.

Highlights include:

1. The development of soil quality indicators for hillsides and savanna agroecosystems. Phosphorus in microbial biomass has been identified as a sensitive parameter to changes in phosphorus cycling. The research suggests that low P fertilizer doses given to grass/legume pastures may be a more efficient alternative to high single doses of P fertilizer in crop-pasture systems.
2. The compilation of soil quality indicators for hillsides and savannas and the development of a guide for use in Latin America and Africa are our first products to achieve an impact beyond the confines of the experimental sites. A training course has been held in Africa with a further course planned for 2001. The guide is being used in Colombia, Honduras and Nicaragua with the participation of over 50 institutions (with PE-3, SW-2).
3. Data from our long-term experiments has contributed to the refinement of the CERES, NuMaSS, PDSS2 and APSIM models in terms of their phosphorus sub-models. The NuMaSS model includes an

economic assessment of crop production and for the llanos suggests that upland rice is more profitable than either maize or cowpea.

4. A decision tree for use of the well-drained savannas has been developed that suggests various cropping system and land management options that are based on climate, topography, drainage characteristics and soil texture. This will feed into land planning activities undertaken by municipalities in the llanos. In cooperation with PE-4 we have also developed a simple database tool for soil diagnosis in the flatter higher land savannas of Colombia.

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

Training and capacity building activities are reported mainly in Output 4 although much of our research reported in Outputs 1-3 is conducted via students and post-doctoral training.

Highlights include:

- 13 field days organized, one training course held in Africa on soil quality indicators.
- 33 students are associated with the project.
- Active collaboration is maintained with 50 partner institutions ranging from NARS, NGO's, Universities and other IARC's.
- The project has 8 special projects.
- 39 refereed papers have been published or are in press, 70% of which are co-authored with other institutional partners.

This year has seen a significant progress in achieving several milestones of the four project outputs.

Progress towards achieving output milestones of the project logframe

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***

A summary of the major constraints in different ecosystems was reported last year. Soil crusting and structural degradation has been shown to be a problem in hillside inceptisols especially when excessive amounts of chicken manure are applied.

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

Data from these is currently the subject of student theses and will be reported next year.

- ***Plant components identified for greater nutrient acquisition and use efficiency***

Last year, we reported the progress made towards the identification of plant components for greater nutrient acquisition and use efficiency for savannas, hillsides and forest margins agroecosystems. This year, using isotopic exchange kinetic method, we found that the forage legume *Arachis pintoi* and the grass *Brachiaria decumbens* can access soil P pools not normally available to plants. However most

(>80%) of the P taken up by the plants is from recently added fertilizer P. Further work is in progress to assess the usefulness of ^{33}P labelling technique to trace the fate of applied P in soil.

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***

Short-term planted fallows can restore soil fertility in soils with limited nitrogen (N) and/or phosphorus (P) by enhancing nutrient recycling through the provision of soil organic matter (SOM). Studies on the impact of improved fallows on soil fertility indicated that *Tithonia diversifolia* has the greatest potential to improve SOM, nutrient availability, and P cycling because of its ability to accumulate high amounts of nutrients. We found that the fractionation of SOM and soil P could be more effective for detecting the impact of planted fallows on improving soil fertility than the conventional soil nalysis methods.

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

The new phase of the Culticore experiment in Carimagua started in 2000 and results have not yet been analyzed. Difficulties in obtaining safe access to the site and withdrawal of staff for security reasons has affected this work.

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

This work has been completed with the Ph. D. thesis of Marco Rondon. Publications are in preparation.

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

This milestone has been achieved through 3 Ph.D. studies. Some 24 publications have been published and are being compiled into a CIAT publication for 2001.

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.***

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.

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

A decision support tool 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 activity was completed in 2000 with a publication in the journal of Advances in Environmental Monitoring and Modelling by a student K. Pallaris.

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

The decision tool prepared by a collaborating institute (TSBF in Africa) has been tested this year and is reported in detail in project SW-2.

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

A brochure on the 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.

- ***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 using 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***

Two Ph.D. theses were successfully defended in Ohio State University and Cornell University respectively. One PhD. student will defend his thesis in the Agricultural University of Norway at the end of this year. Six undergraduate theses were completed.

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

This was completed in 1999.

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

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

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

One project was approved for funding by BMZ and will begin in 2001 and projects submitted to DFID and Colciencias were rejected.

- ***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***

13 field days were held and one training workshop on soil quality indicators. Restrictions on staff and lack of personnel for training has hindered the achievements of this milestone.

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 climate constraints

1.1.1 Characterize the phenomenon of soil crusting and sealing in the Andean Hillsides of Colombia

Highlight:

- Showed that excessive application of chicken manure as a fertilizer can result in the structural deterioration of inceptisols of the Andean hillsides.
- Cassava cultivation with minimum tillage maintains soil structure and reduces risk of soil degradation.

Purpose:
To characterize the phenomenon of crusting and soil surface sealing on Andean Inceptisols.

Rationale:
Soil erosion is a major global problem. Apart from climatic impacts, major reasons are inappropriate land-use and improper fertilizer management as well as socio-economic constrains. In order to acquire a basic knowledge of soil degradation, efforts have been made to focus on structural changes at the soil surface. Recent observations indicate that one of the manifestation of physical and chemical degradation of soils in the Andean zone is related to the phenomenon of soil crusting and sealing.

Soil crusts are thin layers of hardened soil on the surface occurring on dry soils. The term "soil sealing" is used to describe superficial impermeabilities mainly in wet circumstances. Soil sealing occurs if dissolved aggregates infiltrate into the soil pores leading to compact soil horizons thus reducing infiltration. Both phenomena have a negative impact on water infiltration, reduce air permeability and seed germination. Due to the reduction of water infiltration, the surface run-off increases and in consequence enhances soil erosion.

The processes causing soil crusting in Andean soils of volcanic origin are basically unclear. Therefore the overall aim of this work, supported by special project funds from the DAAD/Germany, the Eiselen Foundation/Germany and the University of Hohenheim/Germany, is to characterize the phenomenon of soil crusting on Andean Inceptisols.

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

Treatments
The treatments since December 1999 are described in Table 1.

Table 1. Treatments of 27 Experimental Plots in Santander de Quilichao from 1999-2000.

Treatment	Plots			Cultivation in 1999-2000
(1) Bare fallow	25	26	27	Raking at the beginning
(2) Cassava intensive tillage	28	29	30	Intensive Rototiller, mineral fertilizer
(3) Cassava monoculture	3	11	24	Rototiller, no fertilizer
(4) Cassava minimum tillage	4	17	22	No tillage, mineral fertilizer, Mulch
(5) Cassava + 8t/ha chicken manure	5	9	21	Rototiller, 8t/ha chicken manure
(6) Cassava+ 4t/ha chicken manure (Vetiver)	6	10	16	Rototiller, 4t/ha chicken manure
(6a.) Cassava + 4t/ha chicken manure (trad.)	2	13	19	Rototiller, 4 t/ha chicken manure
(7) Cassava + *Chamaecrista rotundifolia*	7	12	20	Rototiller, mineral fertilizer, *Chamaecrista. Rotundifolia.*
(8) Cassava rotation (*Brachiaria decumbens* .+ *Centrosema macrocarpum* in 2000)	8	14	18	Rototiller, mineral fertilizer

Table 2. The history of treatments in Santander de Quilichao .

	93/94	94/95	95/96	96/97	97/98	98/99	99/00	00/01
1	SB[1]	SB	SB	SB	SB	SB	SB	SB
2	BF	BF	BF	BF	SB	SB	C mF	C mF
3	C	C	C	C	Co	C	C	C
4	BF[4]	C mF	Ma[5] mF	C mF	Co mF	C mF	C mF	C mF
5	Br[9] P[10]	C mF	Ma mF	C mF	Co mF	Ma oF8[8]	C oF8	C oF8
6	Co[6] mF	C oF4[7]	Ma oF4	C oF4	Co oF4	Ma oF4	C oF4	C oF4
6a	Co mF(V)[14]	C oF4(V)	Ma oF4(V)	C oF4(V)	Co oF4(V)	Ma oF4(V)	C oF4(V)	C oF4(V)
7	C Ca[11]	C Ca	Ma Ch[12]	C Co	Co mF	Ma Ch	C Ch	C Ch
8	Br P	Br P	Ma mF	Br Cm[13]	Br Cm	Ma Cm	C mF	Br Cm

[1]SB=Bare fallow
[2]C=Cassava
[3]mF=min. Fert .
[4]BF=Bush fallow
[5]Ma=Maize

[6]Co=Cowpea
[7]oF4=org Fert. (Chicken man. 4 t ha^{-1})
[8]oF8=org.Fert. (Chicken man. 8 t ha^{-1})
[9]Br=*Brachiaria decumbens*
[10]P=*Pueraria phaseoloides*

[11]Ca=*Centrosema acutifolium*
[11]Ca=*Centrosema acutifolium*
[12]Ch=*Chamaecrista rotundifolia*
[13]Cm=*Centrosema macrocarpum*
[14] (V) =Vetiver

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

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

(a) After planting of Cassava in December 1999 field measurements with a Pocket Penetrometer (Model DIK-5560) were carried out. By using penetrometers, soil crusting and surface sealing can be directly measured in field conditions.
(b) Besides pentrometer measurement, a Hand Vane Tester (Model EL26-3345) was used to measure shear strength at the soil surface. Both tools were used weekly, the Penetrometer 24 times and the Torvane 6 times per plot.
(c) To describe direct effects of soil crusting and sealing on infiltration, a mini-rainfall simulator was used in the field. Infiltration was measured by irrigating a defined soil area (32,5cm x 40cm) with a amount of rain (90mm/h). The construction of this mini rainfall simulator enabled the collection of run-off periodically (every 5 min). The difference between irrigated rain and run-off is defined as infiltration. The first measurement was taken in the wet season in April/May 2000. A second measurement will take place in October/November 2000.

Besides field measurements, soil samples were taken at 2 months and 7 months after planting. The analysis was focused on:

(d) aggregate size distribution,
(e) and aggregate stability,
(f) Besides these physical aspects of the soil, soil crust formation was investigated in the laboratory. Soil samples were placed into special moulds, moistened and then dried at 50°C. This preparation of the samples was supposed to simulate natural conditions of the field. After drying, soil samples were photographed and analyzed.

Results and Discussion:
Penetrometer and Torvane: Results of Penetrometer and Torvane measurement are presented in Figures 1 and 2. During the wet season, penetration resistance was nearly the same in all treatments. At the beginning of dry season in May/June, differences between treatments were noted. Especially the Cassava + 8 t/ha chicken manure, the Bare fallow and the Cassava minimum tillage treatments changed into hard soils. The largest peaks in soil hardening were observed in cassava minimum tillage treatment. This high penetration resistance is due to the lack of tillage since 1991. Over time the minimum tillage plot turned to be generally harder than other plots but its well developed and stable aggregate structure prevented negative impact on water infiltration (see below). The Cassava + 8 t/ha chicken manure treatment formed large clods that were extremely hard. It is assumed that this high amount of chicken manure causes a dispersion of clays in the wet season and results in uniform clods after drying. Further research to locate dispersible agents in Chicken manure is needed to ascertain this hypothesis. It was noticed, that the Cassava monoculture and Cassava intensive tillage tend to be extremely soft thus building up a single-grain structure also called pseudo sand.

Torvane measurement data tend to be similar to penetrometer measurement. Figure 2 indicates the increase in shear strength in the dry season especially within treatments of Cassava + 8 t/ha chicken manure, Cassava minimum tillage, and Bare fallow. In general all treatments except the Cassava intensive tillage treatment had a high shear strength from June-July and turned from 13 – 22 kg/cm^2 in the wet season up to 43 – 76 kg/cm^2 in the dry season.

Infiltration: In this study a rain intensity of 90 mm/h (88 to 92mm/h) was used to measure infiltration. Results are presented in Figure 3. The conclusion that high penetration resistance and high sheer strength leads to a decrease in infiltration could be drawn out of infiltration measurement. Cassava + 8t/ha Chicken manure and Bare fallow had the lowest infiltration after 55 minutes. It has to be emphasized that Cassava min. tillage had an excellent infiltration capacity as well as the Cassava rotation treatment. Minimum tillage influences the soil structure positively in the way that aggregation over a long time period is supported. This helps to build up a soil structure, as also the mulch at the surface leads to a better infiltration.

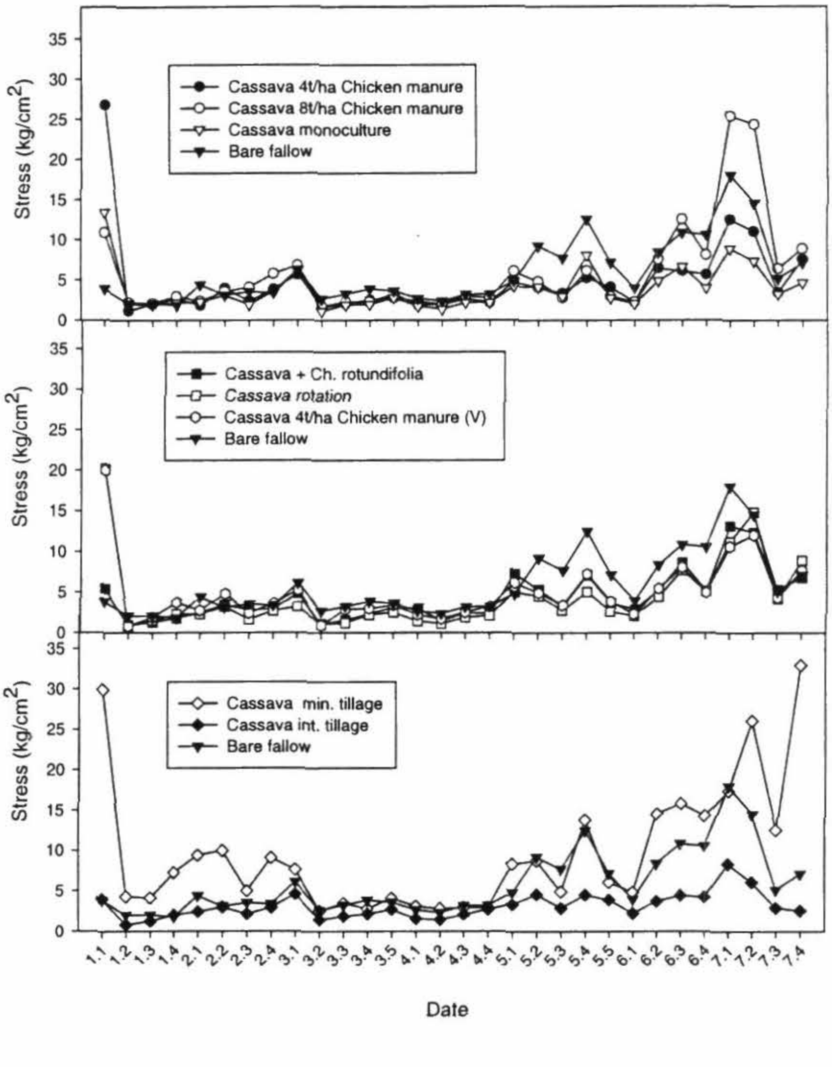


Figure 1. Influence of soil and crop management treatments on penetration, time period: Jan-August 2000. Location: Santander de Quilichao.

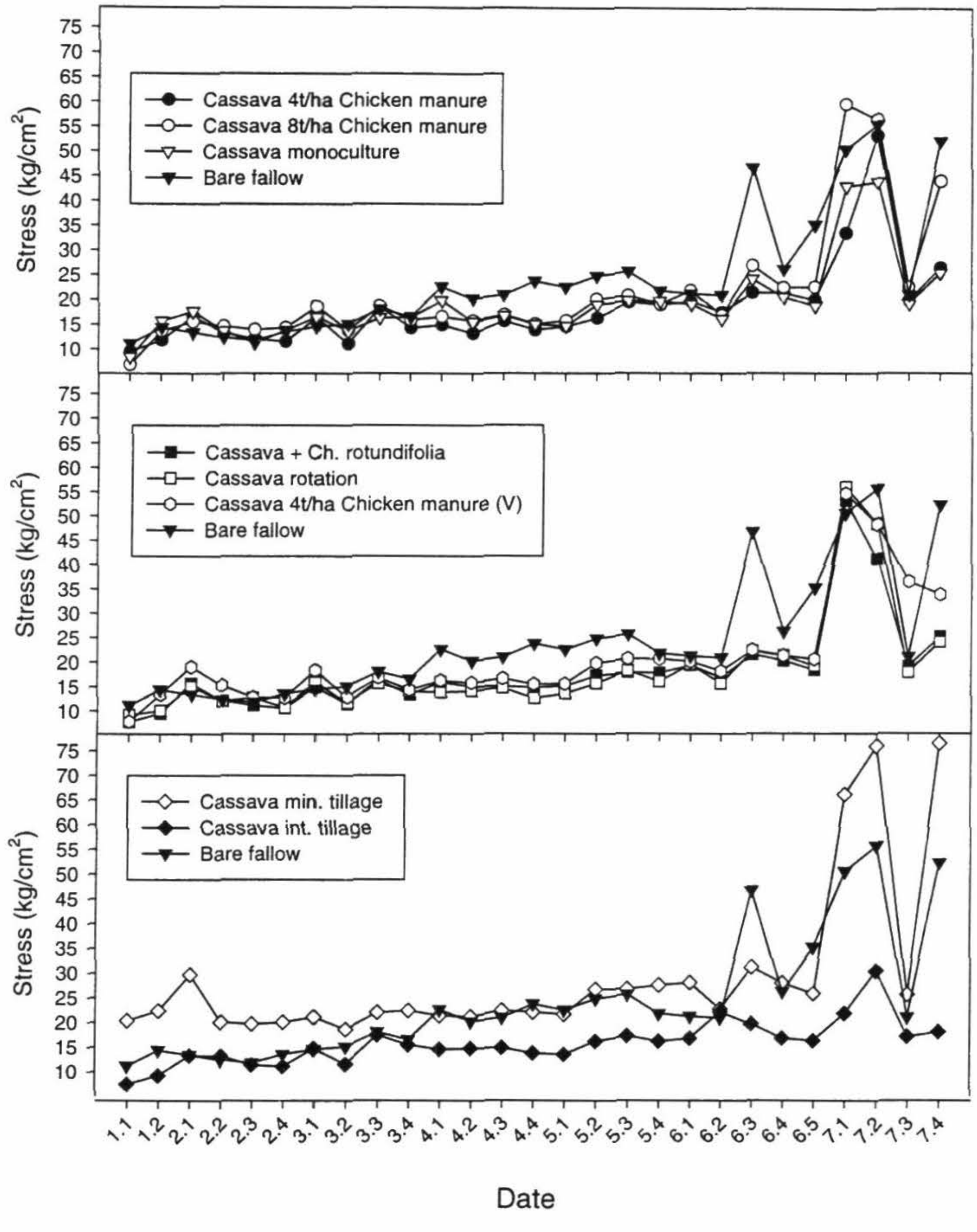


Figure 2. Influence of soil and crop management treatments on shear strength measured by a hand vane tester, time period: Jan-August 2000, Santander de Quilichao.

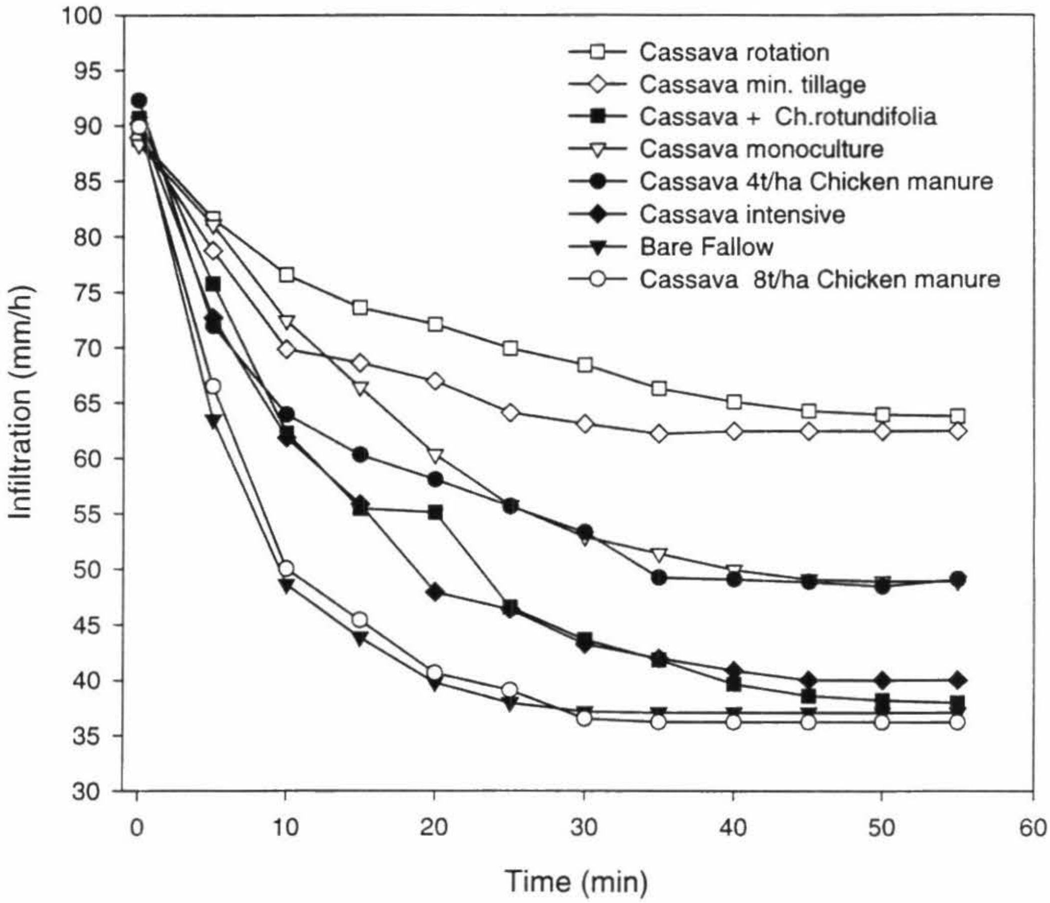


Figure 3. Effect of treatment on infiltration measured by rainsimulation March 2000. Location: Santander de Quilichao.

In general, there is the following gradient from good treatments with high draining characteristics to those with low draining characteristics:

Min. till > Rotation > Monoculture > C. man. (4t/ha) > Int. till > Cass.+Ch.rot. > Bare fallow > C. man. (8t/ha)

Soil physical properties: Results of aggregate distribution are presented in Figures 4 and 5. With regard to aggregate distribution, Bare fallow treatment in February had a significantly lower proportion of aggregates >2mm and a higher proportion of smaller aggregates. As can be seen in Figure 4, Cassava min.tillage, Cassava + 4 t/ha Chicken manure and Cassava + 8 t/ha Chicken manure had a high proportion of big aggregates and a low proportion of smaller aggregates. Cassava monoculture tends to be in the middle. In August Cassava monoculture changed completely. This treatment had, just like Bare fallow, a low proportion of big aggregates and a high proportion of smaller aggregates. Results from laboratory measurement are similar to observations in field. The Chicken manure plots and Cassava min. tillage formed big clods and were hardly destructible whereas Bare fallow, Cassava monoculture and Cassava int. tillage had a single grain structure at the soil surface.

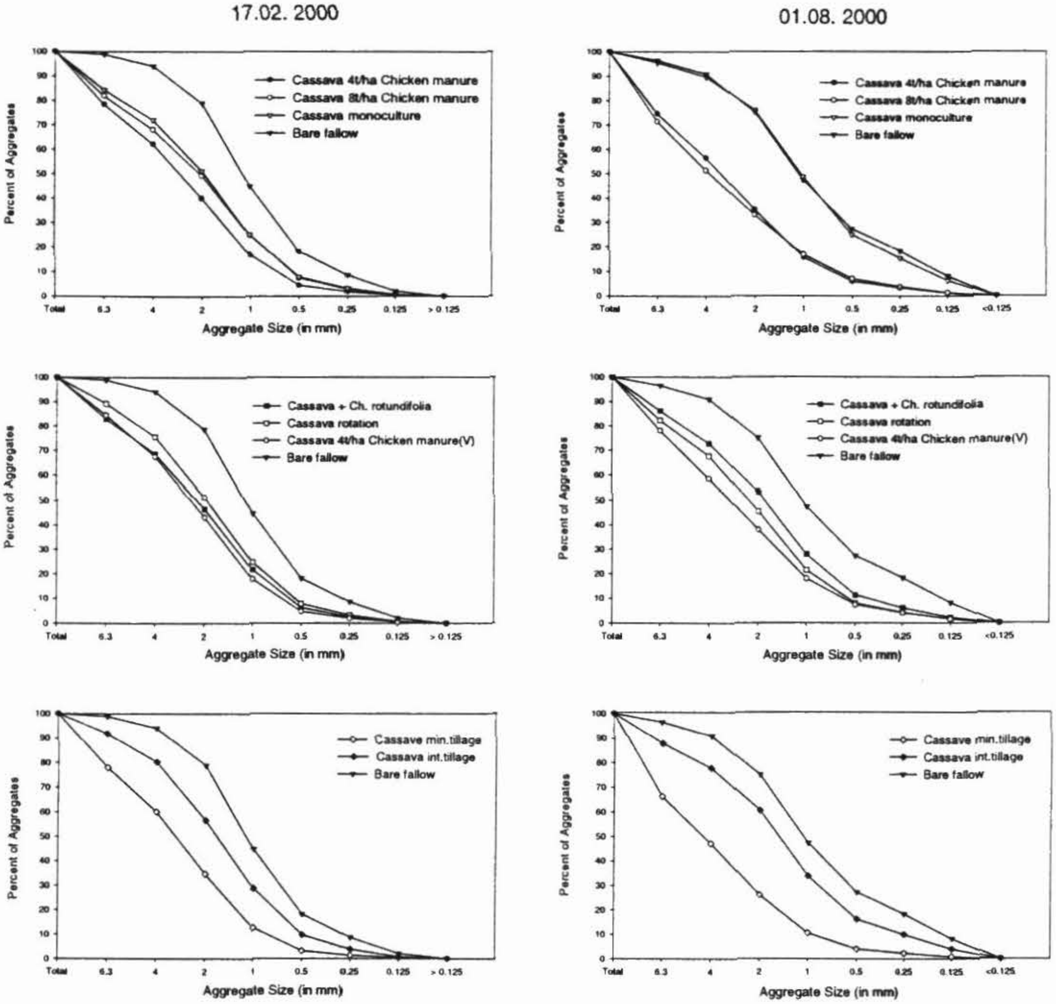


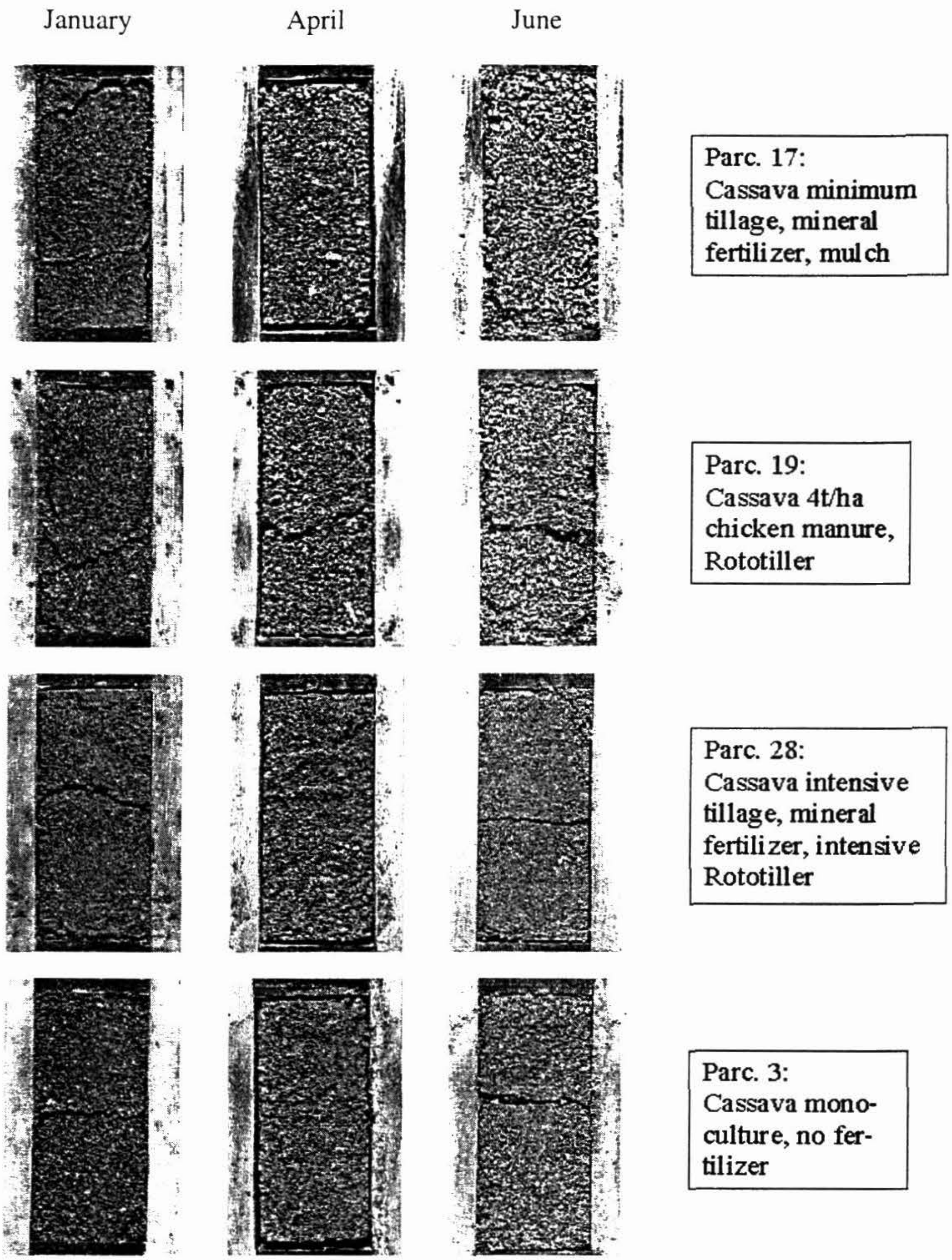
Figure 4. Aggregate distribution, 2 and 9 month after planting as affected by treatment. Location : Santander de Quilichao.

Aggregate stability in February was nearly the same in all treatments. The highest proportion of aggregates > 2mm were observed with Cassava min. tillage followed by Cassava int.tillage. Cassava monoculture and Bare fallow had the lowest aggregate stability in this range. Between 2 and 1mm Bare fallow had the highest proportion of stable aggregates. In August, the situation changed. Now Cassava monoculture had the highest amount of stable aggregates >2mm. Between 2 and 1mm Cassava min.tillage, Cassava int. tillage and Cassava + 4 t/ha Chicken manure had the highest proportion of stable aggregates. It has to be emphasized that the stability of aggregates in Bare fallow and Cassava monoculture decreased in aggregates <1mm. Within these treatments only a few big and stable aggregates could be located. The proportion of smaller aggregates was lower than in the above mentioned treatments.

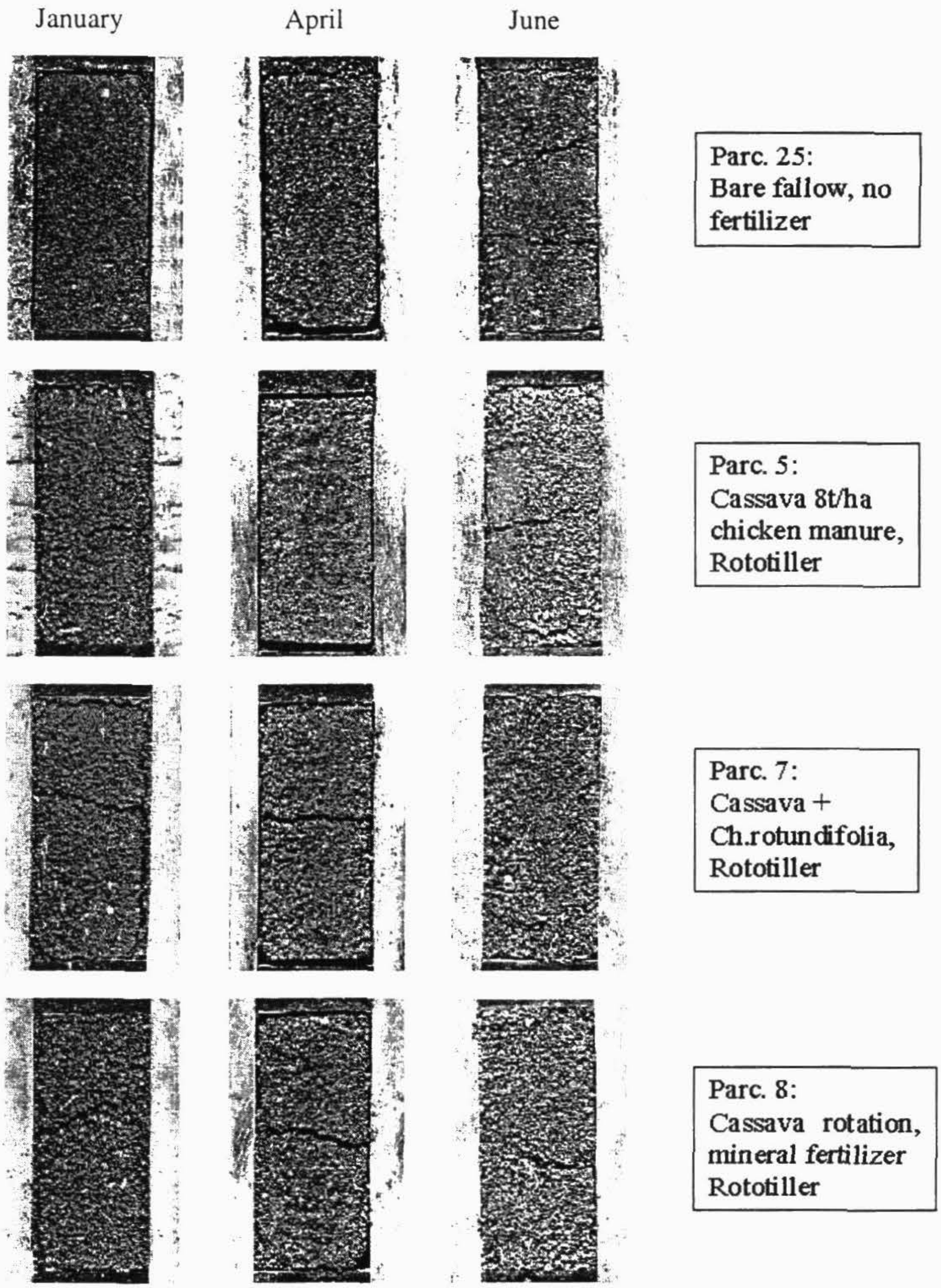
Several researchers found that aggregate stability could be a protecting agent against soil erosion. As a matter of fact, stable aggregates can be seen as a "self-protection" of the soil against climatic influences such as raindrops. Soils with a high proportion of big and stable aggregates (e.g. Cassava min.tillage, Cassava Chicken manure) at the surface suffer less from raindrop impact and in consequence show less detachment of silt and clay. Soil treatments with only a few water stable aggregates and a high proportion of unstable material (e.g. Bare fallow, Cassava monoculture) are highly vulnerable to erosion.

Crust formation: Results from Modulus of rupture procedure are presented in Picture 1. Soil samples were taken at two, five and eight months after planting. Changes in different treatments concerning: 1.) surface aggregates, 2.) cracking, and 3.) differences of specimen sampled in dry or wet phase can be observed.

- Cassava min.tillage only showed cracking in January. In April soil turned in a uniform but aggregated block, in July this tendency continues
- Cassava + 4 t/ha chicken manure showed cracking in all three samples, superficial aggregates were generally big except the wet phase in January.
- Severe aggregate breakdown in January and July could be observed in Cassava int.tillage. Cracking occurred in all time periods.
- Cassava monoculture had small superficial aggregates showing cracking in both dry phases January and July. Stability was quite low in this treatment. Similar to Cassava monoculture and Cassava int.tillage, Bare fallow had severe aggregate breakdown. Especially in the dry season, Bare fallow's formed uniform blocks easily build up cracks.
- Cassava + 8 t/ha chicken manure had cracks in January and July but not in April. In April, aggregate breakdown leading to smaller aggregates at the soil surface could be observed.
- Cassava + *Ch.rotundifolia* showed cracking in all three phases. Aggregates were in equilibrium.
- Cassava rotation had a good aggregation but cracks did also occur in this treatment.



Picture 1a. Crust formation in January, April, and June 2000 influenced by treatment.



Picture 1b. Crust formation in January, April, and June 2000 influenced by treatment

In summary, penetration resistance and shear strength showed no risk of structural damage in the wet season. This worsened in the dry season when Chicken manure treatment and Bare fallow turned into hard and impermeable soils. Although the minimum tillage treatment had high penetration resistance and high shear strength values, this caused no deterioration because of good aggregation status. This can clearly be seen in the infiltration measurement. Monoculture and intensive tillage had neither high penetration resistance nor high sheer strength. In contrast these treatments easily built up the so-called pseudo-sand that lead to high proportions of small aggregates, and thus to high amounts of soil erosion. As state of the art, Minimum tillage and Cassava rotation had the best and most sustainable status. Those treatments had a good aggregation status, showed adequate infiltration rates and did not suffer from human induced fertilizer damage e.g. soil hardening due to chicken manure or deterioration of soil matrix through intensive tillage. Chicken manure, especially 8 t/ha, had a severe impact on soil surface. Further research is needed to specify the reasons why chicken manure has such an influence on aggregates. It is unclear what might be the dispersion agent that leads to aggregate dispersion. Furthermore, structural changes through int.tillage or min.tillage have to be looked at more closely in order to get an idea of how severe aggregate breakdown affects plant growth on Inceptisols.

Impact:
Results from penetration and shear strength measurement showed a viable influence of chicken manure on soil structure. Chicken manure in general resulted in a deterioration of soil structural status. A reduction of infiltration especially in chicken manure plots substantiate the hypothesis that inappropriate fertilizer management is one of the key factors of structural deterioration on inceptisols. Dispersion of clays, often described as the main reason for soil sealing is influenced by the impact of chicken manure. Further research will be necessary focusing on the impact of fertilizers on the soil surface in order to design sustainable systems for Andean hillside farming.

Contributors:
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1.1.2 Characterize the impact of cropping systems on soil water status of soils of the Andean Hillsides of Colombia

Highlight:
- Showed that the type and quality of fertilizers applied to soil influence the water status of inceptisols of the Andean hillsides.

Purpose:
To determine the impact of cropping systems that increase plant productivity, minimize structural deterioration and reduce adverse effects on soil water status.

Rationale:
Plant growth depends on water supply. Especially in areas with seasonal shortage of water, plant growth and seedling emergence are limited. Throughout the tropics, there are regions of high amounts of rain, the amount of water that can be stored depends on treatment characteristics. Besides water requirements, nutrient availability for plant growth is highly dependent on water status.

Soil water studies have long been conducted using water content measurements either gravimetric or volumetric. If more information about water transport and water storage in soils is needed the energy status of soil water should be measured. Tensiometers used in this study measure this energy status in terms of water tension.

Related to the investigation of soil crusting and sealing in Santander de Quilichao, this additional study has been carried out focusing on the link between land management practices and soil water regime. The aim of this study is to find cropping systems that increase plant productivity, minimize structural deterioration and reduce adverse effects on soil water status. Initial results of ongoing research are presented in this article. The DAAD/Germany, the Eiselen Foundation/Germany and the University of Hohenheim/Germany have funded the study.

Materials and Methods:

The study was carried out at the Santander de Quilichao Research Station in the Dep. Cauca of Colombia (3°6'N, 76° 31' W). The research site has a bimodal rain distribution with two maximas in April and November, with a mean annual rainfall of 1799 mm/a, mean annual temperature of 23.8°C. Samples are taken from plots treated such as presented in Table 30.

Table 3. Treatment of Test Plots in Santander de Quilichao from 1999-2000

Treatment	Plots		Cultivation in 1999-2000
Cassava intensive	28	29	Rototiller, mineral fertilizer
Cassava monoculture	3	24	Rototiller intensive, no fertilizer
Cassava minimum tillage	17	22	Minimum tillage, mulch, mineral fertilizer
Cassava + 8 t/ha chicken manure	5	21	Rototiller, 8 t/ha chicken manure
Cassava + 4 t/ha chicken manure (trad.)	2	19	Rototiller, 4 t/ha chicken manure

To measure field water conditions a set of different instruments has been installed. Using a TDR-Probe, (Moisture Point, Model MP-917) continuous measurements of soil water content have been made twice a week. This TDR-probe is designed to measure in five consecutive layers (1. layer 0-15 cm, 2. layer 15-30 cm, 3. layer 30-60 cm, 4. layer 60-90 cm and 5. layer 90-120 cm). In the above mentioned study only the range from 0 to 60 cm has been sampled.

Water tension has been measured by using two different types of tensiometer. First, a Microtensiometer (Fa. UIT, Dresden) measuring in the upper soil layer of 2-6 cm was used. Microtensiometers were used to focus on soil water changes only in the soil crusting/soil-sealing horizon. Secondly, bigger Field Tensiometers were locally installed to take data periodically on the side. The main point of interest was to find out the development of soil water tension in certain time periods focusing on diurnal changes. Furthermore, a battery charged datalogger hourly measured and logged data. Viable differences in tension due to plant suction made it important to measure leaf area. This measurement was made with a LICOR LAI 2000 Fisheye sensor after tensiometer measurement.

Results and Discussion:

Results from TDR measurement are presented in Figure 5. In the first layer the highest amounts of water were found in Cassava monoculture treatment. The Cassava min.tillage exceeds monoculture treatment only when high rain events have occurred. The chicken manure plots showed data in the middle range and Cassava int.tillage had the lowest water content. Over the time of the study a noticeable rise of water content in all treatments due to the wet season can be seen. In the second layer Cassava monoculture showed the highest proportion of water similar to layer 1. Cassava min.tillage exceeded the monoculture treatment only in high rain events. In general, the differences between treatments were smaller. A change can be noticed in the third layer where Cassava min.tillage had the highest water content followed by 8 t/ha

Chicken manure, Cassava monoculture, 4 t/ha Chicken manure and Cassava int.tillage.

It is remarkable that Cassava monoculture showed comparably high amounts of water. Although plant development in monoculture treatment was very small as can be seen in Picture 2, it had the highest water content. This can be explained by lower amounts of transpiration through plants compared to Cassava min.tillage treatment. Another interesting fact is that water content in Cassava int.tillage was generally low. The intensive tillage treatment has led to an aggregate breakdown and therefore to a reduced capillarity of the soil that finally had adverse effects on water regime.

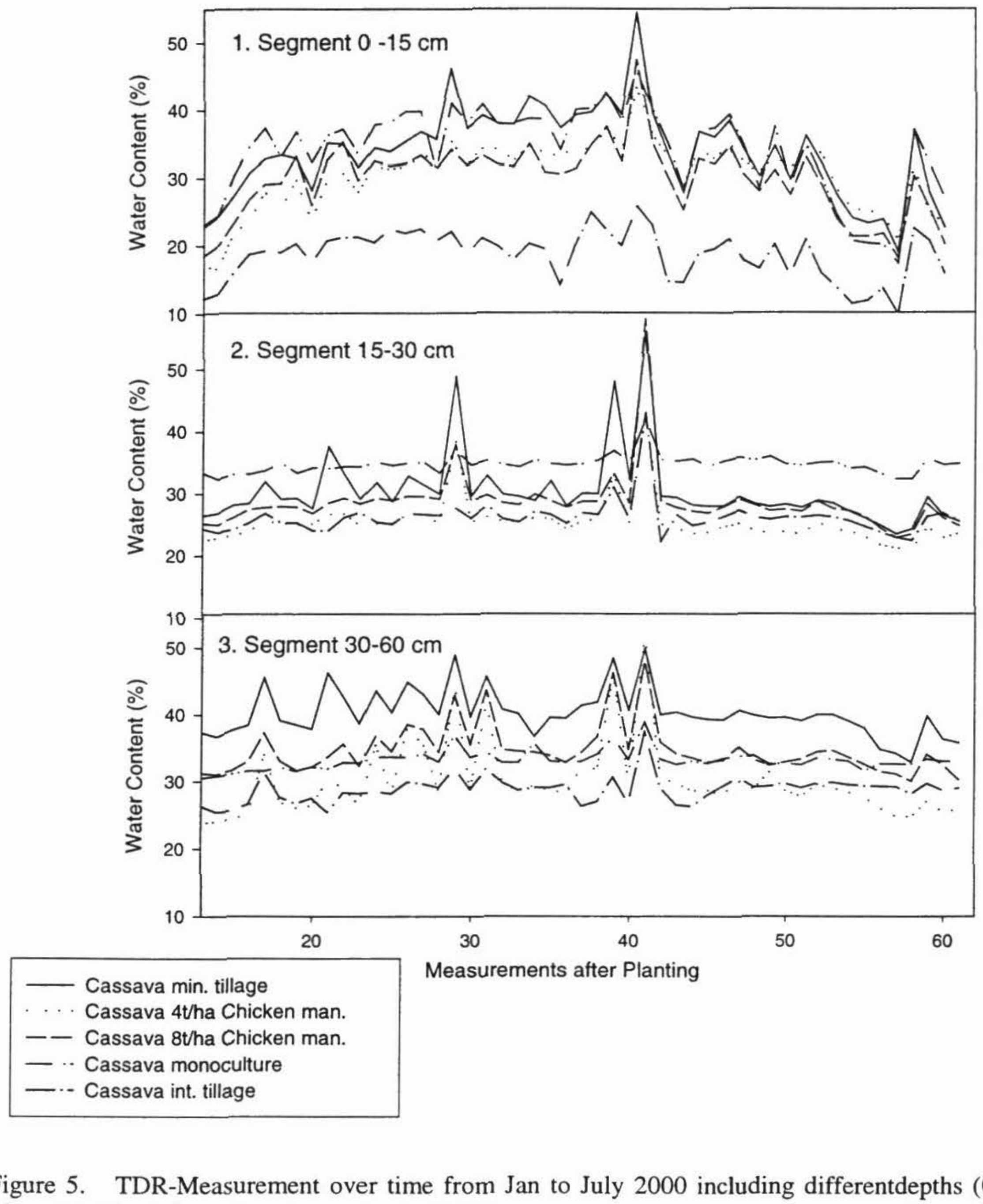
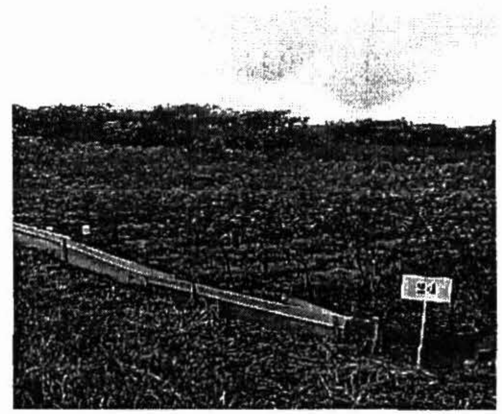
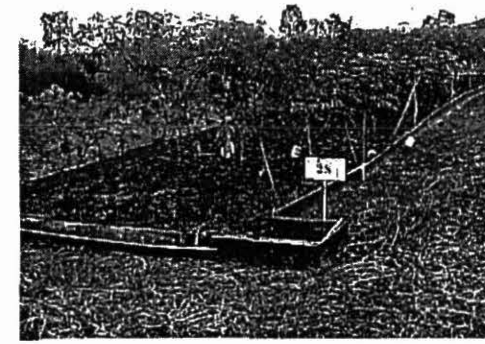


Figure 5. TDR-Measurement over time from Jan to July 2000 including differentdepths (0-15cm, 15-13cm, 30-60cm), Location: Santander de Quilichao.

Cassava minimum tillage
Rototiller, 300 kg/ha mineral fertilizer



Cassava monoculture
Rototiller, no fertilizer

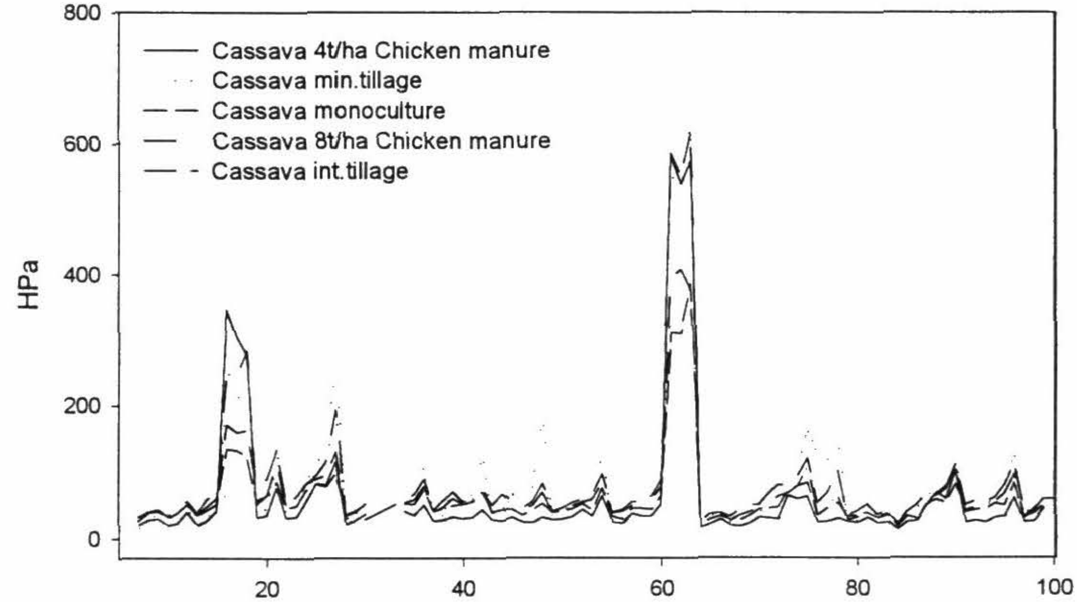


Cassava intensive tillage
Rototiller intensive,
300 kg/ha mineral fertilizer

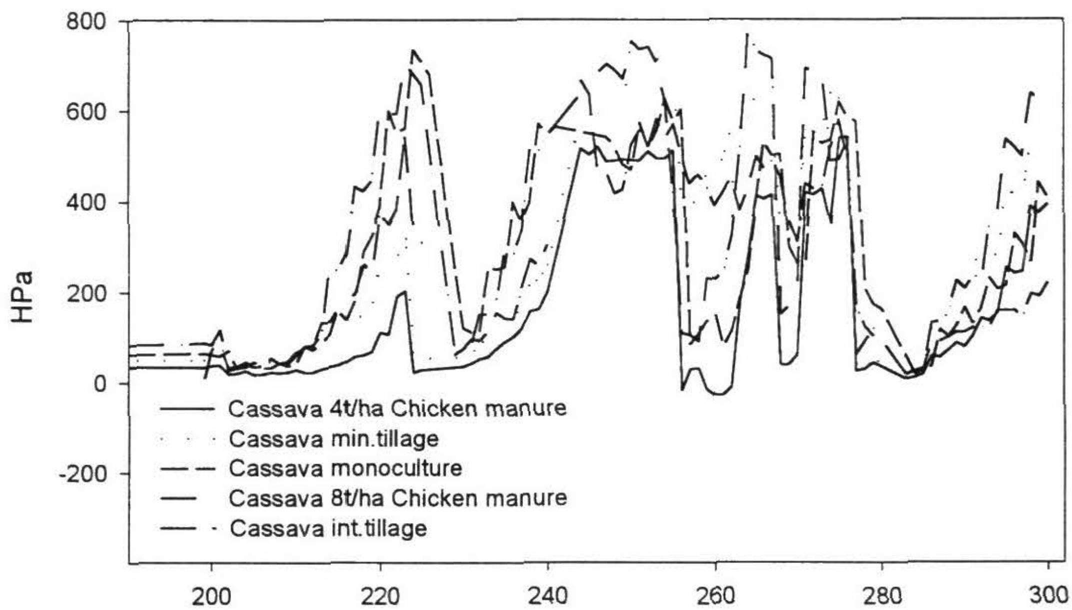
Cassava 4t/ha Chicken manure
Rototiller, Chicken manure

Cassava 8t/ha Chicken manure
Rototiller, Chicken manure

Picture 2: Treatments of experimental plots in Santander de Quilichao, Colombia, June 2000.



6a: Measurements in wet season



6b: Measurements in dry season

Figure 6. Changes in tension in a wet and dry season influenced by treatment.

Figure 6 shows Microtensiometer measurements in wet and dry season. In the wet season two periods of very little rainfall occurred as can be seen in Figure 6a. This led to an overall rise of tension. Here chicken manure exceeded all other treatments despite having shown the lowest tension when the soil surface was wet (see measurement no 14-19 and 60-65).

In the dry season, tension was generally higher than in wet season. Rain events, however, led to a fall of tension as can be seen in Figure 6b (compare measurement no 230-240, 255-266, 267-273 and 278-285). When soil surface was dry 8 t/ha chicken manure exceeded all others. An exception took place when monoculture showed the highest tension, as can be seen in measurement no. 225. Overall, the plots treated with 4 t/ha chicken manure showed the lowest tension. Data was varying more throughout all treatments in dry season than in wet season.

The soil was the wettest at a depth of 70 cm, thus tension was the lowest, due to more clay. At a depth of 30 cm, the mulching effect was lower than expected. Here plant suction has a reducing effect on water content.

Hourly data collected from Field Tensiometer at various depths are presented in Figures 6-10. Figure 7 shows tension data of a Cassava min.tillage plot. Here ongoing drying of the soil due to dry season led to a rise of tension. Highest tension occurred at a depth of 110 cm. This can be understood as a consequence of lower clay contents in this layer.

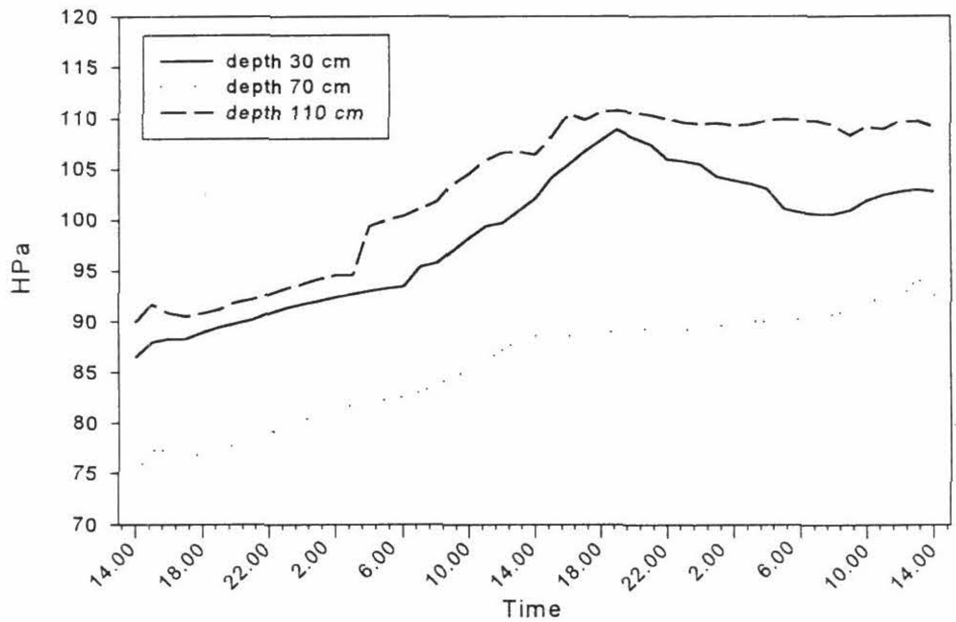


Figure 7. Tension from 16th to 18th of February 2000, Treatment: Minimum tillage.

Results of a comparison of two treatments are presented in Figure 8. The two upper curves represent Cassava monoculture treatment, the lower Cassava min.tillage. Monoculture treatment had higher tension (lower water content) in 30 cm and lower tension in 70 cm. Minimum tillage treatment showed the contrary. The reason why this phenomenon occurs is unclear. Reasons could be the higher mulch content in min.tillage, the higher plant biomass, thus less solar drying (see picture 2), soil texture reasons. Further research is needed to gain more basic knowledge.

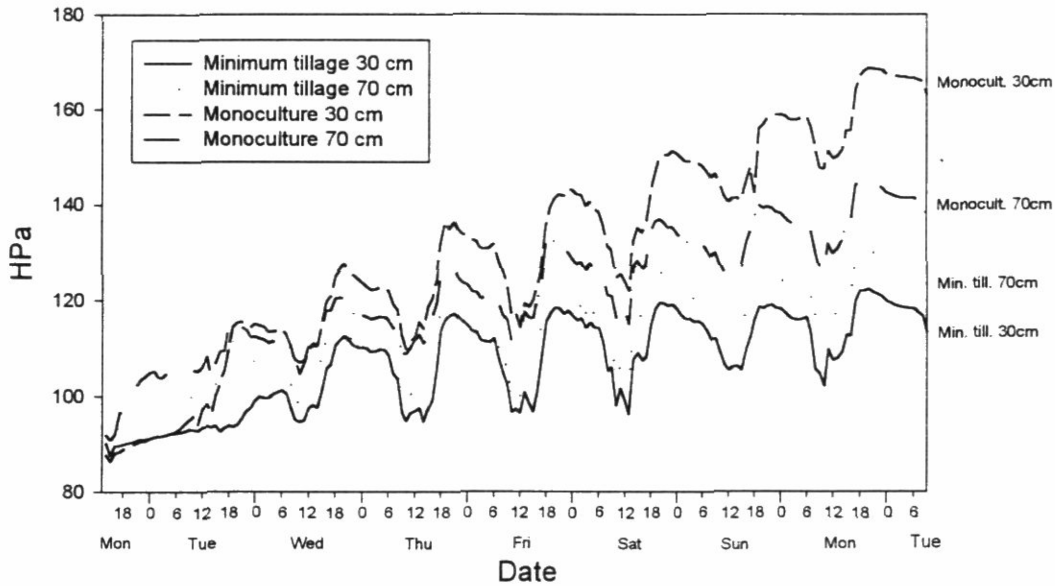


Figure 8. Tension from 22[nd] to 30[th] of May 2000 affected by different treatments and depths.

Leaf area index (LAI) measurement, as presented in Table 4 shows the fact of higher biomass effects in minimum tillage. Plant canopy was significantly higher in Cassava min.tillage. Higher values of tension in 70 cm of the Cassava min.tillage treatment therefore can be explained by plant consumption especially in this soil compartment.

Table 4. Leaf area index measured by LICOR LAI-2000 Fisheye-Sensor.

Treatment	Leaf Area Index (m^2 / m^2)
Cassava monoculture	0.27 a
Cassava 4t/ha chicken manure	0.59ab
Cassava 8t/ha chicken manure	0.56ab
Cassava 4t/ha chicken manure (Vetiver)	0.50ab
Cassava + Ch.rotundifolia	0.48ab
Cassava intensive tillage	0.40ab
Cassava rotation	0.67ab
Cassava minimum tillage	0.84 b

Means followed by different letters within the column are significant at 0.05 probability level.

Figure 9 shows a combined measurement of tension and rainfall data in a Cassava monoculture treatment. As a consequence of heavy rainfalls, tension fell immediately in all depths (15-45 cm). Three days later, the upper layer showed a bigger loss of water content than the deeper layers.

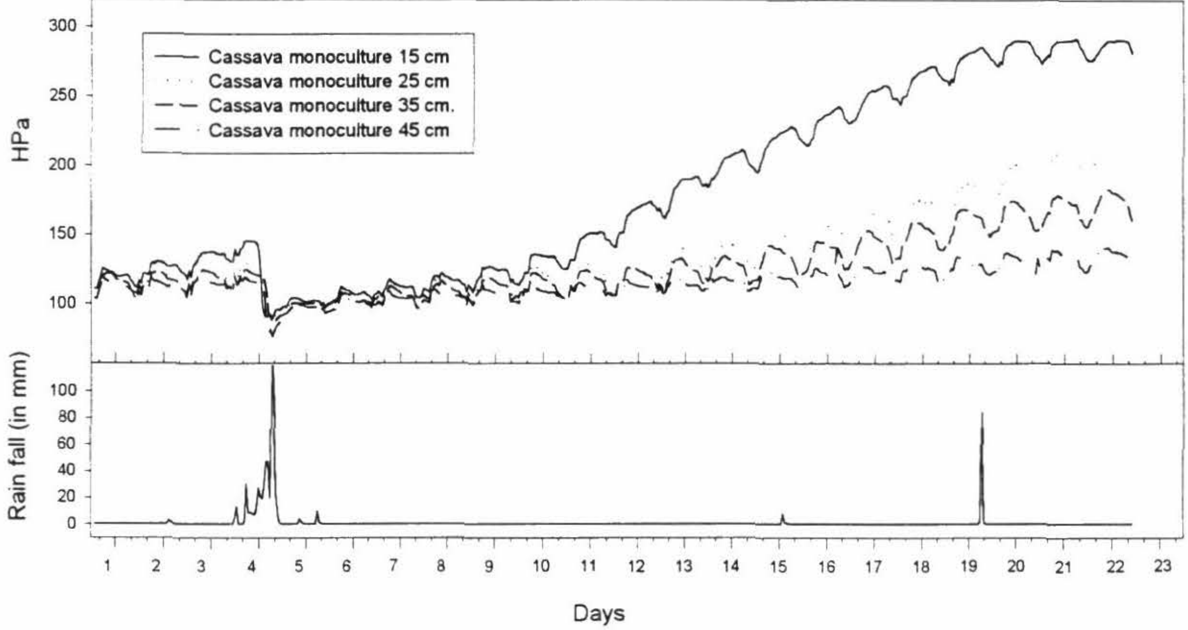


Figure 9. Tension from Tue 20th of June to Wed 12th of July as affected by drying and rainfall.

Results from Figure 10 show a combined measurement of Tensiometers in different depths, and two types of TDR-probes in a Cassava monoculture treatment. As can be seen in Figure 10, the highest tension was found in the uppermost layer (0-15cm), with higher water content the deeper the data was taken. Within those seven days, soil was drying continuously thus rising tension in the upper layers due to reasons as mentioned above. In deeper layers water content was not changed. These results were supported by TDR-probes data especially at 0-20 cm and 0-15 cm depths. Here was a continuous decrease in water content over this time period. Tension in 25cm, 35cm and 45cm were only slightly increasing over the time, thus soil was drying slowly.

Results of a comparison of treatments are presented in Figure 11. Three treatments and two different depths (15 and 30 cm) were plotted. In the first layer, Cassava 8 t/ha chicken manure showed the highest tensions and responded rapidly to rainfall events. Cassava rotation treatment (Cassava, rototiller and mineral fertilizer) had a slightly lower tension and Cassava intensive tillage had the lowest tension. More obvious were differences in water tension at a depth of 30 cm. During the drying phase, Cassava + 8 t/ha chicken manure built up a viable difference compared to other treatments. Results shown in Figure 11 are similar to observations in the field. Soils treated with chicken manure dried very quickly and built up heavy and dry clods.

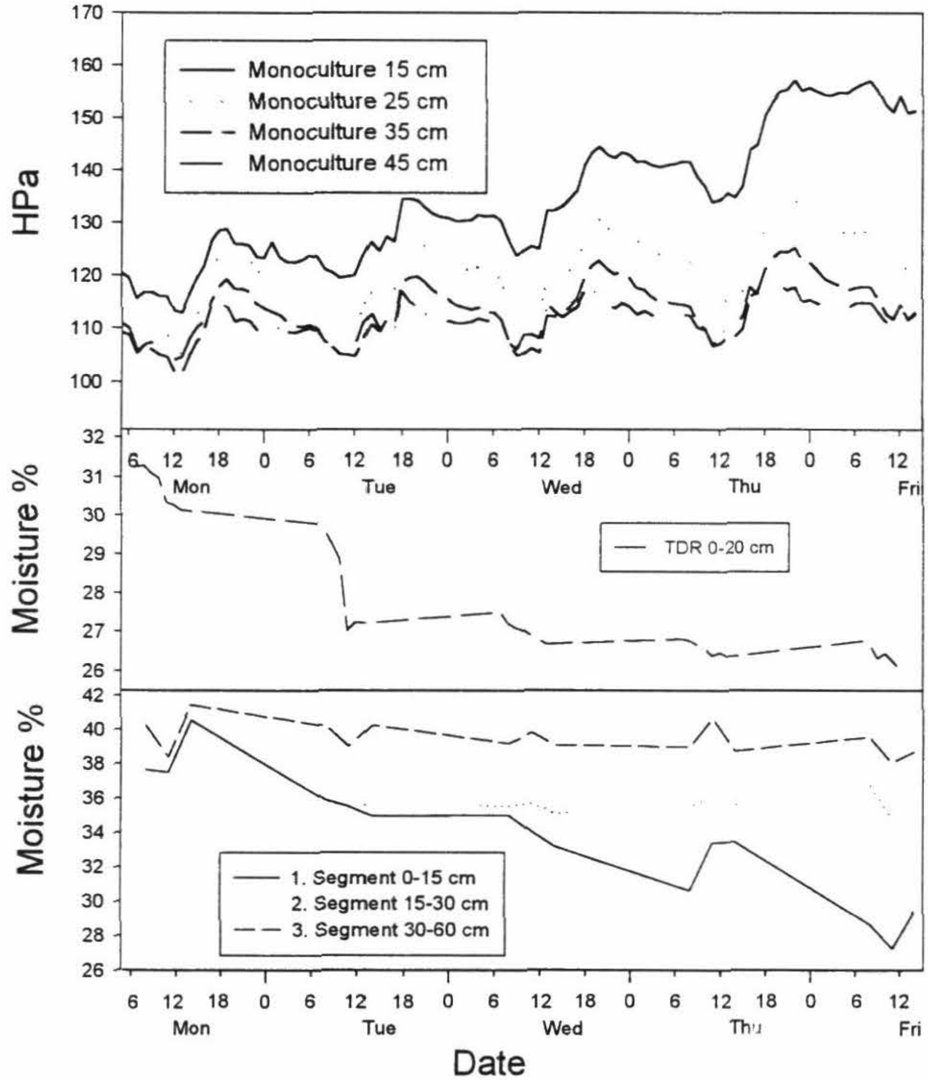


Figure 10. Changes in tension and water content measured by tensiometer and TDR at different depths.

Especially when soil is drying these effects are obvious both in 15 and 30 cm. The larger potential of plant suction during dry periods had led to higher tensions in Cassava + 8 t/ha chicken manure and Cassava rotation, whereas in Cassava int.tillage treatment the destruction of capillarity by intensive tillage and generally smaller plants resulted in lower tensions.

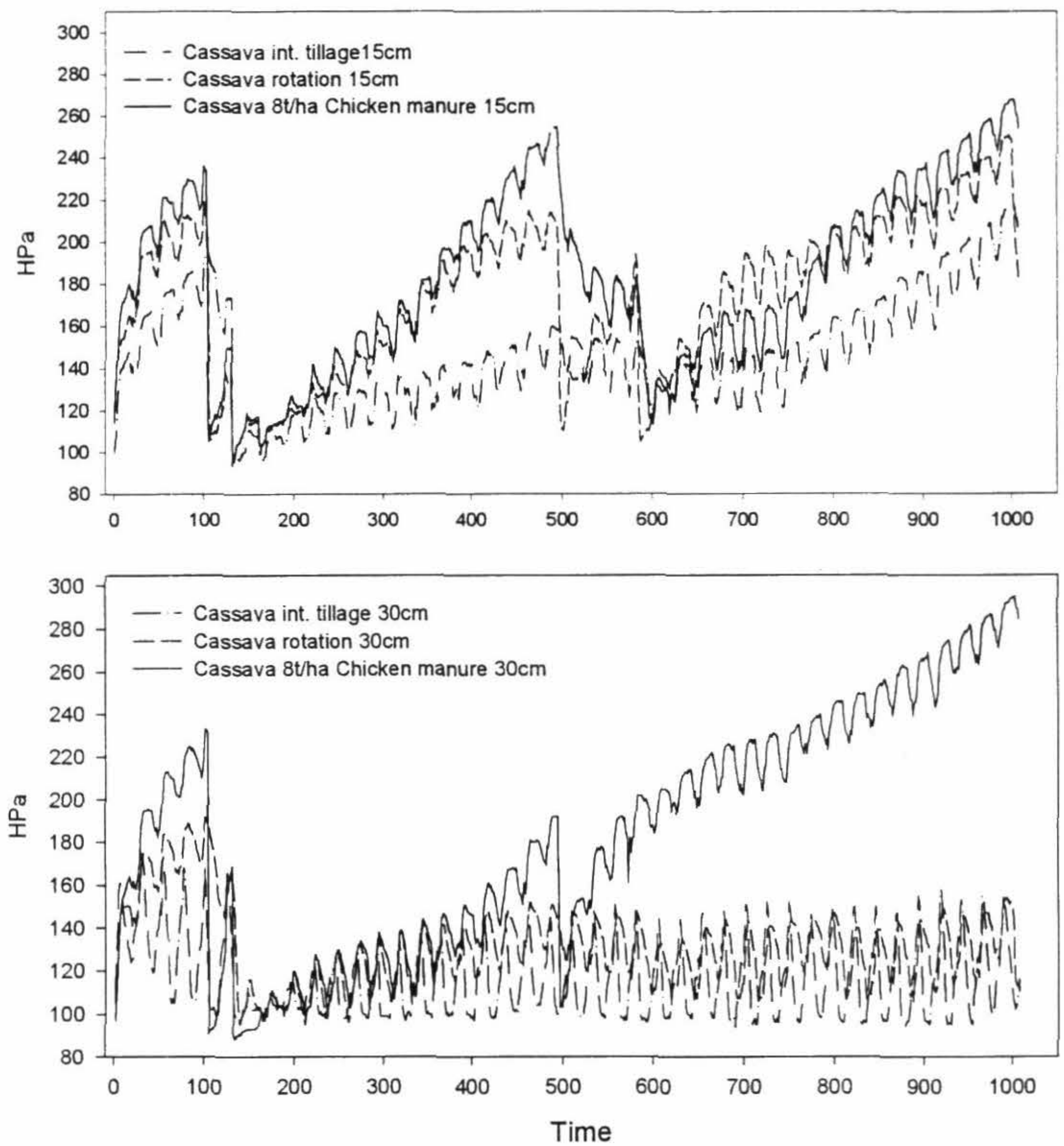


Figure 11. Influence of treatment and depth on tension. Location: Santander de Quilichao, Time Period: 15th of July to 25th of August.

In summary, soil treatment and fertilizer management have an important impact on soil water conditions. Results from ongoing TDR-measurements revealed high water contents in Cassava monoculture and Cassava min.tillage, whereas Cassava int.tillage had a generally lower water content. Microtensiometer measurements resulted in a remarkable change from dry period to wet period. In the wet season Cassava min.tillage and Cassava 4t/ha chicken manure had the highest tension. In the dry season Cassava 8t/ha chicken manure exceeded all other treatments. With a focus on soil depth, tensiometer measurement showed differences between Cassava min.tillage and Cassava monoculture. Monoculture treatment showed higher tensions in the upper layer whereas the contrary could be observed in minimum tillage treatment.

Impact:

Nature and quality of fertilizers have an influence either on water content or water tension. Chicken manure especially, is considered to have a serious impact on the soil surface. Future research is needed to determine the way water storage is affected by this manure. Water content is nearly the same in the upper layers in Cassava monoculture and Cassava minimum tillage treatment, whereas the amount of plant biomass is completely different. Further investigation will reveal whether plant suction or evaporation is the key reason for higher water regime in the soil, and if mulching leads to significant differences in water supply between treatments. The influence of plant cover specifically on Inceptisols has to be investigated. There is a basic need for research on soil water relations as investigation to date has been inadequate. Although results are very promising, further research is needed to draw conclusions of the treatment's influence on water tension.

Contributors:

C. Thierfelder (University of Hohenheim), E. Amezquita, R.J. Thomas and D.E. Leihner (University of Hohenheim).

Activity 1.2 Survey native plants and their potential use as biofertilizers

This activity is the subject of a student theses and will be reported next year

Activity 1.3 Survey land users for soil and crop management knowledge

This activity is the subject of a student theses and will be reported next year

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

1.4.1 Characterize genetically adapted crop and forage components for their ability to access soil P pools using isotope exchange techniques

Highlight:

- Isotopic exchange kinetic methods indicate that *Arachis pintoi* and *Brachiaria decumbens* access soil phosphorus pools which are normally not available to plants. A pot experiment using ^{31}P carrier with the ^{33}P label shows serious limitations to carrier use on low P soils.

Purpose:

To determine the differences among crop and forage components in the ability to acquire P from less available P forms in soil by using isotopic dilution techniques on low phosphorus-supplying tropical soils.

Rationale:

The aim of this special project funded by SDC, Switzerland, is to determine the differences among crop and forage plants in their ability to acquire P from less available P forms in soil by using isotopic dilution techniques on low phosphorus-supplying tropical soils. Plants that are capable of acquiring P from less available P sources could contribute to the sustainability of farming systems through more efficient P cycling. To test whether a selection of crops and forage plants take up P from normally unavailable, i.e. not isotopically exchangeable, sources on an Oxisol, specific activities (L-values) of the P taken up by plants grown on P isotope labeled soils were compared in two pot experiments.

The isotope exchange kinetics technique has been shown to provide an accurate description of the quantity of P that can result through homoionic exchange in the soil solution within 4 months (E-value). However, in high P sorbing tropical soils, the application of this isotopic approach has in the past led to a strong overestimation of soil available P. It is expected that the L-values would be higher than the E-values if genetically adapted plants had P acquisition strategies that render the non- or slowly exchangeable inorganic or organic P pools available.

In the first part of this study, isotopic exchange kinetic studies were carried out on a range of acid soils from Colombia. The resulting E-values were compared with the amount of soil isotopically exchangeable P in a labeled pot experiment using *Agrostis capillaris* (common bentgrass) and calculating L-values using the quantities of radioactivity and P exported by the plant (PE-2 Annual Report, 1999). This comparison showed that for *Agrostis capillaris* the L-values equal the E-values. From this observation, it was concluded that both values describe the normally plant available P. This was a crucial result for the second step of the project, the comparison of genetically adapted crop and forage plant varieties with regard to their P uptake and use strategies. The L-values of rice, maize, beans, the forage legume *Arachis pintoi* and the grass *Brachiaria decumbens* were compared among themselves and with the E-value of the same soil.

Another aspect contributing to an efficient P management with lower costs is the application of alternative P sources like rock phosphate or chicken manure. Cassava is known to be very efficient in P uptake, also on soils where P is depleted to a great extent. The greater P uptake efficiency has on the other hand the risk of P mining. The use of alternative P sources like rock phosphates or chicken manure can contribute to solve this problem without application of expensive water-soluble mineral P fertilizer. Whether cassava is able to take up P from such alternative sources efficiently when compared to readily soluble mineral fertilizer, was tested using two varieties in a pot experiment with the addition of chicken manure, triple super and rock phosphate.

Materials and Methods:
Soil samples were taken from the long term "Culticore" field experiment at Carimagua (Llanos Orientales, Columbia) CORPOICA-CIAT research station. The soil is a well-drained Oxisol (tropeptic haplustox, isohyperthermic). Two experiments were carried out to determine L-values. The cultivars used were *Brachiaria decumbens* (CIAT 606), *Arachis pintoi* (CIAT 18744) and rice (*Oryza sativa* var Savanna-6) in the first experiment. The same plants and additionally maize (*Zea mays* NST 90201(s) co-422-2-3-1-7-2-1) and beans (*Phaseolus vulgaris* AFR 475) were used in the second experiment. In both cases *Agrostis capillaris* was used as control plant.

After harvesting the plants, dry matter accumulation in the shoot and $^{31}PO_4$ (p) and $^{32}PO_4$ or $^{33}PO_4$ (r) contents in the shoot were measured. The L-values were calculated with the P-concentrations and activities measured in the shoot material.

Exp. 1:
Without carrier: $L=R/(r/p)$ [Eq.1]

Exp. 2
With carrier $L=Q\,((R/Q)/(r/p)-1)$ [Eq.2]

The source of P taken up by the plant in the experiment with carrier addition can be calculated as:

$P_{carrier}=Q(r/R)$ [Eq.3]

$P_{soil}=p-P_{carrier}$ [Eq.4]

Where R is the quantity of $^{33\text{ or }32}PO_4$ used to label exchangeable soil P (MBq kg^{-1}), Q is the quantity of carrier added (mg P kg^{-1}), r is the quantity of $^{33\text{ or }32}PO_4$ (MBq kg^{-1}) and p is the quantity of $^{31}PO_4$ (mg kg^{-1}) in the areal parts of the plants. $P_{carrier}$ and P_{soil} are the total amount of P derived from the carrier solution or from soil respectively. However, it should be considered that the P content of the seed is a third P source. The uptake from this source can not be distinguished from the P taken up from soil. So P_{soil} is actually $P_{soil + seed}$.

As P taken up from seed dilutes the specific activity of the P taken up by the plant from soil, the result is an overestimation of the L-value in both experiments. The following correction was made to overcome this problem:

$$L_{th}=L(p/(p+P_{seeds})) \qquad [Eq.5]$$

Where L_{th} is the corrected value, L the value calculated with Eq. 1+2 and P_{seeds} the P content of the sown seeds. This correction assumes that 100 % of seed P was taken up by the plant and therefore corrects for the highest possible influence of seed P. E-values were determined and calculated as described in the last year report (PE-2 Annual Report, 1999) using the incubated soil in both pot experiments.

Use of different P sources by cassava: Two varieties of cassava -- Catumare (CM 523-7), a widely used adapted variety, and CM 507-37, a forage variety of dwarf growth habit -- were grown from stakes of 20-25 cm length. The soil used the same as that used for the L-value experiments. Treatments of P source were: 0 P, chicken manure (CM), triple super phosphate (TSP), and Calfomag (ground rock phosphate with addition of lime and sulfur) at 10 kg P ha^{-1} = 5.13 mg P kg^{-1} soil each. Each treatment was replicated four times. At three and a half months after planting, the plants were harvested and shoot and root (no tubers were developed at this moment) biomass and P concentrations were determined.

Results and Discussion:

L-value comparison: The biomass production of all plants in the first experiment was very low and the total P uptake was hardly greater than the P content of the seeds (Table 5). Therefore, correction for the seed-P, using Eq. 5 resulted in a marked decrease of L-values. As the actual amount of P taken up from seeds is not known, the L_{th} represents a minimal value as it is calculated using the assumption that all seed P had been taken up. The uncorrected L-values in the first experiment were very high and in the case of *Brachiaria decumbens* with the smallest influence from seed P (Table 5), the corrected L_{th}-value remained much higher (131 mg kg^{-1}) than the E-value of 36 mg kg^{-1}assessed on the same incubated soil. This indicates that P additional to the isotopically exchangeable P was taken up.

Small biomass and therefore high or rather unknown seed P influence for most of the tested plants was however unsatisfactory for the purpose of the L-value calculation. To overcome these problems (small total P uptake and biomass production), the second experiment was optimized by using less soil per plant, applying P-fertilizer (corresponding to 20 kg P ha^{-1}) as a carrier with the labeling solution and extending the duration of plant growth from eight to eleven weeks.

The application of a carrier resulted in much smaller L-values (mean of all plants 2.7 mg P kg^{-1} soil) than without carrier (mean 148 mg kg^{-1}) and there were no significant differences between plants. This could be due to the supply of 10 mg P kg^{-1} to a soil with a very low P concentration in the solution (in this case approximately 2 $\mu g\ l^{-1}$). In our experiment, the nearly identical values of the specific activities of the plants and the applied carrier indicate that the carrier P was the main source for the P taken up by the plant. Separation of the P sources using Eq. 3 and 4 shows that on an average 81% of P taken up by the plant derived from the carrier (Table 6). Of the 19 % of the total plant P uptake derived from other P sources, a part of it is actually from seed P. Therefore it can be assumed that almost no soil P was taken up.

Table 5. Biomass production, P uptake and L values of the compared plants in experiments 1 and 2.

Crop/ Species	Dry matter (g/pot)		P uptake (mg/pot)		L value	Mg/kg	L value	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
Arachis	1.6	2.4	0.9	2.1	185	4.0	46	3.1
pintoi	(0.3)	(0.4)	(0.26)	(0.30)	(32)	(0.7)		
Brachiaria	0.3	1.9	0.22	1.1	153	0.9	131	0.9
Decumbens	(0.01)	(0.2)	(0.08)	(0.07)	(24)	(0.8)		
Rice	0.6	2.3	0.25	1.1	125	1.4	39	1.1
	(0.1)	(0.4)	(0.06)	(1.06)	(17)	(1.5)		
Maize	-	6.3	-	3.9	-	4.7	-	3.8
		(1.5)		(0.46)		(3.7)		
Beans	-	1.0	-	1.45	-	1.7	-	1.1
		(0.4)		(0.35)		(0.5)		
Agrostis	0.2	1.0	0.14	0.4	128	3.3	6.7	1.6
Capillaris	(0.09)	(0.2)	(0.05)	(0.05)	(29)	(0.8)		

L=L value without, L_{th}=L value with correction assuming that 100 % of Seed P was taken up by the plant. SD values are in parentheses

Table 6. Amount of P derived from applied carrier and percentage of P derived from other sources (calculated with Eq. 3 + 4). SD values are shown in parentheses.

Plant material	Total P uptake in aerial plant biomass (mg)	P derived from carrier (mg)	% of P derived from other sources (soil and seed)
Arachis pintoi	2.1 (0.3)	1.50 (0.2)	27
Brachiaria decumbens	1.1 (0.07)	1.00 (0.07)	9
Rice	1.1 (1.1)	0.93 (1.0)	16
Maize	3.9 (0.5)	2.57 (0.4)	26
Beans	1.45 (0.4)	0.98 (0.3)	13
Agrostis capillaris	0.4 (0.05)	0.33 (0.05)	24
(Mean)			19

Results from these two experiments raised new questions related to the discrepancy between L-values determined with or without addition of carrier P.

1) Does the determination of the L-value without carrier lead to an overestimation of available P due to fixation of the labeling isotope (specific fixation of the $^{33}PO_4$) or other possible error sources?
2) Does the application of a carrier with the labeling solution cause a change in the behavior of the soil P, i.e. does less P get from the solid phase into the solution when additional P is introduced into the sytem?

To address these questions further experiments are needed to compare E- and L-values with and without carrier on soils with different residual P levels.

Table 7. Biomass production (g plant^{-1}) and P-content (g kg^{-1}) of plant parts of two varieties of cassava after 16 weeks of growth with different P sources applied to soil. SD values are shown in parentheses. Values followed by the same letter in the column are not significantly different.

Variety	Treatment	Total biomass	Root Biomass	Root P content	Leaf P content
CM 523-7 (Katumare)	0 P	11.94 a (2.55)	5.56 a (2.31)	1.08 a (0.19)	1.77a (0.26)
	CM	9.89 a (1.07)	5.01 a (1.33)	1.08 a (0.16)	1.84 a (0.34)
	Calfomag	10.57 a (2.25)	6.13 a (0.96)	1.01 a (0.08)	1.87 a (0.47)
	TSP	10.28 a (2.94)	7.98 a (1.70)	1.03 a (0.08)	1.99 a (0.22)
CM 507-37	0 P	8.56 b (1.06)	6.04 a (1.57)	0.89 b (0.11)	1.43 b (0.22)
	CM	9.86 b (1.15)	7.12 a (1.24)	0.88 b (0.25)	1.42 b (0.20)
	Calfomag	8.81 b (1.19)	6.03 a (1.24)	0.92 b (0.06)	1.62 b (0.11)
	TSP	8.78 b (1.38)	7.14 a (1.63)	0.82 b (0.30)	1.62 b (0.09)

CM = chicken manure; TSP = triple super phosphate.

P uptake by cassava from different sources: The addition of P fertilizers did not affect shoot or root biomass production or the P concentration in cassava (Table 7). However differences were shown between varieties. Total P uptake, biomass production and P concentrations in leaves and roots were greater for CM 523-7. This might largely be due to the higher P concentrations and to the additionally higher dry weight of the stakes of CM 523-7. This observation again emphasizes the greater impact of the P reserves in planting material or seeds on the final results, as observed from the other two experiments. The values of leaf P content indicated that P supply was limiting plant growth based on an internal critical leaf P value (for 95% yield) of 2.2 g kg^{-1}. The lack of response to P fertilizer application might be due to the small amount of applied P although high responses to similar P applications in the field were documented. For example a doubling of the yield for the whole growth cycle with an application of 20 kg P ha^{-1} to a low P soil from Carimagua was reported.

With this pot experiment it is not possible to determine whether the plants did take up any P from the applied fertilizer. For the distinction of different P sources, an experiment with labeled soil would therefore be of high value. However, cassava is not suitable for experiments with radioactive labeling, as it requires big soil volumes and has a long growth cycle. Therefore large amounts of isotope are required which would be above legal limits set up for safety reasons.

Impact:
Using isotopic exchange kinetic method, we found that on an average 81% of P taken up by crop and forage plants is derived from the P supplied to soil as a carrier. Results from one pot experiment indicated greater L-values than E-values for *Brachiaria decumbens* and *Arachis pintoi*, suggesting special uptake

mechanisms. However these results could not be confirmed in a second experiment where the soil was labeled with a simultaneous P carrier application. The L-values were generally much lower and no differences were found among plant species. Further experiments are needed to compare E- and L-values with and without carrier on soils with different residual P levels, but the carrier experiment done in this study indicates serious limitations to carrier use on low P soils. Results from another greenhouse study to test whether cassava is able to take up P from different P sources showed no significant effects of low supply of various P sources on cassava plant performance.

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This activity links with 4 other CIAT projects IP-1, IP-3, IP-4 and IP-5.

Activity 1.5 ***Determine rooting strategies of crop and forage components***
This activity is on-going, results are being analyzed and will be reported next year

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

1.6.1 Establish rotation systems of annual and perennial crops in SOL sites (Supermercado de Opciones para Laderas or Supermarket of technology options for hillsides)

Purpose:
The SOL is an initiative of the CIAT-Hillsides project (PE-3) to develop technological options that are economically viable and environmentally sustainable and to offer these to technicians, producers, and institutions. The aim is to develop technologies that establish profitable, sustainable production systems through multi-institutional alliances, using a participatory approach (design, planning, monitoring, and assessment), which includes shared responsibility at all decision-making levels. The SOL links farmer experimentation with formal research.

Basic hypotheses that need to be tested to prove the worth of the SOL are that it:
1. Promotes farmer adoption of natural resource-friendly management technologies.
2. Facilitates greater interaction between the commodity improvement projects and natural resource management projects.
3. Allows for strategic research issues to be investigated under realistic on-farm conditions.

Rationale:
The experience generated by the alternative cropping systems work in the Colombian hillsides is one of the ingredients to the SOL in Nicaragua and Honduras. The success of this initiative is based on the integration of information from different approaches through a close articulation among several CIAT projects and also globally through the Soil Water Nutrient Management (SWMN) program (Figure 12). It intends to generate a *modus operandi* that optimizes farmer adoption of natural resource-friendly management technologies. The SOL is conceived of as operating within a definable agroecological system (i.e., edaphic, biophysical, sociological) for which geographic information systems (GIS) are useful. They can make sure that anything of value determined in SOL will be applicable to definable aspects of the landscape.

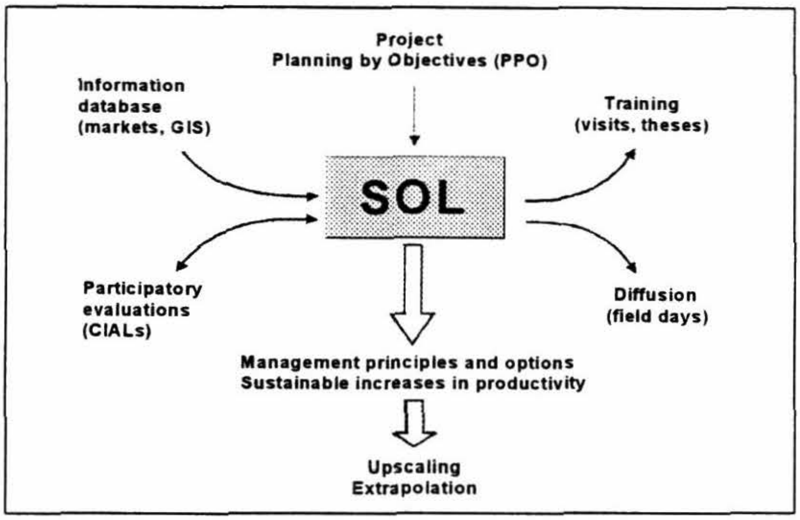

Figure 12. Conceptual model of the SOL's *modus operandi*.

A basic component of the SOL approach is local participation. This is expressed by local community and stakeholders' identifying and prioritizing problems, formulating demands within the realm of the CIAT mandate and expertise, and jointly identifying potential solutions and exploring the potential synergy of joining local and external approaches to problem solving.

The results of these initial steps are made operational at experimental farms or SOL sites where identified potential solutions to local demands are established as new technological options. Participatory evaluation of the merits and weaknesses of proposed solutions are carried out on SOL sites and also on-farm by local farmers and partner institutions.

A characteristic of the SOL is that its strategies of generating and validating technological innovations are more oriented toward satisfying producers and the market than toward the simple self-promotion of SOL products, which makes it different from other strategies. The connection between different SOL actors forms a model that could become a tool to be used by other institutions in the future. Figure 13, for example, shows the institutions in Nicaragua that work together in the SOL, which cover a full range from local to international.

Figure 13. Research partnerships in the SOL in Nicaragua.

This network of landscape-scale experiments involves:

- Participatory planning of options with partners and evaluations by farmers' research committees (Comités de Investigación Agrícola Local or CIALs)
- Linkage to a GIS database for modeling and extrapolation
- Use of sites for training and extension
- Application of strategic research results
- Feedback to direction of strategic research

Strategic research

Strategic research hypotheses to be tested in the SOL sites that receive inputs from PE-2 are:

1. Crop rotations and use of hedgerow plants can help the control of soil-born pathogens and improve the efficiency of nutrient and water use.
2. Crop varieties with differing nutrient acquisition potentials and rooting patterns result in a better use of soil and water resources.
3. Temporal or spatial arrangements of crops and fallow species can improve production and conserve natural resources.
4. Multi-purpose erosion barriers (e.g., cut-and-carry species) improve nutrient and water fluxes compared with traditional erosion barriers.
5. Varying the temporal and spatial arrangements of crop components can enhance the biological activity of soils.
6. The combination of organic and inorganic fertilizers can result in better yields than either fertilizer applied alone.

Strategic research is aimed at developing new land management options and involves a diversity of new technologies that are offered through the SOL experiments in Honduras, Nicaragua and Colombia. Examples of technologies offered are:

- Improved food crop varieties
- Soil conservation techniques
- Silvopastoral systems
- Improved fallows
- Vegetables, fruits

The role of strategic research by CIAT is to better understand principles and processes that can be exploited to make production systems more sustainable. In long-term landscape trials, for example, we have assessed combinations of different plant rooting strategies with improved soil management practices and have found significant differences in N, P, and K acquisition and soil erosion among different systems and genotypes (Outputs 1.4, 1.5,1.6; PE-2 Annual Report, 1999).

Farmer knowledge

In our supermarket, the product of farmers' knowledge goes onto the shelves together with that of strategic research. Farmers are helping our national program research in Nicaragua and Honduras to increase the diversity of multipurpose legumes available. Farmers' selection criteria are important for introducing large numbers of new materials. For example *Arachis pintoi* cv. Pico Bonito and *A. Pintoi* cv. Pucallpa are more highly ranked by farmers than *Centrosema macrocarpum* CIAT 25222 and *Centrosema* b. CIAT 15387, which are usually recommended.

The SOL initiative rests on the belief that the sustainable management of natural resources depends on strengthening the capacity of local population to better manage of natural resources. Local knowledge and demands are a necessary complement to external knowledge for the generation of hybrid technologies.

Recognizing the importance of this fact constitutes an important basis of our strategy to improve the adoption of new technologies.

An example of an on-site SOL, Honduras

In Honduras, we aimed to establish a SOL site representative of the Tascalapa River watershed and to form a SOL with the participation of institutions working in research and technology validation and transfer at that reference site. The methodology followed to establish the SOL included (1) selecting a watershed, (2) biophysical characterization of the site, (3) prioritization of topics to be included in the SOL, and (4) design and implementation of options in the field.

Several meetings were held with regional producers, scientists and technicians to form the SOL. A common vision was achieved at these meetings and a conceptual action framework was defined.

An area was selected for a SOL site in the Luquigue watershed, which is representative of the use given to lowlands in the Tascalapa River watershed. Many of these areas are devoted to cattle raising. The selected site is also representative of the overall condition of the watershed regarding soil chemical characteristics: slightly acid pH and high calcium and organic matter contents. This condition is important when extrapolating developed technological options to other areas of the watershed or beyond.

The joint analysis of the problem of sustainability with the community and other stakeholders, in a Project Planning by Objectives (PPO) workshop, showed that the low sustainability of regional production systems was associated with:

- Low use of inputs,
- Depleted soils,
- Inadequate agricultural practices,
- Limited economic resources,
- Subsistence culture,
- Reduced technological diversification,
- Limited crop diversity,
- Low profitability of prevailing production systems,
- Lack of training in new alternatives, and
- Poor land distribution.

After prioritizing the problems that could be solved by the SOL, several topics and specific activities were identified. Based on recommendations made by the community, several technological options were designed that include the testing and assessment of new components and systems. Table 8 shows these options, which include the testing of new crops and multi-purpose forage and tree species.

Two meetings were held with producers and representatives of Yorito-based institutions to conceptualize establishing a SOL for the community. It was concluded that SOL activities should be based on the following:

- Services oriented toward client needs,
- Feedback mechanisms established to determine product adoption and adjustments made by producers,
- Systems designed to promote and sell technologies, services, and products,
- Systems designed to promote products and services and make them accessible,
- Marketing services provided, and
- Participatory monitoring systems established.

Table 8. Technological options included in the Supermercado de Opciones para Ladera (SOL), Yorito, Honduras.

Options	Systems components
1. Livestock	• Observation plots and silvopastoral systems
2. Reforestation	• Traditional maize-beans; associated maize-beans; beans; and maize-cowpea
3. Arrangements of systems	• Evaluation of native and introduced multi-purpose species
4. Improved fallow	• Legume species to improve soil fertility
5. Fruit trees	• Species to recover and protect fragile areas
6. Satellite tests	• Evaluation plots of new crops
7. Live barriers	• Multi-purpose species
8. Protection of gullies	• Multi-purpose tree species
9. Vegetables	• Species to enhance the home garden

A working group was established to promote networking and prepare a funding proposal to obtain additional resources needed to establish other SOL components. It was integrated by representatives of the CIAT Hillsides project, the CIAT Rural Agroenterprise project, Investigación Participativa en Centro America (IPCA) project, Servicios Técnicos para el Desarrollo Sostenido (SERTEDESO), and the University of Hohenheim.

Impact
In the long term, the SOL will help to balance production systems in hillsides and improve some conditions of life of the participating producers. A lessening of environmental deterioration should be visible (soil conservation, reduction in slash-and-burn, sustainable management of water). There should also be a measurable increase in the quantity and quality of foodstuff and in incomes. In the shorter term, producers and local institutions will accept, adopt and actively run/feed the services and technologies (agricultural and commodity) of the SOL and will be able to maintain the process of innovation and transfer of technology. Once the hypotheses on the adequacy of the SOL mechanism are proven, each of these desired outcomes will themselves become further hypotheses to be verified by monitoring and evaluation.

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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 Strategies for the establishment and maintenance of arable layer for soils of the Orinoquia region of Colombia

Highlight:

- A special project funded by COLCIENCIAS (Colombia) was completed and this project contributed to development of soil and crop management strategies to build up an arable layer in infertile oxisols of the Llanos of Colombia.

Purpose:

To develop soil and crop management strategies thst result in an "arable layer" in infertile oxisols of the Llanos of Colombia

Rationale:

A special project funded by COLCIENCIAS (Colombia) was completed this year. The participating institutions in this project included CIAT, CORPOICA and The Llanos University. The main objective of the project was to understand the susceptibility to degradation of infertile Oxisols of the Llanos of Colombia.

Previous research in the Llanos of Colombia has shown that the natural soil physical conditions of savanna soils do not offer an optimum environment for root growth for crops and pastures. The soils are susceptible to degradation due to the vulnerability of their structure when treated with machinery. Thus, to achieve improved, sustainable crop and pasture production and to avoid degradation, these soil physical constraints must be alleviated by appropriate tillage/cropping practices.

Soil quality is an important concept what is defined as "the capacity of a specific kind of soil to function, within natural or management ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation. Soil quality depends on inherent soil characteristics e.g. structural attributes, rooting depth, charge density, nutrient reserves and soil biodiversity. The impact of soil degradation on soil quality should be assessed in relation to critical limits of key soil properties. Identification of appropriate methods of soil restoration is facilitated by knowledge of the key soil properties that influence soil quality and their critical limits in relation to the severity of soil degradation.

Good soil management should aim to create optimum physical conditions for plant growth such as, adequate available water, adequate aeration for roots and microorganisms, ease of root penetration, rapid and uniform seed germination, and resistance of the soil to slaking, surface sealing and accelerated erosion by wind and water. Traditional methods of cultivation with ploughs, often cause disastrous results in terms of soil structural deterioration and erosion especially in tropical soils. Measurements of water-stable aggregates show that the deterioration in structure is most rapid in the first year after grassland is ploughed. Total porosity, water holding capacity and macroporosity also decline as cultivation is prolonged. This is because ploughing can cause disruption of peds and this exposes previously inaccessible organic matter to attack by microorganisms. In addition the populations of structure-stabilizing fungi and earthworms can decrease markedly.

The relatively weak structure of savanna tropical soils of Colombia (Oxisols) and their susceptibility to sealing, compaction, and erosion when subjected to tillage could make them extremely susceptible to degradation, thus causing negative effects on agricultural and livestock sustainability. To overcome these physical constraints, tillage practices should be conducted using the concept of the development of an "arable layer". "Arable layer" is understood to be a surface layer (0-15, 0-25, 0-30 cm depth), with no or minimum physical, chemical or biological constraints, that is obtained through different soil and crop management practices. This is essential for developing a soil that can support sustainable agriculture.

The "arable layer" concept proposed here, is based on combining: (1) tillage practices to overcome soil physical constraints (high bulk density, surface sealing, low infiltration rates, poor root penetration, etc.), (2) use of chemical amendments (lime and fertilizers) to enhance soil fertility, and (3) use of soil and crop management practices to increase rooting, to promote biostructure, and to avoid soil repacking after tillage. Under the current limiting physical conditions of these soils it is not possible to apply any conservative tillage system (eg. direct drilling) because these soils do not fulfill the conditions required for good root growth and productivity.

Materials and Methods:
As part of the development of remedial measures to reverse soil degradation, a field experiment was established in 1995 to assess the influence of physical and biological treatments on the building-up of an "arable layer". The experiment tested two methods: i) by deep tillage (using chisel) at different intensities (1, 2 and 3 passes) to improve the soil physical conditions in a crop rotation (rice/soybean) system, and (ii) by using agropastoral (rice/grass/legume) systems to improve soil through enhanced rooting and biological activity.

Location: The experiment was established at Matazul farm (4° 9′ 4.9″ N, 72° 38′ 23″ W) on an Isohyperthermic Kaolinitic Typic Haplustox (Oxisol) at 260 m.a.s.l. 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 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 Santa Rosa weather station, located at the Piedmont of the Llanos of Colombia).

Treatments

- Rice (cv. Savanna 6) /soybean (cv. Soyica Altillanura 2) rotation with one pass of chisel.
- Rice (cv. Savanna 6) /soybean (cv. Soyica Altillanura 2) rotation with two passes of chisel.
- Rice (cv. Savanna 6) /soybean (cv. Soyica Altillanura 2) rotation with three passes of chisel.
- Rice + grass alone [*Andropogon gayanus* (Ag)] pasture
- Rice + grass + legumes [*Pueraria phaseoloides* (Pp)+*Desmodium ovalifolium*(Do)] pasture
- Legumes (*Pueraria phaseoloides* (Pp)+*Desmodium ovalifolium*(Do)) only.
- Native savanna, acting as a control to study changes in the soil conditions.

Lime (1.5 $t.ha^{-1}$ of dolomite) and fertilizers ($t.ha^{-1}$: 0.45 triple super phosphate + 0.3 KCl + 0.02 $ZnSO_4$) were applied each year for the first two years. The experiment was laid down in a randomized complete block design and was replicated three times. Measurements of soil physical characteristics (bulk density, total porosity, mechanical impedence), soil nutrient availability, shoot biomass, root biomass, plant nutrient composition, and shoot nutrient uptake were measured for each treatment. Grain yield of upland rice was determined.

Results and Discussion:
Soil physical properties: Changes in bulk density and total porosity at two years after establishment of the field experiment are shown in Table 9. Agropastoral treatments, in general, had lower values of bulk density in 0-10 cm soil layer than those of the native savanna. Bulk density ($Mg.m^{-3}$) decreased in the 0-10 cm layer from 1.43 in native savanna to around 1.20 under the agropastoral treatments. The lowest value of 1.12 was observed with tropical forage legumes (Pp+Do) treatment. In the 10-20 cm soil depth, both

chisel and introduced pasture treatments resulted in lower values than those of native savanna. A similar tendency was observed with 20-30 cm depth. In the 30-40 cm depth there were no significant differences compared with native savanna, indicating that both chisel and agropastoral systems had not influenced the values of bulk density at this depth.

Total porosity increased from 46% in native savanna to values between 53 to 57% in the top (0-10 cm) soil layer of all the treatments. Total porosity in subsoil layers was not markedly affected by either chisel or agropastoral treatments. Changes in mechanical impedence at different soil layers as influenced by chisel and agropastoral treatments are shown in Figure 14. In relation to native savanna, all the treatments have decreased values of mechanical impedence, particularly in top-soil layers (0-20 cm). These results suggest that it is possible to improve soil physical conditions to enhance water and nutrient availability that favors rooting ability of crop and forage components. The improved soil quality can result in greater crop and pasture productivity.

Soil Chemical properties: The effects of chisel and agropastoral treatments on soil nutrient availability and Al toxicity were determined four years after the start of the experiment (Table 10). Compared to native savanna where nutrient availability is low and Al toxicity is high, application of lime and fertilizer to different agropastoral treatments improved nutrient availability and reduced Al toxicity. P availability was particularly improved by 3 passes of chisel compared with either 1 or 2 passes. P distribution to subsoil layers was also improved by chisel treatments. Introduced pasture treatments improved P availability in 0-5 cm layer. Other nutrients, K, Ca and Mg also accumulated in top-soil in a similar way. Higher values of nutrients were found in the 0-2.5 cm layer. Availability of K was 3 to 4 times greater than that of native savanna (0.11cmol$_c$ kg^{-1}). Availability of Ca and Mg was 4 to 10 times higher than that of native savanna. Application of lime markedly decreased the levels of exchangeable Al mostly in top-soil but not in subsoil. Aluminium decreased in the first two layers, but remained at similar values of native savanna below these depths. These results show that application of lime and fertilizer could markedly improve soil fertility mostly in top-soil. However chisel treatments were not very effective to incorporate lime and P to deeper layers.

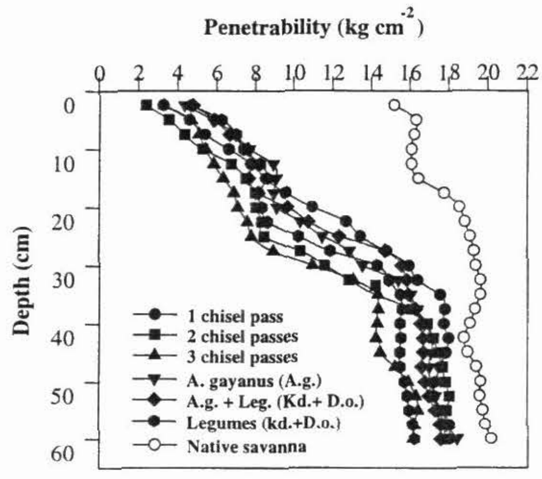

Figure 14. Changes in penetrability (measured at field capacity) depth four year after establishment of different agropastoral systems.

Table 9 Changes in bulk density ($Mg.m^{-3}$) and total porosity (%) with soil depth two years after establishment of different agropastoral systems.

Treatments	Soil depth							
	0-10 cm		10-20 cm		20-30 cm		30-40 cm	
	Bulk density	Total porosity	Bulk density	Total porosity	Bulk density	Total porosity	Bulk density	Total porosity
Rice-soybean (Rotation):								
1 chisel pass	1.19 b	54.90a	1.41bac	46.58abc	1.45ba	45.07ab	1.54ba	41.90ab
2 chisel passes	1.23 b	53.60a	1.29c	51.06a	1.42ba	46.44ab	1.51ba	43.02ab
3 chisel passes	1.22 b	53.72a	1.32bc	49.95ab	1.38ba	48.06ab	1.41ba	46.54ab
Rice+pasture (Agropastoral):								
4- *Andropogon gayanus* (*Ag*)	1.16 b	56.02a	1.30c	50.86a	1.34ba	49.27ab	1.44ba	45.52ab
5- *Ag*+legumes (Pp+D*o*)	1.23 b	53.71a	1.29c	51.30a	1.40ba	45.07ab	1.61a	39.17b
6- Only legumes (Pp+D*o*)	1.12 b	57.82a	1.33bc	49.48ab	1.38ba	47.78ab	1.49ba	43.72ab
7- Native Savanna	1.43 a	45.93b	1.50a	40.07c	1.53a	42.12b	1.52ab	42.70ab
Pr > F	0.006	0.0033	0.01	0.01	0.50	0.50	0.36	0.35

Pp = *Pueraria phaseoloides*; Do = *Desmodium ovalifolium*

Table 10. Changes in availability of nutrients in soil layers four years after establishment of different agropastoral treatments.

Treatments	Depth (cm)	P (mg kg^{-1})	K	Ca	Mg	Al
			(cmol$_c$.kg^{-1})			
Rice-soybean (Rotation):	0-2.5	38.00	0.24	2.22	0.94	0.43
1 chisel pass	2.5-5	31.50	0.15	2.24	0.96	0.43
	5-10	20.70	0.12	1.54	0.68	0.62
	10-20	3.20	0.07	0.54	0.34	1.35
	20-40	1.80	0.05	0.19	0.14	1.46
Rice-soybean (Rotation):	0-2.5	30.80	0.42	1.74	0.80	0.31
2 chisel passes	2.5-5	38.30	0.23	1.64	0.71	0.31
	5-10	15.50	0.14	1.37	0.68	0.31
	10-20	4.50	0.02	0.60	0.36	0.94
	20-40	1.50	0.04	0.13	0.12	1.25
Rice-soybean (Rotation):	0-2.5	47.20	0.28	1.65	0.73	0.42
3 chisel passes	2.5-5	45.20	0.19	1.78	0.77	0.31
	5-10	16.90	0.15	1.41	0.67	0.42
	10-20	1.60	0.07	0.21	0.16	1.25
	20-40	0.96	0.06	0.18	0.12	1.25
Rice+pasture (Agropastoral):	0-2.5	23.80	0.19	0.72	0.31	1.25
Andropogon gayanus (Ag)	2.5-5	15.30	0.15	0.59	0.26	1.25
	5-10	7.20	0.09	0.43	0.19	1.56
	10-20	2.40	0.06	0.21	0.13	1.56
	20-40	1.50	0.04	0.13	0.08	1.56
Rice+pasture (Agropastoral):	0-2.5	18.20	0.30	0.77	0.39	1.04
Ag+legumes (*Pueraria phseoloides+D.*	2.5-5	12.00	0.17	0.76	0.34	1.14
ovalifolium)	5-10	4.60	0.10	0.60	0.30	1.35
	10-20	1.20	0.06	0.19	0.13	1.25
	20-40	0.55	0.04	0.09	0.06	1.14
	0-2.5	16.50	0.31	0.74	0.36	1.25
Rice+pasture (Agropastoral):	2.5-5	13.00	0.21	0.74	0.35	1.25
Only legumes (Kudzú+*ovalifolium*)	5-10	5.30	0.12	0.55	0.28	1.98
	10-20	1.90	0.06	0.17	0.11	1.77
	20-40	1.10	0.05	0.14	0.08	1.46
	0-2.5	4.62	0.11	0.17	0.10	
Native Savanna	2.5-5	2.70	0.06	0.13	0.06	1.98
	5-10	1.95	0.05	0.12	0.06	1.93
	10-20	1.43	0.04	0.11	0.05	1.69
	20-40	1.08	0.02	0.11	0.04	1.25

Table 11. Effect of the buildup of arable layer on plant growth and total nutrient acquisition by different agropastoral systems on an Oxisol at Matazul farm in the Llanos of Colombia.

Treatments	Rice grain yield	Rice biomass	Total shoot biomass (rice+grass +legume)	Nutrient uptake (rice + grass + legume)				
				N	P	K	Ca	Mg
	kg/ha							
Rice-soybean (Rotation): 1 chisel pass	2503a	3992a	3991	41.0	7.2	39.7 c	6.1 c	7.3
Rice-soybean (Rotation): 2 chisel passes	2439a	4213a	4213	50.0	8.0	42.9bc	7.2bc	8.1
Rice-soybean (Rotation): 3 chisel passes	2448a	4368a	4368	50.3	7.3	42.8bc	6.6 c	7.7
Rice+pasture (Agropastoral): Ag+Pp+Do	926b	2419b	5881	65.0	7.7	71.6 a	12.9 a	8.6
Rice+pasture (Agropastoral): *Andropogon gayanus (Ag)*	747b	2275b	5147	54.0	6.6	66.3ab	10.3ab	7.7
LSD (0.05)		1482				26	3.4	

Ag = *Andropogon gayanus*; Pp = *Pueraria phaseoloides*; Do = *Desmodium ovalifolium*.
Means followed by different letters within columns are significantly different ($P < 0.05$).

Plant growth and total nutrient acquisition: Rice grain and biomass production were less when associated with pasture components than under chisel treatments (Table 11). The higher rice production under the chisel treatments could be attributed to the reduced bulk density, reduced soil strength, increased aeration porosity (macroporosity) and increased water infiltration rate observed with chisel treatments. A good porosity is of great importance for soil management purposes as it regulates root growth and rainfall acceptance, water entry and its movement in the soil, which in turn affects nutrient availability and acquisition by plants. Increase in number of chisel passes from 1 to 3 did not significantly affect rice biomass or its gain yield production. Land preparation with one pass of chisel could be sufficient because three passes could be excessive for these soils as it could cause a reduced soil volume.

Total biomass and nutrient acquisition (K and Ca) was generally improved by pastures especially when a legume was included (Table 11). This implies that pasture legumes could be of great importance in nutrient cycling and addition of organic matter to the soil, which have beneficial effects on the production system.

Impact:
It is possible to increase upland rice production on savanna soils in the Llanos through physical and chemical improvement of the soil. However, physical improvement alone without chemical and/or biological improvement of soil conditions is not adequate. Introduction of tropical pasture components into the production system is essential to maintain adequate soil physical conditions to improve nutrient

acquisition and recycling and to facilitate an accumulation of better quality and quantity of soil organic matter leading to the build-up of an arable layer. These studies provide experimental evidence to promote the concept of building-up an "arable layer" in tropical oxisols using chisel and agropastoral treatments to sustain crop-livestock production on infertile oxisols of the tropics. The build-up of an arable layer is a prerequisite to move toward no-till or direct drilling systems to minimize environmental degradation in savanna soils of the Llanos of Colombia.

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

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

Highlight:
- Found that the *T. diversifolia* slash/mulch fallow system could be the best option to regenerate soil fertility of degraded volcanic-ash soils of the Andean hillsides where rainfall is not limiting.

Purpose:
To identify strategies for the recovery of soil fertility of volcanic-ash soils that are degraded following continuous cassava cultivation.

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

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

Slash and mulch agroforestry systems include alley cropping systems where pruning biomass from tree rows is applied in the alleys between the rows before planting. Alternatively, biomass transfer systems include the harvesting and transporting of biomass from one farm location (i.e. live fences) to another as a source of nutrients for the crop. Fallow enrichment of traditional slash/mulch systems of 'frijol tapado' in

Costa Rica have also shown the importance of the inclusion of trees as a source of biomass and nutrients during soil fertility recovery. In the Honduran 'quesunguale' system dispersed trees are allowed in cropped fields and through periodical pruning competition is kept low while provision of plant residues for soil cover and as a source of nutrients is maintained.

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

Materials and Methods:

Site description: The study was conducted on two farms in Pescador, located in the Andean hillsides of the Cauca Department, southwestern Colombia (2°48' N, 76°33' W) at 1505 m above sea level. The area has a mean temperature of 19.3°C and a mean annual rainfall of 1900 mm (bimodal). The experiment started in November 1997 and the fallow phase concluded after 28 months (March 2000).

Soils in the area derived from volcanic-ash deposition and classified as an Oxic Dystropept in the USDA classification with predominant medium to fine textures, high fragility, low cohesion, and shallow humic layers. Soil bulk density is close to 0.8 $Mg.m^{-3}$. Soils are typically moderately acid (pH (H_2O) = 5.1), rich in soil organic matter (C = 50 mg g^{-1}), low base saturation (1.1 and 2.5 cmol kg^{-1} soil for Al and Ca, respectively) and with low P availability (Bray-II P = 4.6 mg kg^{-1}). Low soil P availability is the result of high allophane content (52-70 g kg^{-1}) which increases soil P sorbing capacity.

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

Glasshouse grown two-month old *Indigofera* and *Calliandra* plants, inoculated with rhizobium strains CIAT 5071 and CIAT 4910 respectively and a common *Acaulospora longura* mycorrhizal strain, were planted in the field at a 1.5 x 1.5 m spacing for treatments IND and CAL respectively. Tithonia cuttings were initially rooted in plastic bags before transplanting to the field using a 0.5 x 0.5 m spacing. At the beginning all planted fallows were kept clean from weeds to facilitate rapid establishment, thereafter, no additional weeding took place. The natural regeneration treatment, NAT, received no management at all and served as control since this is the common practice by local farmers once their soils have become unproductive. Treatments IND and CAL were pruned to 1.5 m height at 18 months after planting and weighed biomass was laid down on the soil surface. In TTH plants were pruned to 20 cm for a total of six times, starting six months after planting and weighed biomass laid on the soil surface. Whole plot measurement of biomass production during each pruning event was carried out and a composited subsample taken for laboratory analyses before laying down the pruned biomass on the soil surface. All above-ground biomass was harvested after 26 months with the conclusion of the fallow phase.

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

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

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

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

Separate samples were taken from each field replications to assess soil physical parameters at the end of the fallow period (i.e. 28 months). Bulk density was determined for every 5 cm soil depth by using 50 mm long cores with 50 mm internal diameter. Hydraulic conductivity was measured on undisturbed core samples using a constant head of water and 50×50 mm cylinders. Air permeability was determined by measuring the rate of air flowing in a core sample equilibrated at a suction of 7.5 KPa, using a Daiki DIK-5001 apparatus. Residual porosity was calculated as percentage of porosity remaining in the soil after subjecting it to a 20 KPa confined pressure (50×50 mm cylinder) at a suction equivalent to field capacity.

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

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

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

Results and Discussion:

Initial soil conditions: Experimental sites were of the same soil type and had a similar recent cropping history as stated above; nevertheless, they presented distinct differences in certain soil parameters probably as a result of differences in soil management. The experimental site for BM1 was more acid, had a lower soil total C and had higher total P and considerably higher Bray P and exchageable Al than the experimental site for BM2 (Table 12).

Table 12. Initial soil conditions for experimental sites in BM1 and BM2

	pH	C tot	N (mg kg^{-1})		P (mg kg^{-1})		Ca	K	Mg	Al
Experiment	(H_2O)	(mg kg^{-}	total	inorganic	total	Bray			(cmol kg^{-1})	
BM1	4.67	52674	4240	37.4	653.2	10.83	1.70	0.40	0.65	1.92
BM2	5.28	61741	4249	33.6	485.5	1.59	1.79	0.30	0.57	0.50

Biomass production: Total biomass production of different slash/mulch fallow systems evaluated was higher in BM1 than in BM2 independent of treatment (Fig. 15). In BM1 the order of total biomass production was TTH>IND,CAL>NAT, while in BM2 the order was CAL,IND>NAT. Published values for leguminous trees in different agroforestry systems indicate average annual additions of dry matter biomass up to 20 t.ha^{-1}.yr^{-1}. The highest total biomass production was 17.1 t.ha^{-1}yr^{-1} corresponded to *T. diversifolia* as a result of fast growth and ability to withstand coppicing about every three months. This value is comparable to the mean dry biomass production of 18.0 t.ha^{-1}yr^{-1} for Leucaena leucocephala and greater than the 11.3 t.ha^{-1}yr^{-1} reported for Senna siamea in alley cropping systems. The mean biomass production of C. calothyrsus was 10.2 t.ha^{-1}yr^{-1} and 9.4 t.ha^{-1}yr^{-1} for I. constricta. The natural fallow (NAT), which represents the traditional fallow practice by local farmers, showed the lowest mean annual biomass accumulation (4.3 t.ha^{-1}yr^{-1}). The difference observed in biomass production between IND and CAL as affected by experimental site suggests that I. constricta is more responsive to better soil conditions found in BM1 than C. calothyrsus while the latter is more tolerant to poorer soil conditions found in BM2. However, further multi-location testing of these species is needed to better define the environmental niches for these slash/mulch fallow species.

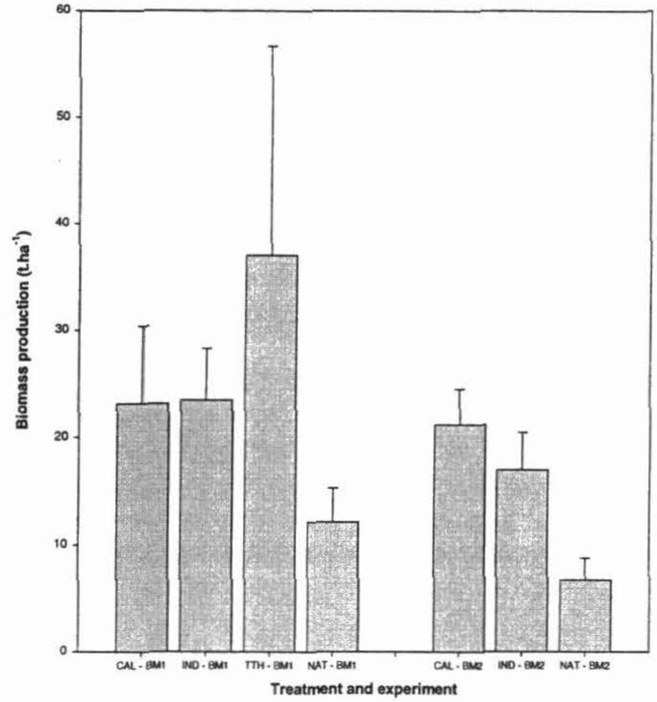

Figure 15. Biomass production by different fallow systems in BM1 and BM2

Amount of nutrients in the biomass: The relative additions of nutrients through slash/mulch fallow management expressed as percent of control (NAT) was generally highest in TTH for all nutrients except N (Table 13). Relative N additions were highest in BM2 for both CAL and IND compared to BM1. This is possibly a result of the considerably lower (i.e. 50%) total biomass production in NAT in BM2 compared to BM1, because actual N inputs values were similar for both species in both experiments (data not shown). Research on the impact of nutrient additions to the soil through the application of organic materials usually focus on N, increasingly P and least frequently on K, Ca or Mg. Nitrogen additions through prunings of L. leucocephala and S. siamea in alley cropping systems were shown to contribute 307 $kg.ha^{-1}$ and 197 $kg.ha^{-1}$ respectively. Nitrogen additions through slash/mulch systems TTH, IND and CAL in this study were 36%, 5% and 0.5% higher than for the L. leucocephala alley cropping systems mentioned above. Published values indicate that leguminous trees in alley cropping systems can add as much as 358 kg N, 28 kg P, 232 kg K, 144 kg Ca and 60 kg Mg per hectare. Nevertheless, nutrient availability is regulated to a large extent by the chemical composition or quality of plant tissues because they affect their rates of decomposition and nutrient release. All species used in this experiment have a N content greater than 2.5% which is considered the minimum concentration needed for N mineralization to occur. Nevertheless, while *T. diversifolia* and *I. constricta* decompose fast because of their low lignin and polyphenol contents and high in vitro digestibility (IVD), decomposition rates for C. calothyrsus are slower because of high lignin and polyphenol contents and low IVD.

Table 13. Differences in total nutrient additions by slash/mulch fallow systems compared to the natural fallow in BM1 and BM2.

		% of control (NAT)				
Experiment	Treatments	N	P	K	Ca	Mg
BM1	CAL	224	55.0	39.8	79.1	57.0
	IND	251	75.4	47.5	145	92.6
	TTH	302	478	584	424	361
BM2	CAL	606	120	138	269	311
	IND	608	164	199	507	540

Additional benefits from slash/mulch fallow systems include the contribution to soil nutrient pools from fine roots through root turnover and root dieback caused by pruning on above ground biomass. The importance of fine root and mycorrhiza turnover has generally been under emphasized as it has been shown in forest systems that they can contribute up to 4 times more N and up to ten times more P than aboveground litterfall. There is little information on the amount of nutrients supplied through roots in agroforestry systesms Root biomas of trees is usually between 20-50% of aboveground biomass giving shoot:root ratios ranging from 4:1 to 1.5:1, but the proportion of roots becomes higher on nutrient- and/or water-limited soils. Very high values of shoot to root ratios of 9:1 to 16:1 were observed for *T. diversifolia* depending on the method of establishment on BM1 experimental site.

One important difference between slash/mulch fallow systems and alley cropping/biomass transfer systems is that while the former presumably promotes soil nutrient availability through remobilization of nutrients from less available soil nutrient pools, the latter relies on nutrient transfer to crops from soil where alleys are grown leading to variable levels of nutrient mining and thus a constraint to their use.

Soil chemical parameters in slash/mulch planted fallow systems: Soil parameters showing significant differences among treatments included total N, available N (nitrate), exchangeable K, Mg and Al for BM1 and available N (amonium, nitrate), and exchangeable K and Ca for BM2 (Table 14). Significant differences for most parameters, however, occurred after 12 or 28 months. The only parameters showing consistent significance across fallow age were total N in BM1 and exchangeable K in both BM1 and BM2. Because of high spatial variability, which is the characteristic feature of these hillside soils, significant changes found are of considerable importance.

Treatment means are presented for total N, amonium, nitrate and exchangeable K, Ca, Mg and Al (Tables 15 and 16) because they were most affected by treatment (Table 16).
Total soil N was highest ($P < 0.05$) in TTH and CAL showed the second highest value after12 and 28 months of fallow duration (Table 14). After 12 months NAT presented the lowest total soil N while IND had the lowest soil total N at the end of the fallow period (28 months). The beneficial effects of *T. diversifolia* on soil nutrients observed in the present study confirm previous published results on P-fixing soils. The high ability to scavenge nutrients by *T. diversifolia* has been reported before. This may be a result of profuse rooting systems in association with native mycorrhizae as well as the possibility of associative N-fixation . *C. calothyrsus* and *I. constricta* are both N-fixers deriving respectively 37 and 42 % of their N from the atmosphere.

Table 14. Effects of four fallow systems on soil fertility parameters for plow layer (0-20 cm) at 12 and 28 months after establishment. Data were subjected to covariance analysis.

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

*Cov = Covariable; Treat = Treatment

After 12 months, slash/mulch fallow systems containing TTH showed the highest exchangeable K and lowest exchangeable Al ($P < 0.05$) in BM1 (Table 16). Studies in acid soils of Burundi have also found a reduction in exchangeable Al by green manure additions suggesting complexing of Al by organic materials. In BM2 highest exchangeable K and Ca values were found in IND and NAT respectively. At the end of the fallow phase (28 months), exchangeable K was highest for TTH overall, but the trend for the common treatments among BM1 and BM2 was the same with NAT and IND contributing significantly ($P < 0.05$) more than CAL. Exchangeable Mg in BM1 showed the same trend as K with the difference that the IND fallow system led to the lowest soil values. The high concentration of cations, especially K in *T. diversifolia* biomass (Table 16), and the pruning management in TTH is likely to be responsible for the highest contribution to soil exchangeable cations by this slash/mulch fallow system.

Table 15 Effect of fallow species on soil total N, amonium and nitrate after 12 and 28 months of fallow period[a].

		Fallow period				
		12 months			28 months	
Experiment	Treatment	Ntot (mg kg^{-1})	NH_4 (mg kg^{-1})	NO_3 (mg kg^{-1})	Ntot (mg kg^{-1})	NO_3 (mg kg^{-1})
BM1	TTH	4390	-	6.61	4913	-
	CAL	4366	-	7.42	4717	-
	IND	4008	-	12.6	4266	-
	NAT	3824	-	8.07	4683	-
	SED	*169*	-	*1.69*	*159*	-
BM2	CAL	-	18.9	-	-	22.9
	IND	-	14.6	-	-	32.2
	NAT	-	13.0	-	-	8.10
	SED	-	*0.96*	-	-	*4.54*

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

Table 16 Effect of fallow species on soil exchangeable cations after 12 and 28 months of fallow period[a].

Experiment	Treatment	Fallow Period									
		12 months						28 months			
		Al (cmol kg^{-1})		K (cmol kg^{-1})		Ca (cmol kg^{-1})		K (cmol kg^{-1})		Mg (cmol kg^{-1})	
BM1	TTH	1.24	b	0.54	a	-	-	0.60	a	0.67	a
	NAT	1.84	a	0.48	ab	-	-	0.49	ab	0.6	a
	IND	1.88	a	0.38	b	-	-	0.36	b	0.48	b
	CAL	1.49	ab	0.43	ab	-	-	0.34	b	0.53	ab
BM2	NAT	-	-	0.33	ab	2.32	a	0.38	a	-	-
	IND	-	-	0.39	a	2.19	b	0.36	a	-	-
	CAL	-	-	0.30	b	2.22	ab	0.29	b	-	-

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

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

Soil fractionation generally increases the capacity to detect soil changes in SOM as a result of treatment compared to bulk soil measures. Recent results focusing on active nutrient forms through soil organic matter (SOM) and P fractionation rather than conventional chemical analyses (e.g. BrayII P), indicate significant differences among treatments in experiment BM1 after 12 months (see activity 2.2.2). The slash/mulch fallow species in TTH, IND and CAL had an overall positive effect on soil fertility parameters when compared with natural unmanaged fallow (NAT). *T. diversifolia* showed the greatest potential to improve SOM, nutrient availability, and P cycling because of its ability to accumulate high amounts of nutrients. The amount of P in the light (LL) and medium (LM) fractions of SOM correlated well with the amount of "readily available" P in the soil. It is suggested that the amount of P in the LL and LM fractions of SOM could serve as sensitive indicators of "readily available" and "readily mineralizable" soil-P pools, respectively, in the volcanic-ash soils studied.

Soil physical parameters in slash/mulch planted fallow systems: Bulk density values reported for BM1 and BM2 in Table 17 are relatively low and are in agreement with published values for other volcanic ash soils. Significant differences ($P < 0.05$) after 28 months of four fallow systems were only found for the 0-5 cm soil depth of experiment BM2. While CAL and NAT were not different, IND showed signficantly higher bulk density values (Table 18). Increased bulk density observed could be the result of a decrease in SOM levels. Although SOM levels in IND were lowest but not statistically significant (data not shown) in BM2, significantly lowest ($P < 0.05$) total N values were found in IND compared to other system treatment for BM1 (Table 15). Since soil total C and soil total N are highly correlated we can assume that the I. constricta slash/mulch fallow generally promoted a reduction in SOM resulting in an increased soil bulk density.

Soil air permeability was sensitive to treatment differences in BM1 (Table 17). This parameter measures the resistance of soil to air flow and is associated to bulk density and hydraulic conductivity. While TTH showed the highest values, CAL and NAT showed intermediate values and IND the lowest values (Table

18). These results indicate that TTH improved structural stability of surface soil presumably as a result of changes in pore size distribution which allowed better air flow while IND led to an increase in resistance to air flow than the control NAT

Table 17. Probability table for effect of four fallow treatments on soil physical parameters in BM1 and BM2 after 28 months.

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

Soil macrofauna in slash/mulch planted fallow systems: The characterization of the soil macrofauna communities after 28 months of slash/much fallow treatments showed taxonomically and functionally diverse taxa. A total of 22 taxonomic units (TU) were found. Macro-invertebrate total density ranged from 94.2 individuals (ind.) per sampling unit (s.u. = soil monolith: 25x25x30 cm^3) in TTH to 76.2 ind./s.u. in CAL. Conversely, macro-invertebrate biomass ranged from 4.54 g/s.u. in IND to 1.53 g in TTH (Fig. 16). Other invertebrates corresponded to some nematodes, hemipterans (sucker beetles), snails (Gastropoda) and grasshoppers (Orthoptera). Termites were almost absent from all fallow treatments being less than 1% of total macro-fauna abundance.

Table 18. Effect of four fallow treatments on soil bulk density and air permeability at 0-5 cm soil depth in BM1 and BM2 after 28 months.

	Experiment	
	BM2	BM1
Treatment	Bulk density ($Mg.m^{-3}$)	Air permeability ($cm.h^{-1}$)
CAL	0.70	50.5
IND	0.80	33.8
NAT	0.69	64.7
TTH	-	91.6
SED	*0.06*	*30.9*

The main groups of soil macro-invertebrates were rather abundant, especially ants. The abundance of ants, comprised of several species, was highest in TTH (63.7 individuals/ s.u.) and lower in IND and NAT (44 ind./s.u.). Earthworm density was lowest in TTH (4.8 ind./s.u.) and highest in IND (26.7 ind./s.u.). These two taxa were the main components of total macro-invertebrate biomass in all systems ranging from 46.9% in TTH to 73.1% in IND in the case of earthworm biomass. We found exotic earthworm species that are normally found when tropical natural ecosystems are replaced by different production systems, i.e. Pontoscolex corethrurus (Glossoscolecidae), which in some Amazonian agroecosystems has a negative effect on soil properties, mainly due to the loss of the original earthworm diversity rather than to the mere presence of this earthworm. Larva of beetles (Coleoptera) were also highly abundant and their biomass was lowest in IND (19.7 g/s.u.) and highest in TTH (30.2 g/s.u.).

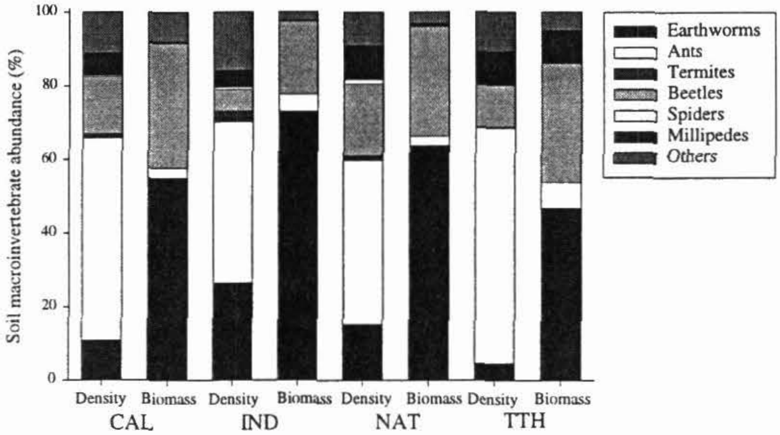

Figure 16. Density and biomass of soil macroinvertebrate communities in the slash/mulch fallow systems studied.

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

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

Impact:
The focus of our efforts is on systems of accelerated regeneration of soil fertility, or improved fallow systems, as an alternative to the natural regeneration by the native flora. Slash/mulch planted fallows

systems evaluated in this study were more productive in terms of greater biomass production and nutrient recycling than the traditional practice of natural regeneration by native flora suggesting that the objective of increased nutrient recycling was achieved. This study attempted to integrate the impacts of slash/mulch planted fallow systems on soil quality by simultaneously evaluating the biological, chemical and physical dimensions of the soil. The TTH slash/mulch fallow system proved to be the best option to recover the overall soil fertility of degraded soils following cassava monocropping. Nevertheless, its use may be restricted to areas with seasonal drought as it is not very tolerant to extended dry periods. The CAL slash/mulch fallow system proved to be the most resilient as it produced similar amounts of biomass independently of initial soil quality and thus has the potential for wider testing as a potential source of nutrient additions to the soil and fuelwood for rural communities. The slower rates of decomposition in CAL, compared to IND and TTH, suggests that benefits provided would be longer lasting and potential losses would be reduced through a greater synchronization between nutrient availability and crop demand. The IND slash/mulch fallow, on the other hand, showed more susceptibility to initial soil quality and this may limit its potential for extended use. Increased soil bulk density as a result of decrease in SOM was possibly mediated by the presence of large populations of endogeic earthworms. Additionally, the decrease in total soil N and increased N availability by slash/mulch planted fallows using this species suggests that the process of mineralization is greatly accelerated. This is consistent with the observation of increased soil bulk density values in this treatment containing large density of earthworm species, *P. corethrurus,* known to stimulate N mineralization and responsible for soil compaction when a diverse earthworm community capable to ameliorate soil physical structure is absent. Although increased available N may be apparently a good short term impact, the significant decrease in total soil N suggest that considerable N losses may be occurring during the fallow phase and benefits to crops subsequent cropping could be limited. Further multilocation testing is needed to confirm these observations.

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2.2.2 Potential of *Tithonia diversifolia* to enhance phosphorus mineralization and cycling

Highlight:

- Assembled a germplasm collection of 20 provenances of *Tithonia diversifolia* from different parts of the tropics and showed that this shrub grows on a wide range of soils with low as well as high P availability in soil.

Purpose:
To discover how variable phosphorus (P) uptake and accumulation are in *Tithonia diversifolia* with respect to plant germplasm across its naturalised range, soil conditions and mycorrhizal infection in order to define the extrapolatable domain for its use as a green manure.

Rationale:
Phosphorus (P) depletion of soils, limiting yields of staple food crops, is a major problem across the tropics. A lot of P is exported in harvested grain, it cannot be fixed biologically and typically a high proportion of soil P is unavailable to crops. DFID, UK has funded a joint proposal of University of Wales (Bangor), CATIE. ICRAF and CIAT entitled "Potential of *Tithonia diversifolia* to enhance phosphorus mineralization and cycling". It was intended to discover how variable phosphorus (P) uptake and accumulation are in *Tithonia diversifolia* with respect to plant germplasm across its naturalised range, soil conditions and mycorrhizal infection to define the extrapolatable domain for its use as a green manure. *Tithonia diversifolia* leaves are high in P even where soils have a low available P content, suggesting that organic P is mineralized by the plant.

Tithonia diversifolia is a shrub of the Asteraceae family, widespread in the tropics, growing 1 m to 3 m in height. It is often found along field and farm boundaries and roads and occurs in indigenous fallow systems. It produces large quantities of leaf biomass with a high nutrient content and tolerates regular pruning. It has long been recognised as an effective green manure for lowland rice. Awareness and expectations of its use as a fertilizer have recently been raised as a result of research in the highlands of western Kenya by KARI, KEFRI, ICRAF and TSBF. Foliar biomass imported onto fields was found to be an effective source of nutrients for maize, supplying as much N, P and K as an equivalent amount of commercial compound fertilizer and in some cases yields were higher with *T. diversifolia* than with inorganic fertilizers although it is not known why. It has also been found to be an effective source of nutrients for vegetables and farmers in Kenya prefer to use it on higher value crops rather than maize. Experience in Africa suggests that farmers find niches to grow *T. diversifolia* hedges on farm, particularly along field boundaries and contours.

Results and Discussion:

Provenance collection activities - areas where collections have been carried out:

CATIE: Mexico, Honduras, Nicaragua, Costa Rica
CIAT: Colombia, Venezuela and Ecuador
ICRAF (Kenya): Kenya, Uganda, Rwanda
ICRAF (Indonesia): Indonesia, Philippines, Thailand

In addition, *Tithonia* material from Nepal has been collected (collected as part of a related project PSP R7154). Plant material has been sent to CIAT, CATIE and Bangor for centralised field and pot trials

Bangor (UK): Tithonia root material from Costa Rica was subjected to laboratory-based mycorrhizal analysis. No ectomycorrhizal infections were found but there was a high level of arbuscular colonisation. A protocol was drawn up to determine the genetic diversity in *Tithonia diversifolia* plants from South Africa, Costa Rica and Colombia using RAPD-PCR (Random Amplified Polymorphic DNA – Polymerase Chain Reaction) which generates a genomic DNA fingerprint. This protocol will be used to identify the VAM fungi at family level. A new suite of controlled environmental experiments were initiated to investigate the efficiency of *Tithonia* roots at acquiring different sources of P from the soil, with and without mycorrhizal assistance, using compartmentalised growth boxes and radio-labelled P.

CATIE (Costa Rica): A living collection of *Tithonia* germplasm from 5 provenances (San Pablo, Costa Rica; Matagalpa, Nicaragua; Valle de Angeles, Honduras; Simojovel and Tapachula from Chiapas State, Mexico) was established. The collection is still at the multiplication stage. Germination seed tests indicated that *T. diversifolia* seeds have a degee of dormancy and/or low viability. Vegetative propagation by leafy stem cuttings in a shaded, non-mist propagator was more successful for propagating the collection.

ICRAF (Kenya): A student from Moi University in Kenya initiated pot trials to assess the variations in P acquisition by *Tithonia* as affected by soil type.

ICRAF (Indonesia): Pot trials at Brawijaya University assessing the value of above and belowground biomass of *Tithonia* for subsequent maize growth are in progress.

CIAT (Colombia): Soil and plant samples from CATIE's collection sites from Central America, ICRAF's collection sites from Indonesia were delivered to CIAT for analysis. Those samples together with the samples collected from Venezuela and Colombia by CIAT were analyzed at CIAT analytical laboratory. Sequential P fractionation of soil indicated that pools of available and total P were lower for the site in Indonesia than that of the other sites. But the proportion of organic P to total P was greater at this site than that of the other sites. Nutrient status of the plant samples collected from different sites indicated that *Tithonia* accumulates large amounts of nutrients, particularly P from the site Tapachula-Chiapas in Mexico.

CIAT's work on soil and plant analysis from different germplasm collection sites indicated that this shrub grows on a wide range of soils with low as well as high P availability in soil. Furthermore, there is a great genetic diversity in accumulation of not only P but also other major nutrients in its biomass. These data showed a positive relationship between available P in soil (Resin method) and content of P in leaves.

A living collection of *Tithonia diversifolia* germplasm from 3 provenances, two from Venezuela (VEN-TAP, VEN-ORI) and one from Columbia (COL-CEM) has been established at CIAT for multiplication purposes.

Impact:
Significant progress is made especially for collection of 20 provenances of *Tithonia diversifolia* from different parts of the tropics. The group from ICRAF has collected 10 provenances from Kenya, Uganda, Rwanda, Indonesia, Phillippines and Vietnam. The experience of ICRAF in Africa and Asia has been very positive for its use as green manure but not as improved fallow. CATIE group has collected 5 provenances from Mexico, Honduras, Nicaragua and Costa Rica. CIAT group collected 5 provenances from Colombia, Venezuela and Ecuador. CIAT's work on soil and plant analysis from different germplasm collection sites indicated that this shrub grows on a wide range of soils with low as well as high P availability in soil. Furthermore, there is a great genetic diversity in accumulation of not only P but also other major nutrients in its biomass. These data indicated a positive relationship between available P in soil (Resin method) and content of P in leaves. Further research is needed to assess genetic variation in nutrient accumulation and nutrient cycling potential of this species when grown in contrasting soil fertility conditions. It is critical to continue the ongoing *Tithonia* work in Cauca and to establish a field trial at CIAT-Palmira to evaluate the potential of this species as biofertilizer to tropical soils.

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2.2.3 Determine the impact of planted fallows and a crop rotation on soil organic matter and phosphorus fractions in volcanic-ash soil of hillsides

Highlight:
- Showed that *Tithonia diversifolia* has the greatest potential to improve soil organic matter, nutrient availability, and phosphorus cycling as improved fallow because of its ability to accumulate high amounts of nutrients.

Purpose:
To determine the impact of planted fallows and a crop rotation on the dynamics and partitioning of soil organic matter and phosphorus in volcanic-ash soil of Andean hillsides.

Rationale:
In the tropics, leaving land as natural fallow has traditionally been used to overcome soil fertility depletion resulting from continuous cropping. In the mid-altitude hillsides of the Colombian Andes, agriculture is typically based on fallow/rotation systems in which forest or bush fallow is cleared for cropping with annuals or perennials. One alternative for poor farmers is to manage short-term fallow systems with

planted herbaceous or woody legumes ("improved fallows") that replenish soil nutrient stocks faster than plants in natural succession. These short-term planted fallows can restore soil fertility in soils with limited nitrogen (N) and/or phosphorus (P) by enhancing nutrient recycling through the provision of soil organic matter (SOM).

Although the organic inputs usually cannot provide sufficient P for crop growth, because of low tissue concentrations, organic inputs can increase P availability in P-fixing soils. Organic anions formed by decomposing organic inputs can compete with P for the same adsorption sites and thereby increase P availability in soil to allow a more complete use of soil P by plants. The dynamics of SOM in natural and managed ecosystems are important because SOM can affect nutrient cycling, influence soil structure, and play a significant role in the biological function of the soil. Soil organic matter controls the interaction between soil processes and plant production, and explains why certain systems of land management perform well whereas others degrade.

The volcanic-ash soils of the Colombian Andes usually contain high amounts of SOM. However, these soils have limited nutrient cycling through SOM because most of it is strongly bound and chemically protected by mineral particles. The rate of decomposition is thus limited and, consequently, so is nutrient cycling. In addition, these volcanic-ash soils have high P deficiencies, resulting from their allophane-rich content, which gives them a high P-sorbing capacity.

Quantitative analysis of SOM fractions is especially important for understanding SOM dynamics for managed systems. Our ability to improve management of cropping systems for sustained production is partly dependent on our understanding how different organic fractions are affected by management systems and how they relate to changes in the soil's nutrient-supply capacity. We therefore need to understand organic matter management intervention practices, which minimize P flows out of the cycle (through "fixation" reactions) and maximize P flows through dynamic pools that can be accessed by plant roots and mycorrhizae.

The objective of our study was to determine the effect of contrasting planted fallows (*Indigofera*, *Calliandra*, and *Tithonia*), a natural unmanaged fallow, and a maize/bean rotation on the dynamics and partitioning of SOM and P.

Materials and Methods:

Site description and experimental design: Our study was carried out in an improved-fallow-systems experiment at CIAT's "San Isidro" experiment farm in Pescador, located in the Andean hillsides of the Department of Cauca, southwestern Colombia at 1505 m above sea level. The area presents a mean temperature of 19.3°C and a mean annual rainfall of 1900 mm (bimodal). The experiment was carried out during the first rainy season (April–August) of 1998. The experimental plot crop history included 3 years under continuous cassava cultivation. The plots were on a slope of about 30%.

The soil's characteristics include pH (H_2O) = 5.1, 50 mg g^{-1} C, 3 mg g^{-1} N, 4.6 mg kg^{-1} soil of Bray-II P, and 1.1 and 2.5 cmol kg^{-1} soil for Al and Ca, respectively. The soil is derived from volcanic-ash deposition and is an Oxic Dystropept (Inceptisol) in the USDA soil classification system and an Andic Dystric Cambisol in the FAO classification. It has a medium to fine texture (45% sand, 27% silt, and 38% clay) of high fragility, low cohesion, and with shallow humic layers. The estimated soil bulk density in the area is 0.8 g cm^{-3}. Availability of P in the soil is low because of its richness in allophanes (52-70 g kg^{-1}), which increase its P-sorbing capacity.

The treatments we used were (i and ii) two leguminous tree fallows *Indigofera constricta* Rydb. (IND) and *Calliandra calothyrsus* Meissn. (CAL); and (iii) a shrubby fallow *Tithonia diversifolia* (Hems.) Gray (TTH). These were compared with (iv) a maize/bean rotation (ROT) and (v) a natural fallow (NAT), where the vegetation was left to regrow naturally without cultivation. The experimental design was a randomized complete block (RCB) design with three replicates. Plot size was 18 × 9 m. The chemical composition of plants used as improved fallows was reported last year (PE-2 Annual Report, 1999).

Soil sampling and analytical procedures: Soil samples were collected in November 1997 at the start of the experiment (0-10 and 10-20 cm soil layers) and in November 1998, one year after the fallows and rotational crops were planted (0-5, 5-10, 10-20 cm). Plant litter on the soil surface was gently removed before collecting the soil samples. A composite sample, consisting of 50 cores, was collected in a grid pattern from within the 18 × 9 m plots. Samples from each plot were air-dried, visible plant roots removed, and the samples gently crushed to pass through a 2-mm sieve. The <2-mm fraction was used for subsequent chemical analyses and size-density fractionation of SOM.

Size-density fractionation of SOM, in the sand-size fraction (150-to-2000-µm), was conducted with density separation done in reverse order. Because of the high SOM levels in this soil, we found working with the 500-g-soil-sample difficult for the SOM fractionation. We therefore reduced the soil sample to 250 g.

Phosphorus fractionation and analysis: A reduced (excluding acid extractants) sequential P fractionation with minor modifications, was carried out on 0.5-g sieved (2-mm) soil samples. In brief, a sequence of extractants with increasing strength was applied to subdivide the total soil-P into inorganic (P_i) and organic (P_o) fractions. Organic P was calculated as the difference between total P and P_i in the $NaHCO_3$ and NaOH extracts, respectively. Total soil-P was determined by the $HClO_4$ digestion method. Inorganic P concentrations in all the digests and extracts were measured colorimetrically by the molybdate-ascorbic acid method. All laboratory analyses were conducted in duplicate.

Statistical analysis and data presentation: 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 differences occurred, least-significant-difference (LSD) analysis was performed to permit separation of means. Correlation and regression analyses were performed, using treatment means. Unless otherwise stated, mention of statistical significance refers to $\alpha = 0.05$.

Results and Discussion:

Soil parameters: Soil K, Ca, Mg, and total N levels were particularly improved by the TTH improved fallow, followed by those of IND and CAL (Table 19). *Tithonia* also considerably reduced the level of exchangeable aluminum (Al) in soil to about half the amount in other treatments, thereby reducing potential Al toxicity problems for crops following the fallow phase. The amount of N in the LL and LM SOM fractions and soil NH_4 nitrogen were particularly reduced in the natural fallow, whereas the improved fallows, especially *Tithonia*, showed less reduction in these parameters (Table 20; Fig. 17). These effects can be attributed to the quantity and chemical composition of the recycled fallow residues in the treatments compared. The beneficial effects of *Tithonia* on soil nutrients observed in the present study confirm previous published results on P-fixing soils. It was reported that *Tithonia* green biomass was at least as effective in supplying N, P, and K to maize as an equivalent amount of commercial N-P-K fertilizer and, in some cases, maize yields were higher with the *Tithonia* biomass than with the application of commercial inorganic fertilizers.

SOM fractionation: Soil organic matter contains fractions with rapid and slower turnover rates. The fractions with a rapid turnover (active fractions) are assumed to play a dominant role in soil nutrient dynamics. Using a density fractionation procedure, we recovered three SOM fractions. The weight of SOM fractions decreased in the order LL>LM>LH, which, in the 0-5 cm soil layer, had, on average, 5.2, 3.4, and 0.9 g kg^{-1} (soil) representing 55%, 36%, and 9% of the sum of all SOM fractions, respectively

(Fig. 17). The light fraction (LL), which is more sensitive to differences in management than is total SOM, on average, accounted for 54%, 47%, and 40% of the total SOM fraction in the 0-5, 5-10, and 10-20 cm soil layers, respectively. Profile distribution of LL decreased by 60% and 30% from the 0-5 to 5-10 and from the 5-10 to 10-20 cm, respectively (Fig. 17). The mean amount of C, N, and P in the LL accounted for 3.8%, 1.7%, and 1.3% C; 2.3%, 1.0%, and 0.6% N; and 0.7%, 0.3%, and 0.2% P of the total soil C, N, and P in the 0-5, 5-10, and 10-20 cm soil layers, respectively. Although significant effects of land use were not detected in the 0-5 cm soil layer, the dry weight, C, N, and P contents for LL followed the trend of TTH>CAL>NAT>ROT>IND (Fig. 17). The LM fraction accounted for 36%, 40%, and 45% of the total SOM fraction at 0-5, 5-10, and 10-20 cm, respectively. This fraction represented 2.1%, 1.1%, and 0.8% of total C; 1.4%, 0.6%, and 0.5% of total N; and 0.5%, 0.3%, and 0.3% of total P in the three soil layers (0-5, 5-10, and 10-20 cm), respectively. All the measured parameters for this fraction (dry weight, C, N, and P contents) were significantly affected by land use and, in the 0-5 cm soil layer, they followed the trend of CAL>TTH>IND>NAT>ROT. The low amounts of C, N, and P in LM in ROT may partly have resulted from continuous cultivation in this treatment, because tillage can lead to reductions in organically bound nutrients through mineralization.

In the 5-10 cm layer, each of CAL and TTH significantly differed from NAT and IND. These differences can be attributed to the high biomass production from TTH and CAL, compared with that of NAT and IND. The LH fraction contributed a very small percentage of the total SOM, and none of the measured parameters were affected by change in land use (Fig. 17). This observation is consistent with other published data, which indicated that changes in land-use system may not affect the heavy-fraction SOM weight and amount of N. This may be attributed to the fact that SOM tends to be more homogenous as it decreases in size and increases in density as it decomposes. These results indicate that the LH fraction of SOM plays an insignificant role in nutrient recycling.

P fractionation

Biologically available P (H_2O-P_o, resin-P_i, and $NaHCO_3$ P_i, and P_o): The resin and bicarbonate P_i are considered as "readily available" for plant uptake, because the chemical extractants used to extract them represent, to some degree, root activity. This fraction consists of labile P_i and represents soil solution P, soluble phosphates originating from calcium phosphates, and weakly adsorbed P_i on the surfaces of sesquioxides or carbonates. The planted fallow and crop rotation systems had little effect on the "readily available" P fraction, which was fairly uniform across treatments and accounted for only 0.04% of the total soil-P. Resin-P_i showed a sharp decrease with increasing soil depth (Fig. 18). The H_2O-P_o and bicarbonate-P_o are considered "readily mineralizable" and highly related to P uptake by plants and are known to contribute to plant-available P. This P_o fraction includes nucleic acid-P, sugar-P, lipid-P, phytins, and other high-molecular-weight P compounds. The "readily mineralizable" H_2O P_o was more or less uniform across treatments and represented only a small fraction of total soil P (Fig. 18). Bicarbonate "readily mineralizable" $P_{o,}$, which is considered relatively labile and actively cycling, was 56% of the total $NaHCO_3$-extractable P. A comparison of NAT with the other treatments showed that bicarbonate P_o was significantly different in the former and, on average, 8% lower in the 0-5 and 5-10 cm layers (Fig. 18).

Organic P is known to be sensitive to microbial activity and has a fast turnover. This is because 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. On average, the "biologically available" P represented only about 1% of the total soil P. This is expected, because these volcanic-ash soils are known to have very high total P but little in the plant-available form. Most of the P is strongly bound and chemically protected by mineral particles, which limit the rate of its decomposition and that of nutrient cycling.

Moderately resistant P (NaOH extractable P): Hydroxide-extractable P_i is less available to plants and is thought to be associated with humic compounds, and amorphous and some crystalline Al and Fe phosphates. Sodium hydroxide (0.1 *M*, pH = 8.5) is known to solubilize completely the synthetic iron and aluminum phosphate and labile-P_o. Compared with other P fractions, of the plant-available P, the largest proportion was recovered in the NaOH fraction, which, in its turn, accounted, on average, for 53% of the total soil-P. Of this, 47% was in the organic form. The large amount of P recovered from this fraction can be attributed to the high contents of exchangeable Al and Fe associated with these volcanic-ash soils. TTH, for all soil layers, had slightly but consistently higher NaOH-extractable P (Fig. 18). All the improved fallow species and ROT had a similar effect over the NAT, which, on average, had 70% and 75% less P_i and P_o, respectively, in the 0-5 cm layer. The P_o contribution to the NaOH fraction by the planted fallows is desirable because the hydroxide-P_o fraction is usually more stable and may represent a relatively active pool of P in tropical soils under cultivation, especially those that are not receiving mineral P fertilizers.

Organic P fraction: The sum of P_o fraction was about the same for all the fallow species and the maize/bean rotation, and significantly different from only NAT. This last treatment had, in the 0-5 cm layer, 25% of the total P_o, compared with an average of 31% for the other treatments (Fig. 18). The increase of total P_o by fallow species, especially *Tithonia*, is desirable because P maintained in organic pools may be better protected from loss through fixation than P flowing through inorganic pools in soil. Loss of P from systems occurs mainly through processes in the soil, and as such minimizing P interaction with the soil is an important management tool for increasing P cycling. This could be particularly important for volcanic-ash soils with a high P-sorbing capacity resulting from their high allophane content.

Residual P: The residue after the NaOH step was digested with perchloric acid to obtain insoluble P_i and more stable P_o forms (or "residual P"). In general, the planted fallows and the crop rotation system had little effect on residual P (Fig. 18). It did not differ significantly among treatments and its proportion of the total soil-P ranged from 37% under TTH and CAL to 42% under NAT. The absence of treatment effects in this fraction is understandable as this fraction is mainly composed of stable humus fraction and highly insoluble P_i forms. The residual P content was related more to the nature of the soil than to the treatments. Our results thus indicate that short-term contributions of P from organic sources (planted fallows) are not readily incorporated into this fraction.

C/N, C/P, and N/P ratios: The TTH fallow had a significant lower soil C/N ratio than did the NAT in the two lower layers. Neither the soil C/P nor the soil N/P ratio was affected by the fallows and cropping system (Table 20). In contrast, the C/N, C/P, and N/P ratios of the SOM fractions were significantly affected by treatment and the ratios increased with soil depth. On average, the highest C/N ratios were found under NAT and the lowest ratios under TTH. Slower decomposition of organic residues is likely to take place in the natural fallow because of the higher C/N of the biomass in this treatment than the rest. The C/P ratios were generally high in the NAT and CAL treatments, whereas they were low in the TTH treatment (Table 20). On average, ROT and TTH had lower N/P ratios than the other treatments. The lower C/N, C/P, and N/P ratios of the SOM fractions under TTH, compared with NAT, reflect the high-quality leaf litter of the former treatment. The low C/P ratio under TTH may indicate favorable conditions for enhanced P availability. Phosphorus release from *Tithonia* green biomass is known to be rapid, and that, for the equivalent amount of P, *Tithonia* supplies plant-available P at least as effectively as a soluble fertilizer. The labile soil-P, as determined by anion exchange resin, is known to be comparable after adding *Tithonia* green biomass and triple superphosphate at equal P rates. This could explain the high amounts of $NaHCO_3$ and NaOH soil-extractable P_i and P_o observed under TTH.

Results obtained for soil P_o and P_i extracted by $NaHCO_3$ and NaOH were correlated with the P content in the LL and LM fractions of SOM to explore potential relationships among them. Both $NaHCO_3$-extractable P_o and P_i correlated significantly with P content in LL and LM fractions of SOM (Fig. 19). Coefficients of determination for linear regression between $NaHCO_3$-extractable P_i and P_o and the content of P in LL and LM fraction were found significant, and they show that the P content in LM fraction is an important factor in determining the amounts of $NaHCO_3$-extractable P_i and P_o. The regression equations are as follows:

$$NaHCO_3\text{-}P_i = 23.6 + 0.51\ (P \text{ in LL}) + 1.93\ (P \text{ in LM}) \quad R^2 = 0.47 \quad (P = 0.031)$$

$$NaHCO_3\text{-}P_o = 16.3 + 0.66\ (P \text{ in LL}) + 1.73\ (P \text{ in LM}) \quad R^2 = 0.44 \quad (P = 0.023)$$

These relationships suggests that systems including plant species that accumulate high amounts of P in their biomass, such as *Tithonia*, when used as fallow species, would increase both the "readily available" ($NaHCO_3$-P_i) and the "readily mineralizable" ($NaHCO_3$-P_o) P in the soil.

The NaOH-extractable P_o and P_i were not significantly related to P content in LL and LM fractions. This was also the case for the amount of inorganic N (NO_3 and NH_4) in the soil and the N content of the LL and LM fractions of SOM in this P-limited soil.

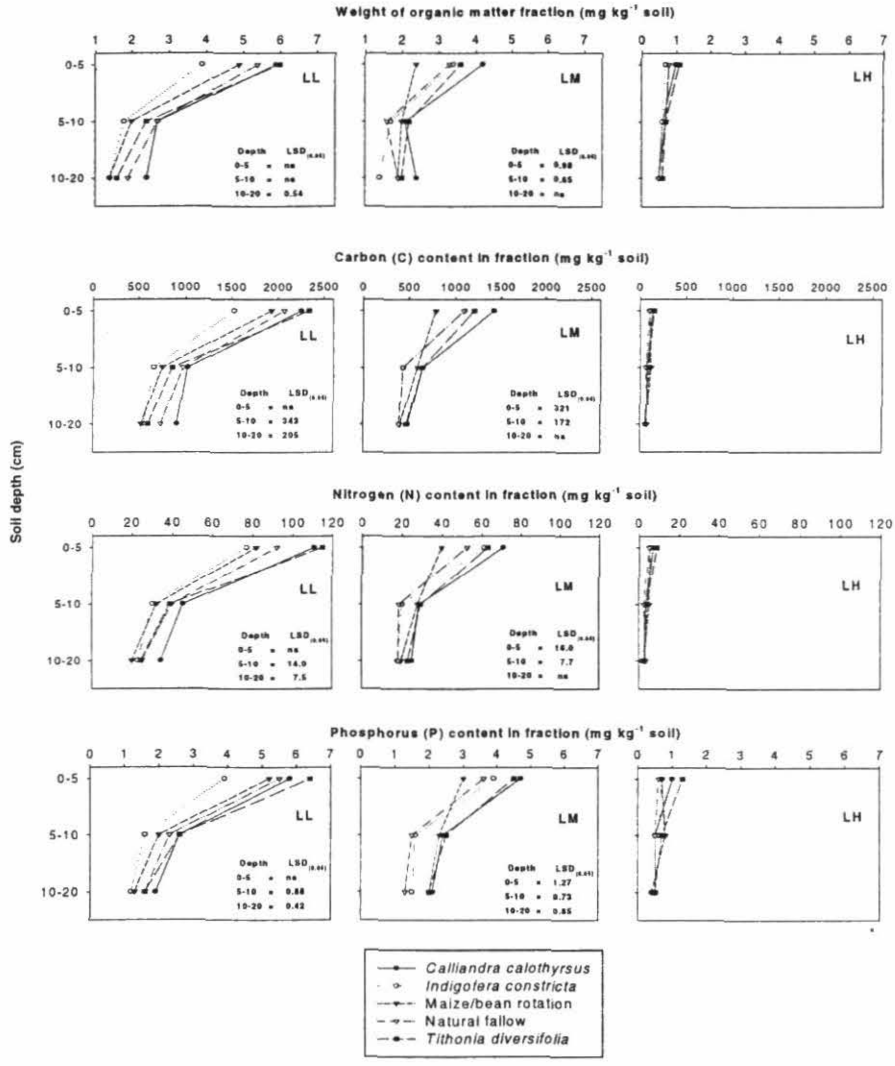

Figure 17.. Profile weight distribution of light (LL), intermediate (LM), and heavy (LH) fractions of soil organic matter (SOM) and their C, N, and P contents as affected by different fallows and the crop rotation system. LSD values are presented only when the differences among treatments are significant.

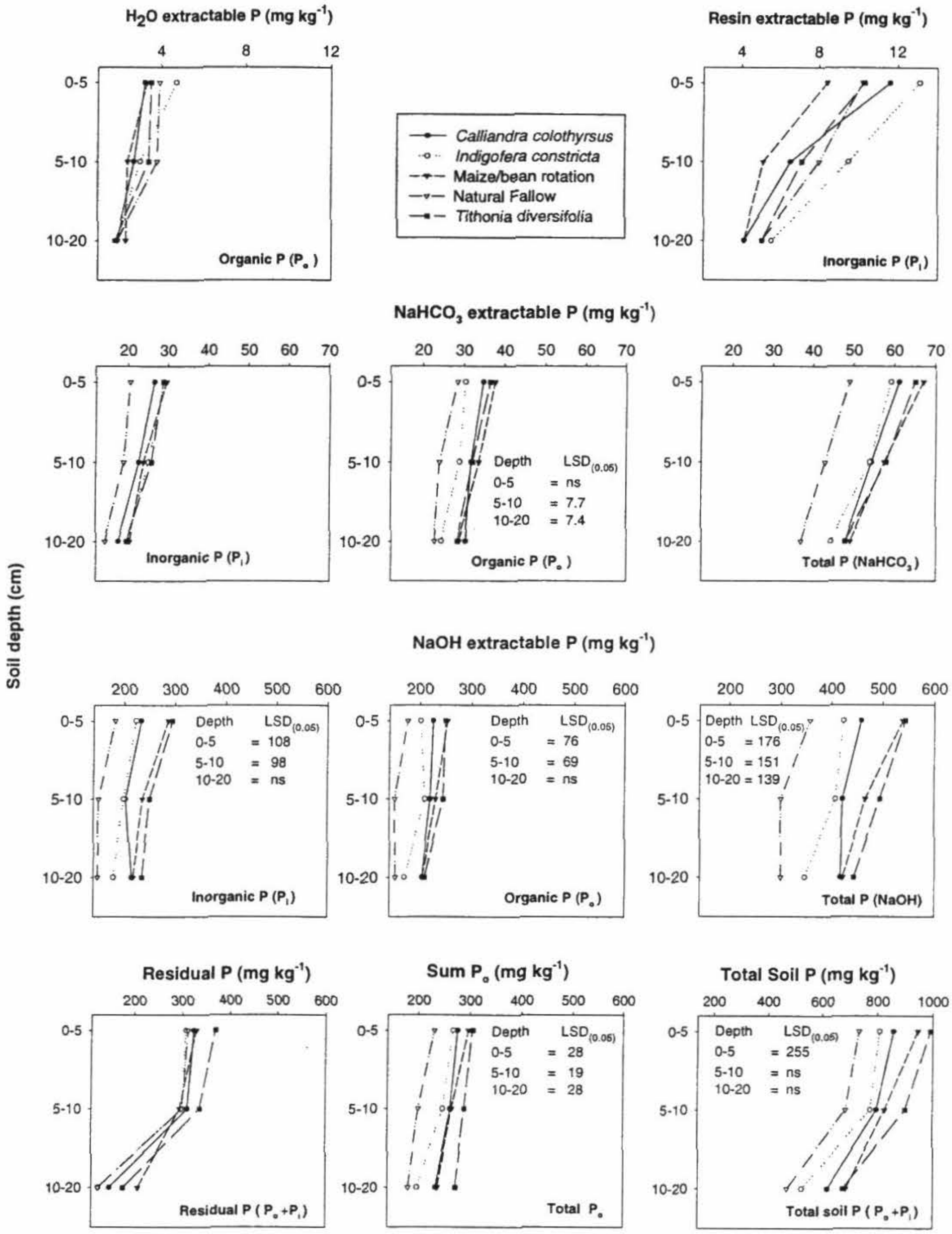

Figure 18. Profile distribution of selected soil-P fractions as affected by different fallows and the crop rotation system. LSD values are presented only when the differences among treatments are significant. LL, LM, and LH = light, intermediate, and heavy fractions of soil organic matter, respectively.

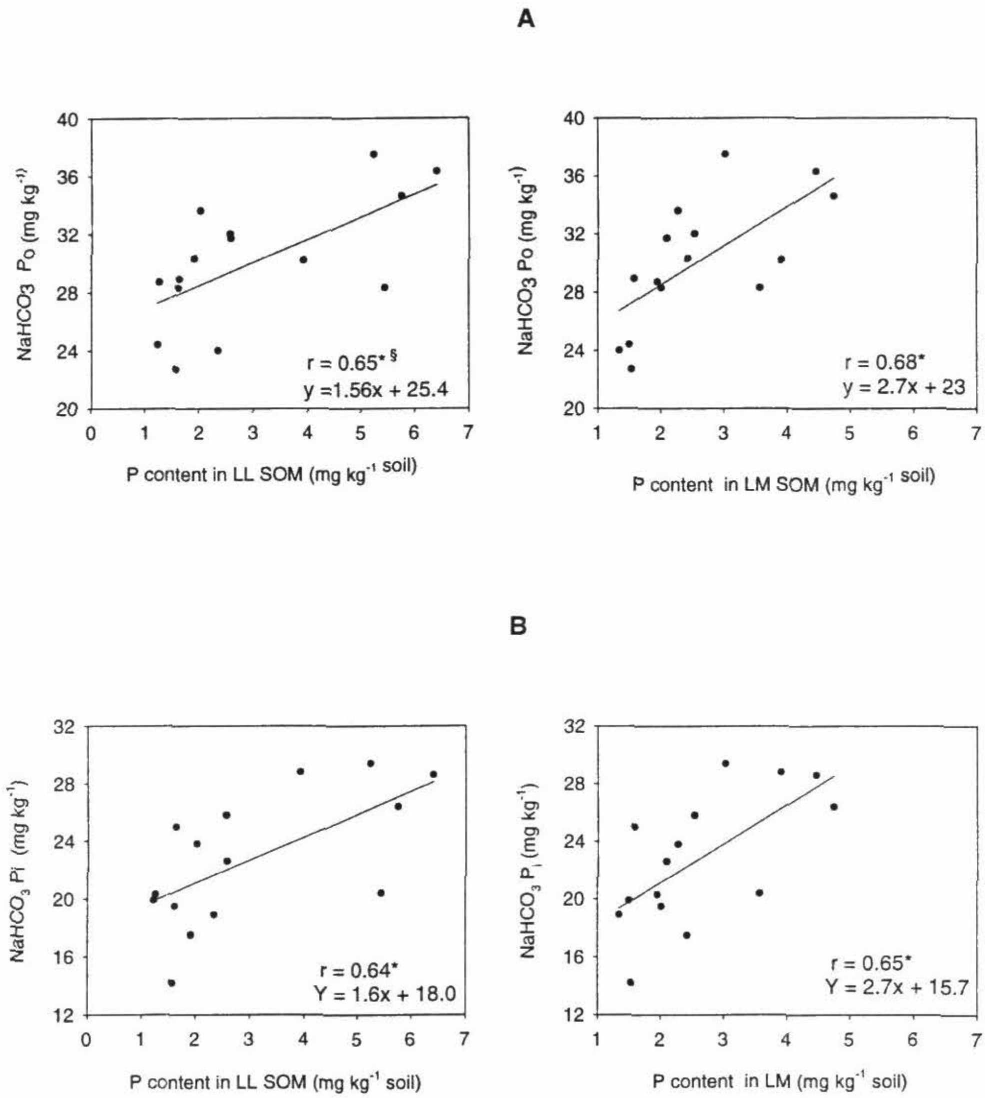

Figure 19. The relationship between P content in the light (LL) and intermediate (LM) soil organic matter (SOM) fractions and sodium bicarbonate ($NaHCO_3$) extractable organic P (A) and inorganic P (B). The asterisk (*) indicates significance at $\alpha = 0.05$.

Table 19. Soil characteristics as affected by different fallows and a crop rotation system at one year after establishment.

Soil depth (cm)	Fallow species or Cropping system	Carbon (Total) -g kg⁻¹-	Nitrogen (Total)	Nitrogen (NH_4)	Nitrogen (NO_3)	Phosphorus (Total)	Phosphorus (Bray-II)	B	Zn	Ca	K	Mg	Al
		$g\ kg^{-1}$	$mg\ kg^{-1}$							$cmol\ kg^{-1}$			
0-5	*Calliandra calothyrsus*	53.8	4172	25	11.8	761	11.1	0.3	3.1	2.7	0.56	1.1	1.4
0-5	*Indigofera constricta*	53.5	4022	21	19.5	754	13.3	0.3	2.7	2.8	0.60	1.1	1.5
0-5	Maize/bean rotation	57.0	4281	16	21.8	784	11.1	0.3	2.4	3.1	0.59	1.1	1.0
0-5	Natural fallow	50.1	3684	18	8.9	673	9.0	0.3	3.1	2.1	0.48	1.0	1.3
0-5	*Tithonia diversifolia*	55.4	4518	25	9.2	837	11.2	0.6	3.0	4.0	1.23	2.0	0.5
$LSD_{(0.05)}$		4.6	785	ns	7.01	127	ns	0.14	0.58	1.31	0.44	0.75	0.52
5-10	*Calliandra calothyrsus*	51.5	4004	26	6.2	729	8.0	0.3	3.1	1.9	0.33	0.7	1.9
5-10	*Indigofera constricta*	51.7	3875	23	13.1	730	11.1	0.2	2.4	1.9	0.41	0.8	1.9
5-10	Maize/bean rotation	55.5	4257	14	15.4	835	8.2	0.3	2.1	2.2	0.38	0.7	1.7
5-10	Natural fallow	44.6	3163	16	5.5	603	7.5	0.2	2.9	1.4	0.25	0.6	2.4
5-10	*Tithonia diversifolia*	53.5	4426	27	6.1	893	8.9	0.3	2.9	3.0	0.62	1.4	1.0
$LSD_{(0.05)}$		5.2	802	ns	4	196	ns	ns	0.61	1.17	0.27	0.73	0.75
10-20	*Calliandra calothyrsus*	53.6	4644	20	5.8	792	7.4	0.2	2.6	1.8	0.27	0.6	1.7
10-20	*Indigofera constricta*	49.7	3700	15	8.9	675	10.5	0.2	2.2	1.6	0.34	0.7	2.3
10-20	Maize/bean rotation	54.4	3912	16	13.4	738	8.2	0.2	1.8	1.9	0.29	0.6	1.9
10-20	Natural fallow	47.0	3296	15	4.6	624	6.5	0.2	2.6	1.3	0.21	0.5	2.1
10-20	*Tithonia diversifolia*	52.9	4307	25	5.6	831	9.9	0.3	2.5	2.6	0.50	1.2	1.1
$LSD_{(0.05)}$		6.7	710	ns	3.01	124	3.9	ns	0.6	1.05	0.24	0.62	0.61

Table 20. The C, N, and P ratios for soil and the soil organic matter (SOM) fractions, as affected by different fallows and a crop rotation system.

Soil depth (cm)	Fallow species or cropping system	Soil nutrient ratios			SOM ratios[a]					
					C/N		C/P		N/P	
		C/N	C/P	N/P	LL	LM	LL	LM	LL	LM
0-5	*Calliandra calothyrus*	13.3	72	5.4	21	20	404	319	20	16
0-5	*Indigofera constricta*	13.5	71	5.3	20	18	390	282	20	16
0-5	Maize/bean rotation	13.3	73	5.5	24	20	372	263	16	13
0-5	Natural fallow	13.7	74	5.5	22	20	375	317	17	16
0-5	*Tithonia diversifolia*	12.7	70	5.5	20	19	364	273	18	14
$LSD_{(0.05)}$		ns	ns	ns	1.3	1.1	25	28	1.5	1.6
5-10	*Calliandra calothyrus*	13.3	73	5.5	23	23	414	323	18	14
5-10	*Indigofera constricta*	13.4	72	5.4	22	21	405	274	19	13
5-10	Maize/bean rotation	13.1	67	5.1	23	21	369	256	16	12
5-10	Natural fallow	14.3	74	5.2	24	23	411	339	17	15
5-10	*Tithonia diversifolia*	12.4	64	5.1	22	22	333	268	15	12
$LSD_{(0.05)}$		1.5	ns	ns	2.0	1.8	61	55	1.7	2.0
10-20	*Calliandra calothyrus*	11.6	68	5.9	27	19	475	200	18	10
10-20	*Indigofera constricta*	13.4	74	5.5	24	24	451	292	19	12
10-20	Maize/bean rotation	13.9	74	5.3	26	21	419	202	16	10
10-20	Natural fallow	14.4	75	5.2	29	21	469	283	17	13
10-20	*Tithonia diversifolia*	12.4	65	5.2	24	20	379	238	15	12
$LSD_{(0.05)}$		1.2	ns	ns	3.9	2.8	40*	66	1.8	2.4

[a]LL = Ludox light fraction of SOM; LM = Ludox intermediate fraction of SOM.

Impact:

We showed that the fractionation of SOM and soil P, together with the determination of C, N, and P contents in SOM fractions, could be more effective for detecting the impact of planted fallow and crop rotation systems on improving soil fertility than the conventional soil analysis methods that are used to determine total soil-P, Bray-II P, and total soil C or N. The conventional methods do not distinguish the active forms of the nutrients. The three improved fallow species had an overall positive effect on soil fertility parameters when compared with natural unmanaged fallow. Among the three improved fallow species, *Tithonia diversifolia* has the greatest potential to improve SOM, nutrient availability, and P cycling after one year as improved fallow because of its ability to accumulate high amounts of nutrients. The amount of P in the LL and LM fractions of SOM correlated well with the amount of "readily available" P in the soil. We suggest that the amount of P_i and P_o in the LL and LM fractions of SOM could serve as sensitive indicators of "readily available" and "readily mineralizable" soil-P pools, respectively, in the volcanic-ash soils of the Andean hillsides.

Contributors:

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Activity 2.3 Develop appropriate and diverse strategies for controlling soil erosion

2.3.1 Impact of different land use systems on soil and water erosion in the Colombian Andes, Department of Cauca

Highlight:

- Using a portable mini rainfall simulator, we showed that intensive cultivation could reduce water infiltration and increase runoff and soil loss. Of the nine land use systems tested, intensive rotation was found to be the most susceptible to erosion. The period of land use should be taken into account when assessing a soil's erodibility - with more time under use, a soil becomes more susceptible to erosion.

Purpose:

To determine the impact of different land use systems on soil and water erosion on Andean soils

Rationale:

The Latin American Andes carry most of the region's population. The Department of Cauca, in southwestern Colombia, is no exception. Agricultural practices, however, have helped erode this hilly area, leading to loss of soil fertility and generating poverty in the area. Changes produced in the soil by agricultural practices are reflected in the soil's physical properties, which regulate the flow and movement of water in the soil. The erosive process is a part and consequence of the soil's hydrology, which, in its turn, is regulated by the soil's physical properties. Long-term agricultural practices reduce a major soil property—macroporosity—and, thus, the soil's capacity for drainage. Poor drainage leads to increased runoff and, consequently, to increased soil drag and loss.

The CIAT Soil Conservation Project has been evaluating the quantity of soil lost under different systems of crop and soil management in the Andes since 1990. This study deals specifically with two Andean soils: amorphous, isohyperthermic oxic Dystropept, found in Santander de Quilichao, and kaolinitic-amorphous, isohyperthermic oxic Humitropept found in Mondomo. Both these sites are located in the Department of Cauca, southwestern Colombia. The aim of this study was to test the relationships between different soil management systems, the soil's physical properties, and erosion. A portable mini rainfall simulator designed at CIAT was used to study water movement in the soil and soil loss. Under field conditions and with the assistance of a mini rainfall simulator, evaluations of infiltration, runoff, and soil loss at two rain intensities (80 and 120 mm h^{-1}) were carried out under different land use systems. These systems were forest, pastures, bare-soil cultivation, cassava monocropping, rotation with intensive management, rotation with fallow, rotation with legume cover, rotation with additions of chicken manure, and rotation with minimal tillage. To complement the evaluations done with the mini rainfall simulator, samples were taken and those soil physical properties most closely related to erodibility were determined.

Materials and Methods:

Evaluations with the mini rainfall simulator: With the mini rainfall simulator, evaluations were carried out with three replicates for each plot. Every 5 min, for half an hour, we measured the quantity of infiltrated water, runoff, and soil loss, and also determined soil moisture at the beginning and end of the trial. Evaluations were carried out for two intensities of rain: 80 and 120 mm h^{-1}. The intensity at 80 mm h^{-1} represented the application of energy at about 43 j or 27,506 j mm h^{-1} m^{-2}, whereas the intensity at 120 mm h^{-1} was equal to energy at 62.5 j or 59,477 j mm h^{-1} m^{-2}. The mini rainfall simulator was fitted with a series of hollow needles for generating uniform and constant drops. The No. 24 needles were used for all evaluations to generate drops measuring 2.75 mm in diameter. The drops fell from about 1 m, and the terminal speed was 4.04 m s^{-1}. The soil study area was delimited by guttering (32 cm deep × 40 cm wide) to measure the runoff. The evaluations were carried out with completely bare soil, except for the pasture treatment, from which plant cover could not be removed without altering the soil.

Location of trials: The evaluations were carried out in Santander de Quilichao and Mondomo, in runoff plots that were established in 1990 for CIAT's Soil Conservation Project.

Soil management systems: We evaluated runoff in plots with an 8-year history of use at the time of the simulations (Table 21). The land use systems studied were bare-soil cultivation (BSC), cassava monocropping (CM), intensive rotation (IR), rotation with additions of chicken manure (RChM), rotation with fallow (RFa), rotation with legume cover (RL), rotation with minimal tillage (RMT), pastures (P), and forest (F). For all rotations and BSC, tilling was carried out with a rototiller set at low revolutions; weeding was done with a hoe, except for RMT; and, chemical fertilization was applied to all rotation systems, except for RChM. Treatments P, RL, and RMT had plant cover that protected the soil from the impact of water drops. Treatments F and P were conducted in places close to the runoff plots but had no documented history.

Measurements on soil physical characteristics: Those physical determinants that are considered as closely related to erosive processes were evaluated. Samples were taken from the 0–2.5 cm layer in both disturbed and undisturbed soils. For disturbed soil, the factors determined were the stability of aggregates to water (Yoder), distribution of aggregates and soil texture (Bouyucos), real density, and organic matter. For undisturbed soil, the factors determined were bulk density; curves of retention at suctions of 50, 75, 100, 1000, and 15,000 cm; and saturated hydraulic conductivity.

Results and Discussion:

Rainfall simulations: The data obtained with the rain simulator were submitted to an analysis of variance and, subsequently, to Duncan's comparative analysis of means. For Mondomo, at a rain intensity of 120 mm h^{-1} (Table 22), the BSC treatment presented the least soil loss. The low soil moisture at the time of testing meant that rainwater was absorbed, thereby preventing runoff and soil loss. This hydrological behavior is a result of the BSC treatment permitting the loss of a large quantity of moisture according to climatic conditions since it was not protected by either live or dead plant cover, which would have dissipated the heat and prevented evaporation. Yet, in the contrastingly fully covered forest treatment with its conditions of high initial moisture, runoff and soil loss were low, suggesting a high macroporosity that favored infiltration, again preventing soil loss. These findings indicate that agricultural intervention alters the percentage of soil macropores, which is highest under forest and other undisturbed soils.

At Mondomo, soil loss in the simulations at 120 mm h^{-1} presented significant differences, which indicates that the soil studied with the mini rainfall simulator is more sensitive or susceptible to this intensity and energy (59,477 j mm h^{-1} m^{-2}) than it is to the intensity at 80 mm h^{-1} (Table 22). At Mondomo, at the intensity of 120 mm h^{-1}, the IR treatment presented the highest values for runoff and soil loss of all the rotation treatments. The P treatment behaved similarly for both intensities, with high runoff and low soil loss.

For Santander, for the intensity at 80 mm h^{-1}, no significant differences were found between the total infiltrated layer and the total runoff layer. The treatments IR and CM presented the highest soil loss values (Table 22). The values for these two treatments are a result of the soil being heavily worked, thus reducing its infiltration capacity by reducing good structural qualities such as macropores and total porosity. In Santander, as in Mondomo, the BSC treatment lost little soil and presented high infiltration, compared with the other land uses (Table 22, Santander, at 80 mm h^{-1}). The moderate soil loss in this treatment resulted from the short time of use of this plot, compared with the other treatments, and which was not sufficient to degrade the soil to the level of erosion found under the other agricultural treatments. The P treatment behaved similarly in the two localities, presenting low infiltration and low soil loss. Again, the IR treatment showed itself to be a most destructive use of the soil. But the CM treatment is

Table 21. Chronology of land use under different systems of plot management, Mondomo and Santander de Quilichao, Colombia.[a]

Period	IR	RFa	RChM	RL	RMT	CM
1990/91	Cassava + *Pennisetum* sp.	Cassava + *Zornia*	Cassava on ridges	Cassava + *Centrosema acutifolia*	Cassava + kudzu (no minimal tillage)	Cassava on the flat
1991/92	Cassava + *Pennisetum* sp.	Cassava + *Zornia*	Cassava on ridges	Cassava + *C. acutifolia*	Cassava + kudzu	Cassava on the flat
1992/93	Assoc. of kudzu + *Brachiaria decumbens*	Fallow	Cowpea fertilized with chicken manure (ChM)	Cassava + *C. acutifolia*	Kudzu + *Brachiaria*	Cassava on the flat
1993/94	Assoc. of kudzu + *B. decumbens*	Fallow	Cowpea fertilized with ChM	Cassava + legume bands	Kudzu + *Brachiaria*	Cassava on the flat
1994/95	Cassava monocropping	Cassava monocropping	Cassava fertilized with ChM	Cassava + legume bands	Cassava	Cassava on the flat
1995B	Maize	Maize	Maize fertilized with ChM	Cassava + legume bands	Maize + beans	Cassava on the flat
1996/97	*B. decumbens* + *Centrosema macrocarpus*	Cassava monocropping	Cassava fertilized with ChM	Cassava + cowpea	Cassava	Cassava on the flat
1997A	*B. decumbens* + *C. macrocarpus*	Cowpea	Cowpea fertilized with ChM	Cowpea	Cowpea	Cowpea
1998	Rest	Fallow	Rest	Rest	Rest	Rest
1999A	Maize	Fallow	Maize fertilized with ChM	Maize + *Chamecrita rotundifolia*	Maize + beans	Cassava on the flat

a. R = rotation; I = intensive; Fa = fallow; ChM = chicken manure additions; L = legume cover; MT = minimal tillage; CM = cassava monocropping.

Table 22. Average comparison by land use[a] for the variables total layer infiltrated (Inf.), total runoff layer (Run.), and total soil loss (SL) at Mondomo and Santander de Quilichao, Colombia, under rain at an intensity of 120 mm h^{-1}.[b]

Site	Variable	BSC	CM	IR	RChM	RFa	RL	RMT	P	F
Mondomo	Inf. (mm)	35.3 ab	26.6 bc	21.6 cd	36.8 ab	24.8 bc	31.3 abc	28.8 abc	10.7 d	40.7 a
(80 mm h^{-1})	Run. (mm)	5.64 c	14.8abc	19.4 ab	4.36 c	15.7 abc	9.77 bc	12.7 bc	30.0 a	0.00 d
	SL (g m^{-2})	10.0	29.2	33.8	4.79	8.27	10.1	33.7	9.29	0.00
Mondomo (120 mm h^{-1})	Inf. (mm)	60.9 a	41.7 b	22.2 d	35.5 bc	45.3 b	42.5 b	26.2 cd	22.4 d	59.6 a
	Run. (mm)	0.00 f	19.2 cd	39.9 a	25.8 bc	13.2 d	18.3 cd	33.5 ab	35.2 ab	1.48 e
	SL (g m^{-2})	0.00 b	29.7 b	204.8 a	55.9 b	23.0 b	27.2 b	86.0 b	15.6 b	1.02 b
Santander	Inf. (mm)	31.5	23.1	24.3	33.3	35.7	34.7	39.0	25.2	33.3
(80 mm h^{-1})	Run. (mm)	9.11	17.9	17.2	7.30	4.84	8.45	1.65	15.2	8.98
	SL (g m^{-2})	6.93 b	48.3 a	32.7 ab	10.6 b	2.80 b	7.96 b	1.35 b	2.22 b	3.72 b
Santander (120 mm h^{-1})	Inf. (mm)	40.4 a	28.7 a	21.1 ab	47.5 a	45.5 a	39.7 a	46.6 a	28.1 ab	5.48 b
	Run. (mm)	20.0	32.5	39.9	15.1	16.3	22.1	14.3	33.3	55.9
	SL (g m^{-2})	50.6	82.9	61.0	42.3	12.1	46.6	11.8	7.27	100.9

a. BSC = bare-soil cultivation; CM = cassava monocropping; R = rotation; I = intensive; ChM = chicken manure additions; Fa = fallow; L = legume cover; MT = minimal tillage; P = pastures; F = forest.

b. At 5% significance, Duncan's test.

more destructive still, because of the high degree of working of the soil that this crop requires. We "call attention" to this finding, because cassava is heavily used by small farmers in hilly areas where soil is more susceptible to erosion.

The two sites responded differently to erosion, runoff, and soil loss because of differences in the parental rock material and climates. Of the nine treatments, F had the lowest values for apparent density. This is consistent with the values of total porosity and macroporosity, because, with increased aerial space, apparent density tends to diminish (Santander, Table 23). Because macroporosity is responsible for water movement in the soil, the F treatment in Mondomo showed the highest infiltration values (Table 22) and the highest macroporosity and hydraulic conductivity (Table 23) during evaluations with the mini rainfall simulator in the field. The BSC treatment behaved similarly to the F one. This plot was established in 1996, and had not yet arrived at the point where degradation by erosion and management practices destroy the soil's physical qualities. However, Table 23 (section Mondomo) suggests that bulk density is higher in this treatment than under F, and that total porosity is also smaller, indicating that degradation is advancing.

The P treatment had the lowest values, according to Duncan's test, for the variable "macroporosity". Infiltration rates were therefore low and runoffs high. Treatments F, RFa, and BSC received either less agricultural use or lower levels of mechanization (the BSC treatment was only 3 years old at trial time), giving rise to the highest values for aggregate stability (Table 23) and least soil lost. This agrees with the findings of other authors, who found that aggregate stability decreases with cropping intensity, erosion severity, and irrigation.

Differences in soil organic matter separate the F and P treatments from the other treatments (rotations, BSC, CM), indicating that the working of the land and the agricultural practices used reduced organic matter content in the soil. The F treatment in Mondomo shows good physical conditions, resulting in the least soil lost and the highest values for infiltration (Mondomo, Tables 22 and 23). This treatment could be regarded as a "star treatment" and could be used to study how human intervention affects the soil in terms of infiltration, runoff, soil loss, and physical soil properties. The absence of soil loss and high infiltration rates in the BSC treatment could be attributed to low bulk density, which, itself, may have been caused by high porosity. The low values for soil loss may also strongly affect the high values of aggregate stability that appeared for this treatment (Mondomo, Table 23).

For Mondomo, at 80 mm h^{-1} (Table 22), we must emphasize that the F treatment did not present runoff, but presented maximum infiltration, whereas the P treatment presented maximum runoff associated with low infiltration. The P patterns were due to the plant cover that the grass offered the soil, hindering direct contact of raindrops with the soil, thus favoring runoff and impeding infiltration. The F treatment permitted infiltration over the entire soil profile, due in part to soil structuring by organic matter. The structuring is reflected in the total porosity and in the macropores, which both affect the way in which water infiltrates the soil (Mondomo, Table 23).

Of the rotations, IR presented more runoff, leaving only a thin layer of water that the crop could take advantage of and, although soil loss did not present significant differences, it was nevertheless the highest in this treatment. The rotation treatments with the highest capacity for infiltration were RChM, RL, and RMT. The BSC treatment (Table 22) presented high infiltration, which is explained by the high values of macroporosity shown in Table 23 (Mondomo). Low values of bulk density are related to high total porosity, which is subdivided into macro-, medium-sized, and micropores. Macroporosity, as already mentioned, is the means by which water enters the soil in liquid form. For this reason, soil that has a high percentage of macroporosity has increased infiltration and diminished runoff.

Table 23. Comparison of means for soil properties[a] in the 0 to 2.5-cm soil layer by land use variables[b] for Mondomo and Santander de Quilichao, Colombia.[c]

Site	Land use	BD (g cm^{-3})	Total P (%)	Macrop. (%)	HC (cm h^{-1})	SOM (%)	AgD (mm)	AgS (mm)
Mondomo	BSC	0.84 cd	66.93 bc	29.09 b	37.04 a	6.20 cb	2.83 e	3.69 b
	CM	1.01 a	67.17 bc	22.89 cd	10.98 ab	5.22 c	3.63 ed	1.11 c
	IR	0.92 bc	65.97 c	25.93 cb	21.32 ab	7.17 cb	4.47 bcd	1.89 c
	RChM	0.99 ab	72.19 abc	29.00 b	10.25 ab	6.84 cb	3.58 ed	1.06 c
	RFa	1.05 a	65.06 c	19.86 d	9.86 bc	6.46 cb	4.53 bc	4.14 b
	RL	1.06 a	67.69 bc	21.19 d	6.00 bc	5.51 c	3.82 cd	1.47 c
	RMT	1.05 a	68.30 bc	28.57 b	7.95 bc	5.36 c	4.16 cd	1.93 c
	P	0.81 d	74.71 ab	19.96 d	3.01 c	8.02 b	5.75 a	--
	F	0.52 e	78.24 a	34.55 a	27.28 a	19.35 a	5.04 ab	6.44 a
Santander de Quilichao	BSC	0.93 bc	74.55 abc	33.83 a	32.22 a	7.89	2.30 e	3.71 b
	CM	0.92 bc	72.14 bcd	31.72 ab	26.08 abc	6.80	3.19 d	1.36 d
	IR	0.88 c	70.29 cd	30.96 ab	27.95 a	7.07	3.59 cd	1.56 d
	RChM	1.01 ab	69.40 d	28.05 abc	24.80 ab	7.23	3.98 c	1.33 d
	RFa	0.92 bc	75.41 ab	31.50 ab	33.05 a	7.33	3.84 cd	1.85 cd
	RL	1.03 a	67.33 d	22.95 cd	7.61 cd	7.04	3.80 cd	1.11 d
	RMT	1.02 ab	68.33 d	26.03 bc	9.37 cd	7.14	3.81 cd	1.54 d
	P	0.95 abc	70.06 d	17.42 e	16.85 cd	7.22	6.36 a	6.65 a
	F	0.86 c	76.71 a	19.53 e	2.65 d	6.86	5.05 b	2.37 c

a. AD = apparent density; Total P = total porosity; Macrop. = macroporosity; HC = hydraulic conductivity; SOM = soil organic matter; AgD = aggregate distribution; AgS = aggregate stability.

b. BSC = bare-soil cultivation; CM = cassava monocropping; R = rotation; I = intensive; ChM = chicken manure additions; Fa = fallow; L = legume; MT = minimal tillage; P = pastures; F = forest.

c. At 5% significance, Duncan's test.

Soil under IR has degraded in terms of bulk density, macroporosity, total porosity, and aggregate stability, meaning that soil loss is highest under IR and the infiltration values are the lowest after the P treatment. In general, organic matter was of good quality, but insufficient to counteract the deterioration of other soil properties. Under the different land use systems, the soil's physical properties influence, to different degrees, erosive dynamics in the soil. For example, as already observed, macropores favor infiltration, thus reducing runoff and erosion. Evaluations with the mini rainfall simulator and in the laboratory show that the soil at Santander was less sensitive, presenting fewer significant differences, than was the soil at Mondomo.

The F treatment at Santander presented low macroporosity (Table 23), thus reducing infiltration and probably being responsible for high runoff and erosion at 120 mm h^{-1} (Santander, 120 mm h^{-1}, Table 22). Although the low value for macropores can explain the runoff and erosion patterns for the F treatment, it does not explain the findings for the CM and IR treatments, which show high porosities, yet high runoffs. These results suggest either compaction or encrusting of the soil, thus inhibiting entry of water in these treatments. At Santander, the CM treatment had the lowest values for aggregate stability (Table23), together with RChM, RL, and RMT (all were located in group "d", Duncan's analysis). When comparing aggregate stability with soil loss in Santander (Table 22), the CM treatment presented the highest values for soil loss. This agrees with the findings of other authors, who found that soil loss is highest under conditions of low aggregate stability. In contrast, RMT presented low values for soil loss and is located in the same group as RChM for aggregate stability. Soil loss therefore cannot be explained only by aggregate stability, there being other variables that probably influence this treatment's behavior.

Impact:
Intensification of cultivation caused reduced infiltration and increased runoff and soil loss. In Mondomo, the forest and bare-soil cultivation systems presented the least soil loss, whereas intensive rotation and rotation with minimal tillage presented the largest runoffs and soil losses. The soil at Mondomo was more sensitive to use and management than the soil at Santander, which did not present significant differences among land use systems. Santander de Quilichao presented fewer differences among treatments than did Mondomo because of high deviation in the data. In Santander, then, for future studies a larger number of replicates must be conducted to minimize the effect of variability in the soil at this locality. Physical properties such as porosity and, more specifically, macroporosity, influence erosion's progress by influencing infiltration. Soil management, in the long run, affects the soil's physical properties and these, in their turn, greatly influence erosion's progress. Of all the treatments, intensive rotation (IR) is the most susceptible to erosion. The period of land use should be taken into account when assessing a soil's erodibility—with more time under use, a soil becomes more susceptible to erosion.

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

2.4.1 The role of the llanos in the context of global greenhouse gas balances

- ***Highlight:***
  The introduction of improved grass/legume pastures is estimated to convert the savannas from a net source of global warming potential into a net negative potential. This finding has important implications for planned land use changes and for policy makers

Purpose:
To determine fluxes of greenhouse gases under different land use systems in the Colombian savannas or "llanos".

Rationale:
The CGIAR centers have been encouraged to participate in the debate on global climate change and to provide information on the effect of agriculture on land use changes and subsequent implications for greenhouse gas emissions. However there is a paucity of data on the balances of greenhouse gas fluxes from different land use systems. Consequently we initiated a study in the Colombian llanos that included the first measurements of gas exchanges made in this agroecosystem.

Summary:
Measurements of the emissions of greenhouse gases (GHG's) from different land uses in the Colombian llanos have been completed and are reported in detail in the Ph.D. thesis of Marco Rondon (Thesis entitled "Land use change and greenhouse gases in Colombian Tropical Savannas", Cornell University, 2000). This is the first report on the role of the savannas in global climate change. The main conclusion is that the introduction of improved grass/legume pastures is estimated to convert the savannas from a net source of global warming potential into a net negative potential. This conclusion was reached by considering the emissions of CO_2, CH_4 and N_2O together with their overall CO_2-equivalent warming potentials under different current and predicted land use systems. This surprising result is predicted in spite of the introduction of more grazing cattle and a modest increase in land under crops that receive N fertilizer. The main contributing factor to this result is the increased accumulation of carbon in soil under improved pastures together with correspondingly low emissions of methane and nitrous oxides. The introduction of improved grass/legume pastures can be considered as a win-win option for land use in the llanos and combined with crop rotations on 3-5 year crop cycles provides options for the establishment of sustainable production systems in this marginal environment.

Other important points include;
- Cattle-associated emissions of methane dominate methane budgets in the Llanos. Improving estimates of their actual contribution as well as exploring promising opportunities to reduce their impact by offering forages of higher nutritional value, are important topics for research in the near future.
- Emission of methane by biomass burning is a key factor in the balance of this gas in the Llanos. Any action that can reduce the area burned and/or the frequency of burning, will improve the radiative balance in the region. In this respect, conversion of savanna into croplands or pastures is clearly an advantage because burning is eliminated. Promoting the re-colonization of the land by gallery forests constitutes a win-win situation as it will not only eliminate the burning, but also will increase the methane sink strength of soils.
- Conversion of savanna into cropland increases soil methane sink strength, but on the other hand it also increases emissions of nitrous oxide and is expected to increase losses of soil carbon as a result of tillage. Losses of soil carbon were not included in this study but clearly this should be addressed by future research to improve the assessment of the role of crops in the balances of GHG's in the Llanos. As the main contributing factors to greenhouse gas emissions (burning and cattle) are excluded in cropland, it can be anticipated that agriculture will be a better option than savanna for reducing the radiative forcing of the Llanos.
- Preservation of gallery forests should be of priority concern as this not only provides an environment for a large biodiversity of plants and animals, but also plays an important role in regulating fluxes of methane and nitrous oxide in the region.

Sources of greenhouse gas emissions in the Llanos

1. The soil:

The soils of the Llanos are both net sources and sinks for atmospheric methane at different times of the year. Land use plays a role affecting annual sink strength. Except under pastures, soils under other land uses are a net annual sink for methane. Soils are also a minor net source of nitrous oxide to the atmosphere and the main disturbance to the natural condition was found in croplands due to the use of external nitrogen inputs. The integration of the contribution of soils to the overall budget of CH_4 and N_2O is presented in Table 24 showing estimates for the areas of various land uses found in the Llanos together with their estimated contribution to annual net fluxes of methane and nitrous oxide. Given the uncertainties in average annual emission estimates, especially for the savannas and pastures, figures presented here should be used with caution.

Table 24. Contribution of land uses to the budgets of CH_4 and N_2O from soils in the Llanos.

Land Use	% of the area	Area x10^6 ha	CH_4 Oxidation rate g $ha^{-1}y^{-1}$ (^)	Annual CH_4 oxidation ton	N_2O emission rate g $ha^{-1}y^{-1}$	Annual N_2O emission Ton	% of total CH_4 sinks	% of total N_2O sources
Silty- Clay Savanna	69.0	8.28	256 (90) b	2120	944 (375) ab	7819	28	63
Sandy savanna	14.0	1.68	1014 (199) c	1703	758 (291) a	1273	23	10
Gallery forest	9.5	1.14	3057 (736) a	3484	1442 (449) b	1644	46	13
Cropland (*)	2.5	0.30	762 (267) c	229	2961 (1079)c	888	3	7
Pasture	5.0	0.60	-1915 (683) d	-1149	1266 (382) b	759	-	6
Llanos total	100	12.0	532 (201)	6387	1032 (389)	12383		

(*)Average of the values found for rice monocrop sites and cowpea - rice rotations. (^) Values in parenthesis are standard errors. In a column, values followed by the same letter indicate non-significant difference at $p<0.05$.

By contributing about half of the total methane sink, soil in the gallery forest plays a key role in the net balances of this trace gas in soils of the Llanos. Given the relatively small area covered with forest, any disruption could have an important impact on regional soil methane sink strength. Crops included in this study are not the only ones currently used or likely to be used in the future, and therefore a degree of uncertainty arises in regional gas budgets when it is assumed (as in table 24) that rice as a monocrop and in rotation with green manure represent the effect of cropland in the region. However, given that the area under crops is still small, their potential contribution to changes in balances of methane in the Llanos is probably not high, even under the scenario of a three fold increase in cropland expected for the next two decades. The annual sink strength of methane in soils from the Llanos (0.0064Tg/y) represents only 0.02% of the estimated 40 Tg/y global soil sink strength.

The area under pastures is expected to double in the next 20 years. Assuming that this and projected cropland expansion occurs at the expense of savannas with the more favored clay soils, the new annual sink of methane would be 5,069 tons, which represents a net decrease of 30% from the present situation. Assuming that no corrective measures are taken to reduce the negative impact of pastures on methane sinks and without improvements in consumption rates by agricultural lands, the region could reach a zero sink level if the area covered with pastures approaches 30% (a five fold increase). However, this scenario is unlikely to occur in the midterm, because the introduction of pastures requires relatively high investments, not only for inputs but also for infrastructure. Therefore, it can be anticipated that considering more realistic rates of development in the Llanos, the soils of the region would continue to be a net sink of atmospheric methane for some time to come. A more alarming scenario arises when considering the role of the gallery forest. If its current area were reduced by 50%, the net methane sink by soils from the Llanos would be reduced by 50%, and with a destruction of 90% of the forest, the zero sink level for methane could be reached with around 18% of pasture coverage, which is not far from the projected expansion. Preserving the forest should consequently be a priority when considering the development of the region.

For N_2O, total emissions are greatly influenced by the native land uses (savannas and gallery forest) due to their high area coverage. Crops and pastures contribute similar proportions to the overall budget of this gas in the Llanos. The global annual emission is low (0.09%) with respect to the estimated global planetary emissions of 13Tg/y.

2. Termites:

Results show that all methane generated by subterranean termites is oxidized by soils before escaping into the atmosphere. The only contribution to net emissions of this gas is made by mound building termites. Annual estimated fluxes of 6.7 and 7.2 g CH_4/ha for pastures of *B. humidicola* and native savanna respectively, are fairly low compared to net soil sinks in the region, and consequently methane emissions by termites do not constitute an important component in the budgets of this gas in the Llanos. In addition the release of nitrous oxide from the mounds was negligible on an annual basis.

3. Biomass burning.

The contribution of biomass burning in the Llanos has been found to have two components: direct emission to the atmosphere in the form of the products of combustion, and indirect effects created by disturbance of the normal fluxes of gases from the soils. Extrapolating annual emissions to the area of the Llanos which is susceptible to burning (9.96 million hectares), direct emissions of methane due to burning are 67,728 ton CH_4/y, while indirect effects represent a reduction in 723 ton CH_4/y in the soil sink capacity. The net annual release of methane by burning is then 68,451 ton per year, which is nearly 11 times higher than total methane oxidation by soils. Burning is consequently one of the major factors in the annual budget of methane in the Llanos. The combined release of nitrous oxide in the region due to burning is 6,928 ton N_2O/year, which is about 37% of the total emissions of this gas by soils in the region. Its contribution is therefore also important though not dominant in the regional balance of nitrous oxide.

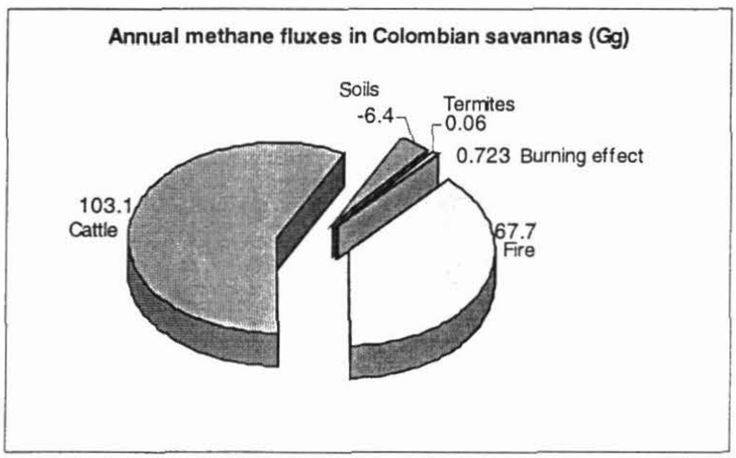
4. Cattle.

Methane emission by cattle is a well-documented process, believed to be responsible for annual emissions on the order of 90 Tg or approximately half of total agricultural sources. Unfortunately there is a complete lack of data regarding methane emission by cattle grazing native savanna vegetation or improved pastures in the Llanos. This makes it difficult to provide a more comprehensive analysis of the methane budget of the Llanos. However, one can advance some preliminary calculations regarding the role of cattle. Although uncertainty is very high, cattle population in the Llanos is estimated to be around 2,500,000 animals. Using the reported value of 113g CH_4/cow-day when fed tropical grasses (however, different to those existing in the Llanos), the estimated production of methane by cattle in the region would be approximately 103,000 ton/year, which is about 16 times higher than the net sink by soils. This demonstrates the key role of cattle in controlling the budget of methane in the Llanos.

Forage quality influences the emission of methane by cattle. It is known that higher quality forage reduces the emission factor of methane per unit of feed intake and also reduces the time required for the animals to gain their final weight. Improved pastures are clearly a source of much better quality forage and result in much higher weight gains by cattle in the Llanos. Stocking rate has been increased from 0.5 animal per hectare to 3 animal /ha in the region by using improved pastures. The effect of introduced grasses on emissions of methane is unknown in the Llanos, but it is expected to cause a net reduction compared to grazing of native savanna. The total number of cattle in the Llanos is not expected to increase significantly in the near future due to market and demand constraints. What is expected with the introduction of improved pastures, is that cattle will move from native savannas frequently in remote locations, to improved pastures near to the roads and infrastructure. There are probably good opportunities to improve balances of methane in the region by offering better quality forage for the cattle.

Balances of CH_4 and N_2O in the Llanos:

Our measurements in the llanos show that at least four main different components contribute to the balances of methane and nitrous oxide in Colombian Savannas: soils, cattle, biomass burning and termites. In Table 24 estimates for the contribution of each of these components are presented and extrapolated to the respective area of influence to generate total annual fluxes for the Llanos. Data in Table 25 and in the corresponding Figure 20 indicates that all together, the savanna ecosystem constitutes a net source of atmospheric methane, being largely controlled by direct emissions generated by burning and by cattle. The Llanos emit only about 0.03% of the total estimated global annual emissions of methane (535Tg), and about 0.09% of total annual emissions of nitrous oxide. Covering an area of approximately 0.094% of the land area of the planet, the region shows emissions of N_2O similar to planetary averages, while emission of CH_4 is only around one third of average global emissions. The Llanos can consequently be labeled as an environmentally friendly ecosystem. Despite that, there are opportunities to further reduce emissions of GHG's in the region.



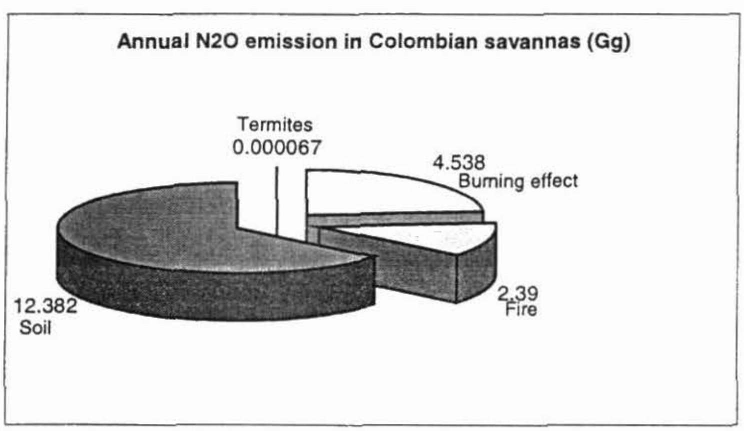


Figure 20. Contribution of various components to annual emissions of methane and nitrous oxide in the Colombian savannas

Mitigation strategies:

Data in figure 20 shows that mitigation strategies should be directed towards reducing the frequency of fires and reducing emissions by ruminants. Probably there is a little opportunity to favorably alter emission factors by burning at different times during the dry season. Burning is however very important for maintaining the productivity and functioning of the ecosystem and also to permit the current economic exploitation of the savannas.

Therefore, unless more profitable management options could be offered to farmers, there is little opportunity to reduce fires in the savannas. Pastures could play a role here, as they are economically feasible options for the development of the region. As previously mentioned improved pastures with mixtures of high productivity grasses and forage legumes could also play a role in reducing emissions of methane by animals in the region.

Table 25. Net annual fluxes of CH_4 and N_2O in Colombian savannas

Contributing factor	CH_4 flux g $ha^{-1}y^{-1}$	N_2O flux g $ha^{-1}y^{-1}$	Total area affected Mha	Net CH_4 flux ton y^{-1}	Net N_2O flux ton y^{-1}
Soils (*)	- 532	1,032	12	-6,387	12,383
Effect of burning on soil emissions	73	456	10	723	4,538
Direct emission in burning products	6,800	240	10	67,728	2,390
Emission by cattle (♣)	24,747	--	4	103,110	--
Termite mounds	7	0.008	11	76	0.1
Total in the Llanos			12	165,250	19,311
Total flux in the Llanos (Tg/y) (^)				0.17	0.02

(*) Value was calculated as the weighed average of fluxes and areas under various land uses in the region.
(♣) An average stocking rate of 0.6 heads/ha was assumed for the Llanos
(^)Termite mounds were considered for the soils under savannas and pastures.

In Table 26, the combined effect of all components on the balances of methane and nitrous oxide has been integrated to provide annual emissions per unit area in each land use system. Although pasture soils were found to be a net source of methane, the fact that burning is eliminated in well managed pastures counteracts emissions by soil. However, given that stocking rate is increased six fold when converting a unit area of savannas into pastures, there is a 4.6 fold increase in the net release of methane to the atmosphere due to the cattle. Taking all the factors into consideration, the conversion to cropland is the only alternative that can change the savanna ecosystem into a net sink of methane by eliminating the sources (burning and termites) and enhancing the soil sink. However converting land into agriculture would result in a net increase in emissions of nitrous oxide and consequently a "compromise solution" should be adopted when trying to include the environmental perspective within the development programs for the Llanos. It is clear however that under the low fertilizer application rates expected to be used in the Llanos, crops can provide a viable development option for the region in an "environmentally friendly way".

Clearly, regenerating forest on deforested land will provide the best alternative to mitigate emission of greenhouse gases in the Llanos. Unfortunately this is not an easy option, because fire normally prevents the advance of forest into the savanna. This implies that measures to prevent the fire from reaching the borders of the forest should be reinforced. This normally involves high cost in building roads which farmers will not be able to afford on the basis the environmental benefit. One possibility to cope with this problem would be to foster the use of areas near the borders of the forest as pastures or croplands. It is however reasonable to expect that government subsidies should be employed to make this option feasible. Perhaps there is an opportunity to attract some funds by selling the equivalent GHG offset resulting from recovering forest, and this is an option that policy managers should explore under the recently created umbrella of "environmental services" or C quotas, following the Kyoto protocol.

Table 26. Annual integrated emission of CH_4 and N_2O per hectare in various land uses in the Llanos.

	Savanna	Sandy savanna	Gallery forest	Pastures	Crops
CH_4	27.3	26.5	-3.1	125.7	-0.8
N_2O	1.6	1.5	1.4	1.3	3.0

Values are in kg $ha^{-1}y^{-1}$ (Negative values indicate a net sink)

Soil carbon, a key component in the greenhouse gas analysis: Soils of the Llanos have been found to be able to sequester important amounts of atmospheric carbon when deep rooted grasses are introduced in these lands. Net C sequestration by pastures of *Brachiaria humidicola* in the top 1m deep soil was reported as 25.9 ton C in a ten year period, while grass-legume pastures of *B. humidicola* and the forage legume *Arachis pintoi* increased such amounts to 70.4 ton/10 years. Though in this study fluxes of CO_2 were not considered, It is clear that the extent of the reported carbon accumulation in soils under pastures plays a main role in configuring the complete scenario of GHG's in the Llanos. Consequently, an analysis will be attempted here to include this component.

The radiative forcing strength of the Llanos: As a mechanism for integrating the combined effect of all greenhouse gases involved in the Llanos, the CO_2-equivalent global warming potential (E-GWP) of CO_2, CH_4 and N_2O has been calculated for two time horizon scenarios (20 and 100 years), for every land use in the Llanos. In a 20-year time scenario, CH_4 has a GWP equivalent to 35 times that of CO_2, while that of N_2O is 260 times compared to CO_2. In the 100 years time horizon, the corresponding GWP values for CH_4 and N_2O are respectively 11 and 270 times that of CO_2. The calculation of integrated E-GWP expressed as kg of CO_2, was done by multiplying the per hectare annual emission of CO_2, CH_4 and N_2O from each contributing factor, by the land area associated with that factor and then by the relative GWP of each gas. Adding together the values obtained for each factor gives the overall equivalent E-GWP for the Llanos, expressed as equivalent units of CO_2. For the calculation, it was assumed that burning does not make a net contribution to emissions of CO_2. Stocking rate of cattle was assumed as 0.5 head/ha in clay and sandy savannas and 3 head/ha in pastures. The same CH_4 emission factor for cattle was used for improved pastures and for native savannas. Soil emissions of CH_4 and N_2O were assumed to be the same in grass alone and in grass-legume pastures. Figure 21 shows calculated E-GWP values (for one year total emissions of all GHG's) on a hectare basis for the various land uses and has been calculated for two time horizons, 20 and 100 years of influence. Figure 21 includes the reported values for carbon sequestration in pastures of grass-legume, with a high rate of carbon sequestration (70.4 ton C/ha in a 10-year period) , as well as pastures of grass alone with lower rate of carbon accumulation (25.6 ton C/ha in a 10-year period). Annual carbon sequestration by pastures was calculated assuming the same rate of accumulation for each year, and then converting it into CO_2.

All natural land uses (savannas and forests) show positive equivalent E-GWP values, indicating that they are contributing to the radiative forcing of the atmosphere. The gallery forest is clearly the best natural land use from the perspective of the heating effect on the atmosphere. Its equivalent E-GWP is very low in both time scenarios. At the 20-year horizon, the warming contribution from the gases emitted during one year by one hectare of forest is equivalent to that of the CO_2 emitted by the combustion of 35 gallons of gasoline. Including all the sources and sinks, the radiative power of savannas is low and decreases when the 100 year time scenario is used, because most of the contribution is in the form of CH_4, which is a short lived gas in the atmosphere. Crops have integrated E-GWP lower than that of the savannas in the 20 year scenario and approximately the same as the savannas in the 100 year scenario. The conversion of savanna land into cropland does not have a detrimental effect on the E-GWP.

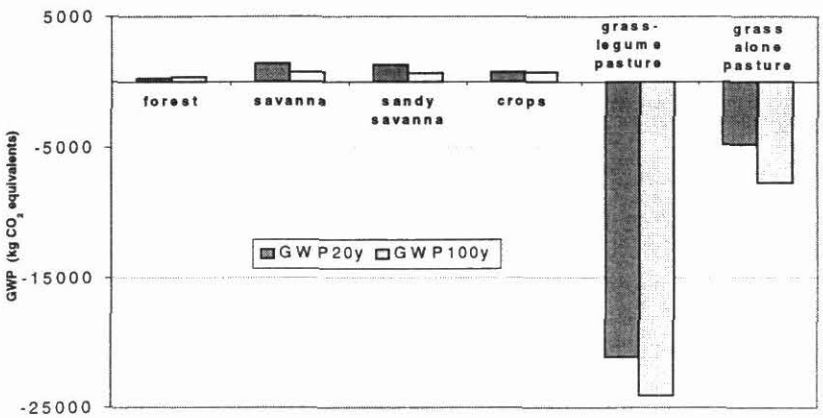


Figure 21. Global warming potential for various land uses in the Llanos under two time horizon scenarios (20 and 100 years), expressed as CO_2 equivalents. Values represent the contribution of annual emissions per hectare.

The inclusion of pastures in the Llanos plays a much more important role in affecting the overall E-GWP. Due to the low emissions of methane and nitrous oxide from pastures and the very high sequestration of atmospheric CO_2 as soil organic carbon, pastures can convert the system from a modest source into an important net sink of radiatively important species. The rate and persistence of C accumulation plays a major role in the strength of the sink, especially in the 20-year horizon. Even with rates of C accumulation in soil of around half of the reported value for grass alone pastures in Carimagua, the equivalent E-GWP of annual emissions from one hectare of pastures would be zero.

The Llanos in the year 2020. Land use patterns in the Llanos are expected to change in the next two decades. It is not an easy task to try to anticipate the extent and direction of development in the region. However, some studies suggest that the area of crops could increase up to three times the current values while the area under pastures will at least double in the same period. Area under grass-legume pastures is expected to grow from 0.1 to 0.3 Mha, while the area under grass alone pasture will continue to dominate and will increase from 0.5 to 0.9 Mha. This expansion will be at the expenses of the clay-loam savanna, which has slightly better levels of soil nutrients than the sandy savanna. The area under gallery forest will probably decrease by 10% in the next 20 years assuming the same rate of current intervention. Annual rate of C-sequestration by pastures in soil was assumed as reported for grass alone and grass-legume pastures at Carimagua .

Employing these assumptions, a calculation can be made of the integrated E-GWP for the Llanos in the year 2020. In Table 27, results of such calculation for the 20-year time horizon are presented. Data in Table 27 indicates that, under current land use distribution, the Llanos as a whole plays a minor role in the radiative forcing in the earth's atmosphere using a 20-year horizon for the analysis. Its integrated E-GWP of 9.6 Tg of CO_2 equivalents is only about 0.004% of estimated global planetary radiative contribution of about 242,000 Tg of CO_2 equivalents.

In Figure 22, in addition to the 20-year time horizon a longer term 100-year time horizon has been used to calculate effects of present and expected land use distribution in the Llanos. The development of the Llanos will have small net benefits to the environment by reducing the radiative force of the atmosphere. This benefit will be accentuated in the longer term scenario. Once more the minor role of the Llanos in the context of warming of the planet is emphasized.

Table 27. Integrated E-GWP for the Llanos under present and expected land use distribution in the year 2020. Values are equivalent Tg of CO_2 calculated for a 20-year time horizon.

Land use	E-GWP Kg CO_2equivalents per ha	Area (Mha)		Integrated E-GWP (Tg of CO_2 equivalents)	
		Present	Year 2020	Present	Year 2020
Forest	268	1.14	1.03	0.306	0.275
Savanna	1380	8.28	7.19	11.43	9.92
Sandy savanna	1305	1.68	1.68	2.19	2.19
Croplands	743	0.3	0.9	0.223	0.67
Grass alone pasture	-4769	0.5	0.9	-2.38	-4.29
Grass-legume pasture	-21085	0.1	0.3	-2.11	-6.32
Total				9.65	2.45

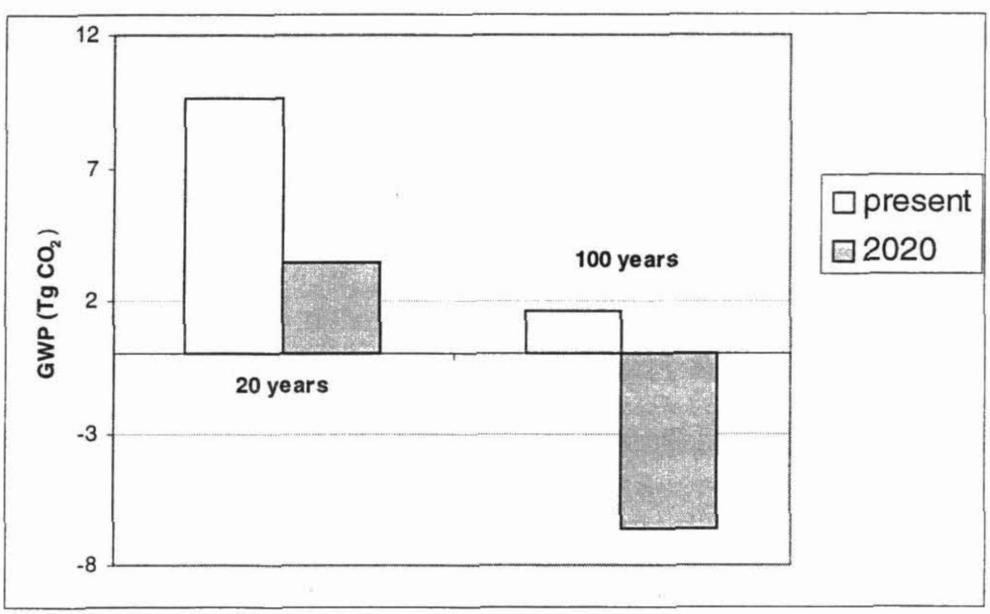


Figure 22. Integrated Global Warming Potential for the Llanos under present land use and expected land distribution in the next 20 years. Two time horizons have been considered for the calculation of E-GWP, time horizons have been considered for the calculation of E-GWP.

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

2.5.1 Nature's plow: Soil macro-invertebrate communities from the Neotropical savannas of Colombia. General conclusions, research impact and future needs
Highlight:

- A beneficial population of soil earthworms should consist of one or more epigeic species and one or more anecic species that construct vertical galleries, produce biogenic structures on the soil surface and mix plant residues with the mineral soil substrate.

Purpose:
To develop guidelines for the management of beneficial soil biota through an evaluation of the effect of agricultural systems on the structure and abundance of soil macro-invertebrate communities. In addition to characterize the community structure, population dynamics and species ecology of earthworms in natural savannas and introduced grasslands, and evaluate the effects of a functional group, i.e. the ecosystem engineers, on soil properties at different spatio-temporal scales in the eastern plains of Colombia.

Rationale:
Soils host extremely diverse and abundant populations of invertebrate communities. The study of the macro-invertebrate biodiversity in soils and the possible use of biological resources were neglected during the green agricultural revolution. The management of these communities and the benefits derived from their activities is considered part of the second paradigm of soil fertility management whereby there is more reliance on biological activity than on purchased inputs. However our knowledge on the management of soil biota is still very meager as are details of the composition and structure of their communities and responses to disturbances or specific soil conditions. We have completed a detailed collaborative study that includes the first in-depth field approach to soil biological studies in the savannas of South America (Colombian llanos) (Picture 3).

Picture 3. Sampling procedure to collect earthworms at field site and one of the main species found at Carimagua.

Summary:
Studies on soil macrofauna communities with a special emphasis on earthworms, their biology, ecology and their effects on physical and chemical processes from different land uses in the Colombian llanos have now been completed. These are reported in detail in two Ph.D. theses (one from Juan J. Jiménez, entitled "Estructura de las comunidades y dinámica de las poblaciones de lombrices de tierra en sabanas naturales y perturbadas de Carimagua, Colombia", Universidad Complutense, 1999, and the other from Thibaud Decaëns entitled "Rôle fonctionnel et résponses aux practiques agricoles des vers de terre et autres ingénieurs ecologiques dans les savanes colombiennes", Université Pierre et Marie Curie - Paris VI, 1999). The majority of the research was done at the Carimagua (CIAT – CORPOICA) experimental station. The main hypothesis tested was to consider earthworms as a resource suitable for management for beneficial means in sustainable agroecosystems where biological resources can be considered potential indicators of soil health and fertility.

An inventory of biological resources including abundance, diversity and ecology, and an evaluation of their impacts on soil and plants was produced for the savannas of Carimagua. The composition of the soil macrofauna communities in natural and agricultural systems, as well as the assessment of their basic biology, population dynamics, adaptive survival strategies and earthworm life cycles have been described. In addition the effects of earthworms as a group of ecological engineers on the soil physical, chemical and biological properties at different spatio-temporal scales are detailed. The main results and discussion on options to conserve and use the biological resources in the soil under different land management practices are presented here.

Main findings include:

- Macro-invertebrate populations clearly responded to perturbations induced by soil management. Earthworms are favored by pastures and moderate grazing and fire but their importance decreases with overgrazing. The long-term association of *B. decumbens* and Kudzu (15 years) is of high value with respect to the conservation of soil quality and biodiversity as it maintains the taxonomic richness of the savanna. Annual crops have a dramatic negative effect on earthworms and arthropod populations with a spectacular decrease of biomass, population density and taxonomic richness.

- The original species richness of earthworms in the savanna was conserved in pure or legume-based improved pastures and no aggressive peregrine earthworms invaded these agroecosystems. The earthworm community at Carimagua was comprised by species of the main ecological categories, of different size and precise adaptive strategies for the severe environmental conditions. When the savanna was converted into improved pasture differences in density and biomass, (10-fold greater under improved pastures) were significant mainly due to a large increase in populations of the large anecic *M. carimaguensis*.

- Fourteen macro-invertebrate species produce epigeic biogenic structures in savanna soil of Carimagua, eight types of ant nests, three types of termite mounds, one type of termite plate and two types of earthworm casts. Casts produced by an endogeic species and *M. carimaguensis* (anecic) are formed by aggregates of large size that were more stable than soil aggregates of comparable size in the case of the anecic species. Three types of structures produced by soil ecological engineers have been identified: (i) compacted structures enriched in organic matter (earthworm casts), (ii) slightly compacted structures with enriched organic matter (termite mounds) and (iii) granular, non-compacted structures with low organic matter contents (termite plates and ant nests). From the typology of biogenic structures a functional classification approach of soil fauna and their effects on ecosystem functioning can be assessed.

- Carbon content in casts increased significantly over time resulting in a build up of a rather active but physically protected C pools. When total casting activity per ha is considered we estimate as much as 8.6 tons C ha^{-1} yr^{-1} is accumulated in surface earthworm casts on improved grass/legume pastures in comparison with 0.6 t C ha^{-1} yr^{-1} in the native savanna. Because of the large quantities of soil processed by earthworms in the pastures, the global effects on soil fertility and plant production are extensive,

especially in the context of soil organic matter management, which is a fundamental step in improving agroecosystems sustainability and decreasing CO_2 emissions to the atmosphere.

- The effects of the absence of the deep-burrowing *M. carimaguensis* on soil properties and plant growth was associated with high soil compaction, low C contents, high Al saturation, low herbaceous biomass and high weed biomass in pastures, although main factors influencing soil properties were pasture type and age. The loss of one species, especially when it is associated with an important decrease in biomass, resulted in significant losses in ecosystem function. Attention should be paid to managing earthworm populations in tropical agroecosystems in order to profit from their impacts on soil fertility.

The resource

The soil macro-invertebrate communities in the native savanna at Carimagua are characterized by a high taxonomic richness and population density with termites (47% of the total) and earthworms (31%) comprising the most abundant groups. Representatives of various groups such as earthworms (Oligochaeta), termites (Isoptera), ants, wasps (Hymenoptera), beetles (Coleoptera), spiders (Arachnida), millipedes (Myriapoda), rounded worms (Nematoda), harvest flies (Homoptera), sucker beetles (Hemiptera), isopods (Isopoda) and flies and mosquitoes (Diptera) were also recorded.
However, a characterization of the macrofauna in any ecosystem ought to be accompanied by an evaluation of the biogenic structures and the organisms responsible for their formation. In addition the biogenic structures represent the main focus that unites the biodiversity of the organisms with functional performance in the ecosystem. The main functional groups are represented in the savanna communities i.e., litter transformers such as beetles and epigeic earthworms, and ecosystems engineers such as termites, ants and earthworms. In agreement with the high species richness of the savanna, we found a high functional diversity at Carimagua with 14 different types of superficial biogenic structures produced by soil ecological engineers: 4 termite structures, 8 types of ant nests and 2 types of earthworm casts.

When natural ecosystems are replaced by agroecosystems the extent of the changes in earthworm communities will depend largely on the amplitude of the environmental changes in the soil induced by agricultural practices. For example, species richness decreases dramatically when the tropical forest or savanna is converted into agricultural monocultures. On the other hand slight changes are observed when the agroecosystem is functionally similar to the original ecosystem such as the introduction of improved pastures after natural grassland savannas or an agroforestry system following a natural forest. The loss of biodiversity of earthworm communities can result in an alteration of ecosystem functioning.

Effect of agricultural intensification on ecosystem engineers

Agricultural practices can be classified from less intensive (use of fire, low animal stocking rates) to more intensive (regular use of machinery, application of large amounts of inputs and heavy grazing). Agricultural intensification and associated practices such as the elimination of native vegetation, mechanization and use of pesticides, results in environmental changes, i.e., microclimate and trophic resources, that decrease a large part of the soil biodiversity. Agroecosystems are known to have a reduction in plant and animal communities compared with natural systems. The concept of agricultural intensification includes the changes to the structure of the agroecosystems associated with the transition from traditional agriculture to a more intensive agriculture. This intensification involves three types of changes: (i) the more frequent use of the soil in a plot, i.e., an intensification of the resource use; (ii) the specialization of productive species i.e., loss of vegetation cover diversity and (iii) the use of inputs such as fertilizers and pesticides and mechanization.

The different agroecosystems studied in Carimagua can be classified as a function of the degree of agricultural intensification. This can be expressed as an index (preliminary assessment in Decaëns, unpublished) that facilitates a visualization of intensification in the savannas:

$$IA = US + FT + ARP + ME + CA + UF + PS$$

where IA is the degree of intensification, US is the degree of use of the soil for crops, FT is the degree of fertilization, ARP is the degree of use of agrochemicals to control pest and diseases, ME is the degree of mechanization, CA is the animal stocking rate, UF is the degree of soil utilization and PS is the level of productivity of the system. IA ranges from 0 to 7 while the others range from 0 to 1. With this index we can rank the different systems studied in Carimagua according to a gradient of intensification (Figure 24).

The taxonomic richness of the soil macrofauna varies along this gradient, mainly varying in (a) both intensity and frequency of perturbations, and (b) the productivity of the system (quantity and quality of the resource).

In general we can assess the effects of agricultural practices using this index and can distinguish two main contrasting agroecosystems: pastures and annual crops. Pastures not only maintain earthworm species richness but also increase their populations, i.e., the carrying capacity is greater. This process occurs in various stages, firstly pastures provide an organic fertilization via animal excretion with dung being a high quality organic resource for earthworms and litter transformers. Dung then encourages a rapid decomposition and incorporation of litter into the soil via the ecological engineers and through its ingestion when mixed with mineral soil (anecic earthworms) or soil with different amounts of organic matter and roots (endogeic earthworms). The quantity of roots under pastures is much greater than that under native savanna (Rao, 1998), thus favoring an increase in the populations of endogeic earthworms such as *Andiodrilus* n. sp. and also influencing the amounts of carbon accumulated at depth in the soil.

In some cases the combination of agricultural practices favors the above processes. For example in rice-pasture agropastoral systems (Sanz et al., 1999) where pastures, established with the sowing of upland rice, benefit from the inorganic fertilizers applied to the rice crop. In the case of organic fertilization associated with grass-legume pastures there is an increase in both the quantity and quality of the organic matter. The beneficial effects of forage legumes in pastures includes an increase in nutrient cycling and biological nitrogen fixation.

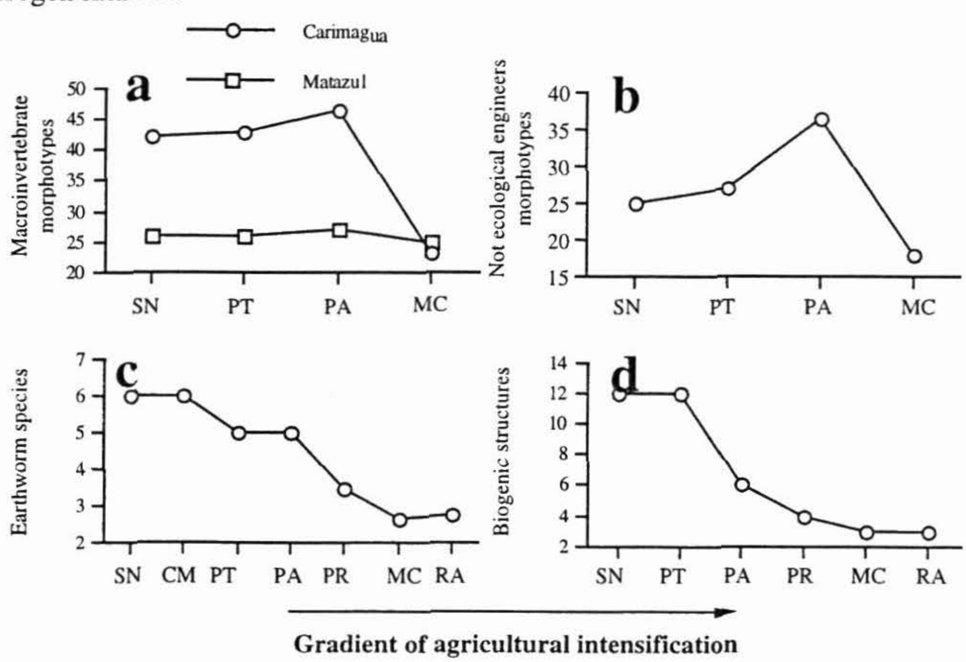

Figure 23. Number of morphotypes of macro-invertebrates (a), of macro-invertebrates that are not engineers (b), of earthworms (c) and of ecological engineers that produce structures on the soil surface (d) along a gradient of agricultural intensification. SN = native savanna; CM = cashew nuts (*Anacardium occidentale* L.); PT = traditional pasture; PA = old introduced pastures; PR = newly introduced pastures; MC = crop monocultures; RA = annual rotations (Decaëns unpublished).

Agricultural intensification generally affects all groups of invertebrates. In Carimagua only the most intensive system, annual crops, significantly reduced taxonomic richness (number of species in the macro-invertebrate communities (Figure 23a). The species richness of litter transformers was greatest in moderately intensive systems (Figure 23b). These results differ in principle from published reports who suggested that agricultural intensification results in a systematic reduction of biodiversity (T. Decaëns, unpublished). This type of result however may not be general, as studies done at the Matazul farm did not show a significant decrease in taxonomic richness across a similar intensification gradient.

The number of earthworm species decreased progressively from the native savanna to monocultures (Figure 23c). Finally, the number of biogenic structures identified on the soil surface, which are often linked to the number of ecological engineers that create structures onto the soil surface, decreased rapidly with intensification.

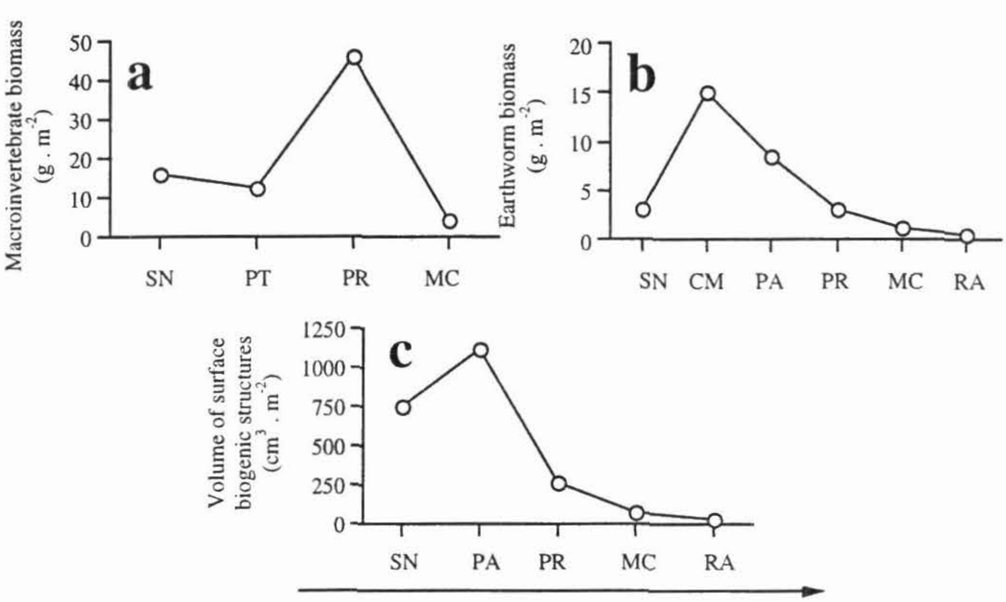

Figure 24. Macro-invertebrate biomass (a), earthworm biomass (b) and quantity of biogenic structures on the soil surface (c) along a gradient of agricultural intensification (SN = native savanna; PA = long-term introduced pasture (= intensive); PR= recent introduced pasture (= intensive); MC = monocultures; RA = annual rotations; CM = Cashew nut trees; PT = traditional pasture (Decaëns, unpublished).

In terms of quantitative analyses, the most favorable systems for soil macrofauna activity were the moderately intensive systems. Total biomass of macro-invertebrates, such as earthworms, increased in areas with trees or with introduced pastures (Figure 24, b). The quantity of biogenic structures also varied in the same way (Figure 24c). These results could explain the observed variations in species richness of the functional group of litter transformers (Figure 24b). *M. carimaguensis* modifies conditions for other organisms through the creation of biogenic structures, with an increase in the abundance of certain groups of arthropods. Therefore the activities of the ecological engineers could be one the factors responsible for the increase in taxonomic richness of the litter transformers in moderately intensive systems (Decaëns, unpublished).

Earthworm species from the savannas of Carimagua did not respond equally to agricultural intensification. Generally earthworm density increased in moderately intensive systems and decreased in intensive systems even though the extent of the changes varied widely according to the particular species (T.

Decaëns, unpublished). In intensively managed pastures, Ocnerodrilidae n. sp. responded rapidly to the improved trophic conditions, whereas the other species decreased in density with a variable recovery from perturbations (Figure 25).

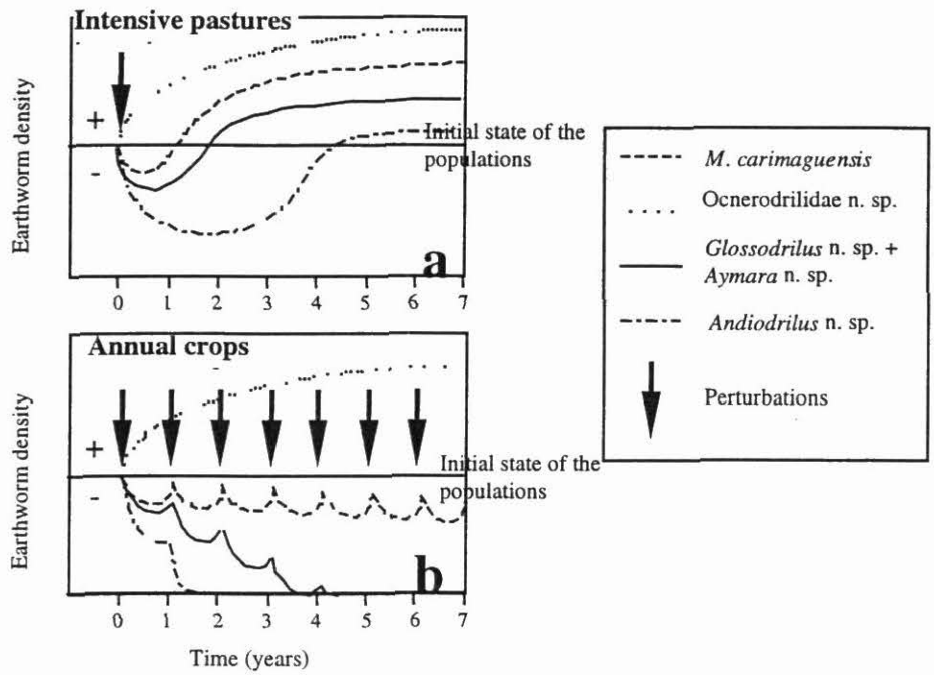

Figure 25. Response of different earthworm species in Carimagua to perturbations resulting from agricultural practices (tillage, pesticides): (a) in an improved pasture and (b) in a crop monoculture .

The rate of increase in density depends on the resources used with Ocnerodrilidae n. sp. and *M. carimaguensis* being the most responsive. Ocnerodrilidae n. sp., is a species with a rapid and strong demographic growth that is little affected by tillage. *M. carimaguensis* has the ability to move over the soil surface and consume materials enriched in organic matter (dead roots, leaf litter, organic residues of diverse nature such as surface casts of other earthworm species and invertebrates). In annual crops there is no enough time for the species to recover their initial densities following perturbations and the majority disappear from these systems.

Life cycles

The study of ecological processes and functions associated with biodiversity constitutes the basis for both the understanding and management of natural and human intervened ecosystems. In general, earthworm communities are sensitive to climatic and edaphic factors within a hierarchical scale that determine the availability of food resources and the microclimatic conditions. Under this assumption there is always a potential risk of changing communities due to alterations in natural ecosystems. The capacity of the fauna to respond to these changes can be used to manage their activities.

In terms of the biology and ecology of the savanna earthworm species we tested the following hypothesis (i) the replacement of native savanna with introduced pastures results in a drastic reduction in species richness and diversity that could originate the depletion of native species; (ii) if these are able to adapt to the new agroecosystem the community structure will change; (iii) the management and increase in primary production of pastures influences the abundance and biomass of earthworm species increasing or reducing their populations.

The change in the natural ecosystem (native savanna) influenced the functional structure (hypothesis i) of the earthworm communities but had little effect on species richness (hypothesis ii). In the introduced pastures at Carimagua the same species were found as those in the native savanna without any presence of exotic species. It was the difference in community structure that changed, i.e., the relative contribution of the different ecological categories and their effects on the agroecosystems. *Andropogon gayanus* and *Brachiaria decumbens*, alone or in association with the forage legumes *Pueraria phaseoloides*, *Brachiaria humidicola*, alone or in association with *Arachis pintoi* or other legumes were agroecosystems that conserved the native earthworm community at Carimagua. These results are exceptional because generally disturbances to natural systems results in a decrease or disappearance of the native species. It is more usual to observe the appearance of pantropical species with a wide range of tolerance to physico-chemical properties (peregrine species) such as *Pontoscolex corethrurus* Müller and *Polypheretima elongata* Perrier (Table 28).

Table 28. Macro-invertebrate species richness in a primary forest and pasture of *Brachiaria humidicola* Rendle in Manaus, Brazil (Barros et al., 1998) and in a native savanna and introduced pasture of *B. humidicola + P. phaseolides* at Carimagua in the Colombian savannas (Decaëns et al. 1994).

	Tropical forest (Manaus, Brazil)		savanna (Carimagua, Colombia)	
	Forest	Pasture	Savanna	Pasture
N° morphospecies	151	48	31-57	42-55
Common spp. (%)	15		54	
Total biomass (g fresh weight m^{-2})	51.5	51.2	15.3	28.8-62.5
Biomass *P. corethrurus* (%)	0	90	0	0

* It refers to different management of savanna and pastures without or with legume association.

It seems that the main factor determining the maintenance of the native fauna is the structural and functional similarity between the original ecosystem and the derived one. One of the causes for the establishment of exotic populations of earthworms is the colonization of vacant niches left by native species after habitat alteration. The abundance of only two of the savanna species were increased significantly by the introduction of improved pastures in Carimagua. The biomass of *Andiodrilus* n.sp. was increased three-fold (from 0.82 to 2.39 g fresh weight m^{-2}) while the biomass of *M. carimaguensis* was increased more than a 10-fold (from 0.47 to 50.74 g fresh weight m^{-2}). Extrapolating these values from the plot to the ecosystem level a density of 2.000 ind ha^{-1} for *Andiodrilus* n. sp. and of 182.000 ind. ha^{-1}. for *M. carimaguensis* is obtained.

Adaptation to drought

The tropical savannas are ecosystems that are subjected to a strong pattern of rainfall and drought with a dry period ranging from 3 to 9 months. This pattern strongly influences the type of savanna in terms of soil humidity and vegetation, which in turn determines the dynamics and activity of earthworm populations. These result in different adaptive strategies, feeding regimes, localization in the soil during the dry period, size etc. in response to the severity of the environment in order to avoid population extinction. There are three main types of ecological categories that are the responses of the organisms to the limiting soil factors; little or no nutrient reserves, compaction and unfavorable climatic conditions

There are three population parameters all explained by climate variations that define the structural function of the earthworm communities in Carimagua: abundance, degree of activity and vertical distribution in the soil profile. Species adapt to such conditions through changes in their activities and population demographic structure (development parameters such as growth, fertility and death). In Carimagua the seasonality appears as the determining factor of activity of the populations and of the diverse adaptive strategies to confront these conditions.

Based on these observations in Carimagua three groups of species can be distinguished:

a) Small sized species superficially located during their activity and with a quiescence phase including, *Aymara* n. sp. (epigeic), *Glossodrilus* n. sp. (endogeic) and Ocnerodrilidae n. sp. that shows a deep vertical distribution with the exception of the first two species.

b) Medium sized species superficially located with no special adaptation to drought, e.g., *Andiodrilus* n. sp. (endogeic).

c) Large sized with a diapause in deep layers of the soil, e.g., *Andiorrhinus* n. sp. (endo-anecic, without diapause) and *M. carimaguensis* (anecic).

Effects of the engineers on soil properties

The effects of ecosystem engineers on soil processes have been addressed under three main hypotheses :

(1) The ecological engineers produce biogenic structures that are species specific.

(2) The ecological engineers show significant effects on soil processes and on other soil organisms via the biogenic structures.

(3) Agricultural intensification produces contrasting effects on the communities of ecological engineers that alter their impact and can result in variations in community composition.

The testing and validation of these hypotheses has resulted in the establishment and description of the functional role of the ecological engineers in the soils of the Colombian savannas and an evaluation of the effects of agricultural practices on their populations.

M. carimaguensis as a soil ecological engineer

By definition, ecological engineers are organisms that show the facility to alter the availability of resources for other living organisms through the production of biogenic structures. Numerous macro-invertebrates comply with this definition of ecological engineers. *M. carimaguensis* corresponds to a particular type of ecological engineer. This species in effect modifies the environment by passing materials (leaf litter, humus and soil) from one physical state to another. This transformation is achieved mainly through a mechanical process (creation of macropores, incorporation of leaf litter into the soil and the formation of stable aggregates). The structures produced, i.e. galleries and casts, constitute a resource (microhabitat and trophic resource) that is directly available to macro-invertebrates and plant roots. In a more indirect way *M. carimaguensis* transforms the soil from its initial physical state into a bio-perturbed state through a series of modifications of the physical properties, the organic matter dynamics, the availability of nutrients and finally, a positive effect on plant growth.

In summary *M. carimaguensis* has three types of effects as a soil ecological engineers by producing the biogenic structures: (i) they serve as a trophic resource for *Andiodrilus* n. sp. and Ocnerodrilidae n. sp. that ingest them, and as a spatial resource as it creates space for certain macro-invertebrates, for example the galleries and/or under the casts; (ii) they physically modify the availability and quality of the resource in an even more indirect way, through the modification of the soil structure, organic matter dynamics and nutrient availability to plants; (iii) they transport some organisms and allows them be in contact with the resource.

The functional attributes of a species or functional group are considered at different levels of organization through the hierarchical systems. As the scale of observation increases from the nearest to the furthest, the levels describe the same processes. A first ascending approximation has shown that the biogenic structures produced by *M. carimaguensis* have influenced the soil structure, the dynamics of soil organic matter, the macrofauna and the growth of plant roots. In an descending approximation the effect of *M. carimaguensis* in the ecosystem continues to be appreciable, if not marked, i.e. it remains progressively marked by the effects produced by other communities of organisms and by environmental factors that regulate soil processes through the hierarchical scale.

Typology of the biogenic structures

The soil ecological engineers of Carimagua produce biogenic structures with particular physico-chemical characteristics that are species specific and that are generally different to those of the surrounding soil. This opens the possibility of a new classification of ecosystem engineers based on the functional attributes of the biogenic structures without taking account of the taxonomic aspects (T. Decaëns unpublished)

As we have mentioned before *M. carimaguensis* produces visible effects at different scales in some ecosystem processes measured. Its activities decrease soil compaction, an effect that balances the compacting effect produced by the production of large compact excretions. In addition the effect of Ocnerodrilidae n. sp., and its probable marked and important effects on the structural stability of the soil even if its effects on plant growth are small must be considered in further studies.

Management guidelines of beneficial fauna

The research presented here and those from the literature guards against making general guidelines for the management of soil macrofauna. Certain practices such as improved pastures can undoubtedly result in increased populations of soil macrofauna. However, these can be beneficial as in the case of *M. carimaguensis* in the Colombian savannas or detrimental, e.g. *P. corethrurus* in Amazonian pastures, where the loss of a diverse soil fauna is responsible for pasture degradation and not the presence of this peregrine species. The similarity of the original ecosystem and the derived agroecosystems tends to be the major factor determining the survival and adaptation of native species, their resilience and stability within the boundaries of ecosystem management.

It is clear that there needs to be an understanding of the general biology and ecology of the macrofauna in any particular environment before guidelines can be established. This involves labor-demanding activities that have restricted the number of studies to a few in the tropics. Such an understanding needs to focus primarily on the main species that are ecological engineers as the effects of these species tend to dominate other effects of changes in macrofauna populations. The case of *M. carimaguensis* in the Llanos is an exception to date in that increased populations that result from pasture introduction tend to have an overall beneficial effect. This is a unique example where conservation, productivity and sustainability of an agroecosystem is maintained and improved.

The spatial arrangement of pastures alongside cultured plots can result in a faster recovery of the macrofauna populations in the cropped plots. This management practice needs further exploration especially when the beneficial species, that can be more rapidly established, can also help reverse some of the degradative effects of cropping on the soil structure. This may help avoid the need for expensive machinery-intensive solutions to soil degradation problems. Earthworms then can be considered a resource that can be harnessed to achieve better ecosystem health.

The spatial arrangements of plots that conserve earthworm populations alongside those that tend to reduce populations are an example of indirect management. Figure 26 shows how this technology is an example of the management options currently available.

Even though a large number of species that can be called ecological engineers exist and that these can affect physical changes in the environment, not all of the changes will have important ecological consequences. Some ecological engineers have only small effects on the ecosystem. These effects can be very marked with some engineers via the action of their functional domain. This depends on a series of factors that include population density, local and regional spatial distribution and the type and formation of physical structures that they produce. However it is important to identify the species present in the soil, the structures they produce and to describe in detail the mechanisms through which the ecological engineers affect the soil environment. The trophic interactions and indirect interactions can be included in predictive models of the effects of the ecological engineers. There models will be particularly useful for agroecosystems that the aim to improve the sustainability of the systems through an increase and/or diversity of the soil macrofauna. The models could also be used to investigate hypotheses on the function of biodiversity in agroecosystems.

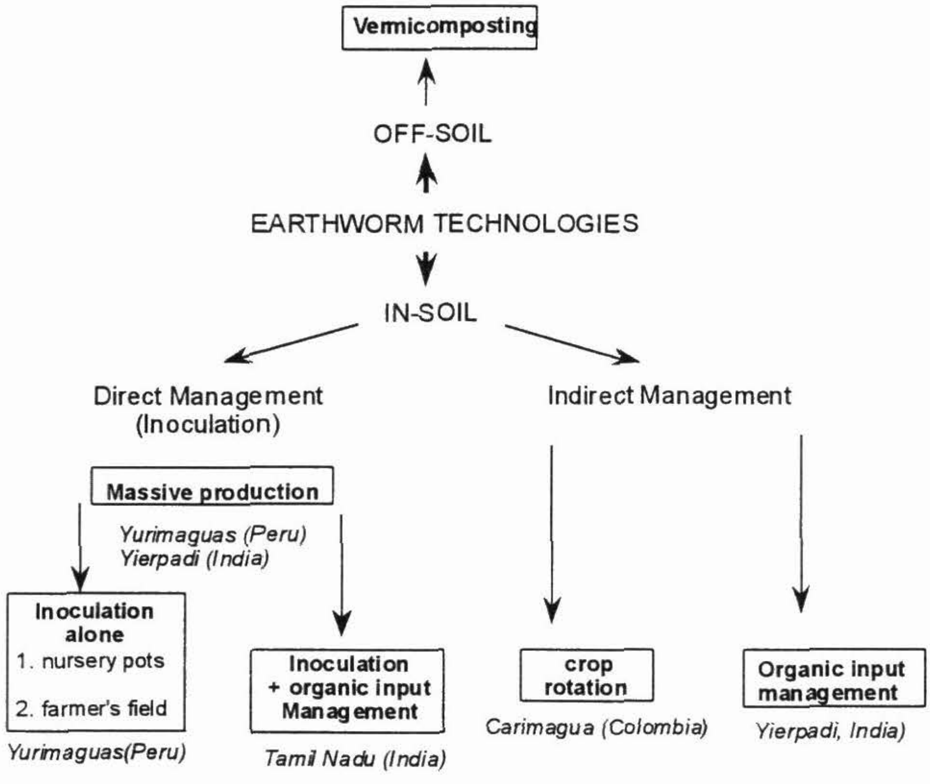

Figure 26. Management alternatives for earthworm technology

We have learned that the management of earthworm biodiversity in agroecosystems should favor a community that consists of one or more epigeic species and one or more anecic species that construct vertical galleries, produce biogenic structures on the soil surface and mix plant residues with the mineral soil substrate. Additionally there should be one or more endogeic species that feeds on the soil organic matter, root exudates and plant roots and that forms horizontal galleries. The earthworm community in Carimagua is such a community and it is possible to suggest a management of these communities in the agroecosystems studied.

The management options for earthworm activities should consider the following aspects:

- The community of soil ecological engineers in the agroecosystem should be the same as that in the original ecosystem (normally a natural ecosystem).
- The engineer organisms in the soil and in particular, *M. carimaguensis*, influences different processes of soil fertility.
- The activities of the soil engineers are well developed under improved pastures and strongly diminished in monocultures.
- The effects of the engineers are manifested over time through the biogenic structures that persist in the environment even after the disappearance of the organisms that form the structures.

Both Ocnerodrilidae n. sp. and *M. carimaguensis* are the only species that tolerate the intensification associated with continuous monocropping. Ocnerodrilidae n. sp. is a polyhumic endogeic that tolerates tillage because of its small size. *M. carimaguensis*, in addition to its survival strategy for the unfavorable dry season during which time it occupies the deeper soil layers, also has the ability to migrate to the soil surface. The colonization by *M. carimaguensis* of earthworm-poor plots could be facilitated by inoculation of the plots. Crop rotations associated with a monoculture and a pasture phase of several years can also favor the development of significant populations of earthworm species. An agricultural system that conserves earthworms could be established by: (a) native pastures that serve as reserves of biodiversity, (b) forages used as protein banks that result in the establishment of an large biomass of earthworms; (c) annual crops in rotation with pasture phases of various years length (protein bank) and/or with forages that maximize the phenomenon of migration. With this type of system the presence of the biogenic structures would be qualitative and quantitative indicators of the state of the populations of ecological engineers.

An important challenge for the near future is the identification of sustainable agroecosystems that maintain acceptable levels of diversity and biomass to optimize the activities of soil macrofauna. The research reported in the forthcoming CIAT working document is an example of the opening the "black-box" of soil biota and subsequent development of management guidelines. To be acceptable and adoptable by land users however these studies need to be combined with a larger multidisciplinary approach that includes indigenous farmer knowledge, farmer experimentation and socio-economic studies in order to achieve a diverse, productive and healthy soil via a process that increases the number of viable options for the land user.

6. Acceptance of practices by farmers

Any new management practice for the manipulation of soil organisms must be acceptable to the land user and often requires development and adaptation by the land users themselves to be successfully taken up. Our knowledge on farmer perceptions of soil organisms is still very limited. For example, recent studies on farmer perceptions of earthworms showed great variation in both farmer knowledge and use of earthworms in their agricultural systems. While farmers in Mexico were relatively well informed on the importance and benefits of earthworms in soil fertility, farmers in the Congo were poorly informed. Gender differences were also apparent in Mexican studies. It is likely that farmer knowledge of microscopic organisms is even less than that of the larger, visible organisms with perhaps only plant disease symptoms being obvious indicators of the presence of detrimental organisms. Encouragingly however farmers in Mexico were able to distinguish three or four types of earthworms on the basis of size, color and habitat but this was probably the first report of such distinguishing abilities.

In order to gain a much wider acceptance of the concepts of beneficial soil biota and of the management practices that can encourage the build up of significant populations in farmer fields, there is a need to develop a common language between farmers and scientists on soil biota. Also required is the development of simple user-friendly guidelines for the management of beneficial organisms. Farmers need to be able to distinguish for example between compacting and non- or de-compacting earthworm species.

They need also simple and rapid surveying methods to be able to at least have a semi-quantitative estimate of macrofauna numbers. Scientists need to establish or verify threshold levels of organisms or populations that are required for significant effects on soil processes and plant production.

These tools and decision guides need to be developed by farmers and scientists together, incorporating the existing indigenous knowledge and where it does not exist, educational material suitable for readers and non-readers is required. Examples of such material are available. For example a series of guides for the management of natural resources up to the watershed level has been produced (CIAT, 1999). These provide examples of how to identify and develop an approach to the goals of resource management and how to encourage the development of user-friendly material by land users and other stakeholders such as extension workers and non-governmental organizations. Training modules on soil biota are currently being developed.

Future research needs
To synthesize the knowledge gathered in these studies a model of indirect management of earthworm activities is being developed with the objective of optimizing the beneficial effects of earthworms in the agroecosystems (Figure 27; Mariani, unpublished). The aim of the model is to establish a permanent fauna activity in the soils of different agroecosystems.

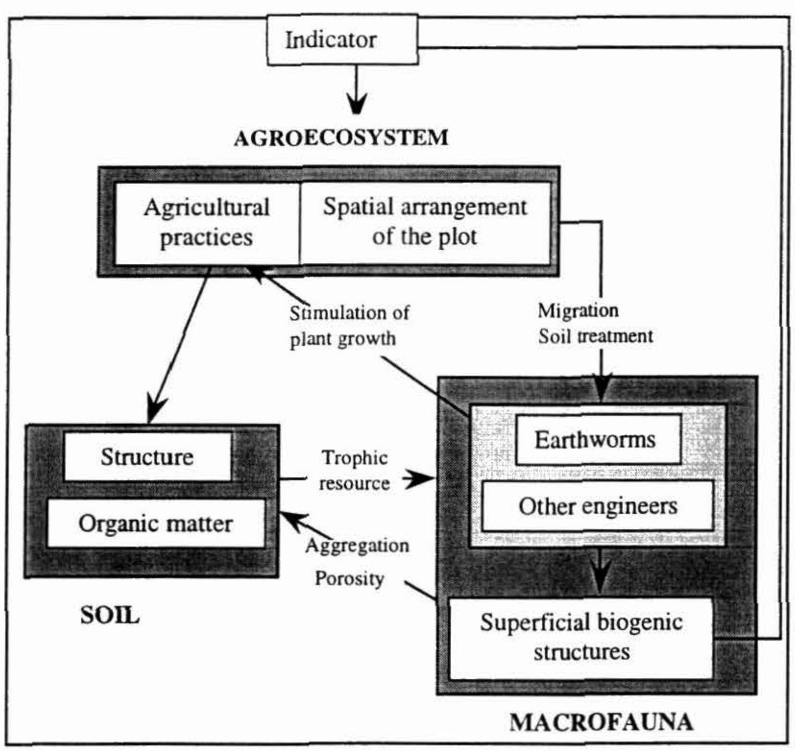

Figure 27. Proposed management model for earthworm populations and other engineers (L. Mariani, unpublished)

The monitoring of the biogenic structures produced by soil ecosystem engineers is a first step to understanding the links between biodiversity and its functioning. Together with this preliminary approach it is necessary to strengthen the efforts to understand the functional aspects of these structures through studies at different spatio-temporal scales, from the scale of the structure to the plot or population. The dynamics of the biogenic structures during ageing and the accompanying effects on different soil properties should be also considered. Then soil ecosystems engineers may be classified according to their effects on soil structure and nutrient dynamics, on the biodiversity of other soil organisms and on primary plant production. The development of alternative management options requires further detailed studies if we wish to prevent or reverse soil degradation through the directive use of the activity of the ecosystem engineers that have a significant and positive impact on soil structure and fertility. In addition the conservation of a diversified soil fauna with epigeics, endogeics and anecics will also favour the none ecoystem engineers, i. e. epigeic species or litter transformers. We can therefore optimize and increase soil beneficial organism activities within the scale of the plot and/or agroecosystem.

Within the **scale of the plot** the carrying capacity of selected species might be increased. To achieve this objective we need to know the sensitivity of different species to agricultural practices such as tillage, the use of fertilizers and pest control and to different feeding regimes.

At the **scale of the agroecosystems or land management practice**, studies are needed on the capacities of key species to migrate from pastures and the native savannas with high levels of biodiversity to land management systems such as cropland with low levels of biodiversity.

Biogenic structures can be used as an **index of engineering activities** in cultivated plots. This could be an indicator that can serve as a proxy for the more laborious measurement of populations of ecosystem engineers. If the dynamics of the biogenic structures are understood, i.e. their production and degradation, it may be possible to establish critical densities that can be used as early warning indicators of the effects of a change in agricultural practice.

The difficulties of studying scales greater than that of the size of the biogenic structures has been a handicap and hence most of the chapters on the effects of ecological engineers have been done at this scale. Studies that establish the functional role of soil organisms and options to optimize these activities through an integrated management model in agroecosystems are still required.

Firstly it is necessary to characterize the biogenic structures produced by other earthworms in order to test the hypothesis that the effects noted on soil processes are indeed hierarchically regulated. Weed dynamics and activities of earthworms are also worthy of further study, as is the role of earthworms in the dispersion of mycorrhizal propagules and in the stimulation of microflora.

There is a need to investigate the role of macrofauna in the degradation of tropical pastures especially in the Brazilian "cerrados" where, unlike Carimagua, there is evidence of physical, chemical and biological degradation. The causes of degradation are not clearly known for pastures of the humid tropics. The possible contribution of endemic species that are adapted to the changes in the ecosystem, ought to be considered in order to design practices with less damaging effects on the ecosystem. With this knowledge it may be possible to improve sustainability via the manipulation of the biological resources that could maintain the fertility of natural ecosystems and achieve high levels of primary productivity on infertile soils.

The bio-indicators of diversity and soil quality are important themes that ought to be considered as a priority for further research. An index is estimated from the presence and abundance of the most sensitive groups of macrofauna and related to agricultural practices in order to evaluate the value of biodiversity in terms of the maintenance of soil physical properties, the conservation of organic matter and primary production. It may be possible to estimate an indirect index through multi-variate analysis that establishes the relation between biodiversity, structural function and physical and chemical properties of the soil. These studies taken together will result in a better management of the agroecosystems where productivity, sustainability and conservation of the natural resources are integrated.

Finally the adoption of practices that encourage or stimulate the establishment and /or maintenance of significant macrofauna populations requires efforts in training and the encouragement of farmer research. This will vary from country to country and from region to region. A common language for land users and scientists needs to be developed so that the principles and concepts for the management of beneficial soil organisms can gain widespread acceptance and be further developed by the land users themselves.

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Output 3. Improved decision making for combating soil degradation and improved agricultural production

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

3.1.1 Test the suitability of microbially bound phosphorus as an indicator of soil biological fertility and of land use sustainability

Highlight:

- Found that the amount and turnover of P that is held in the soil microbial biomass is increased when native savanna is replaced by improved pasture while it was lowered when soils are cultivated and cropped continuously.

Purpose:
To test the role of soil microbial biomass in phosphorus transformations in an oxisol under contrasting land use systems.

Rationale:
As a non-renewable resource with relatively low concentrations in the biosphere, use of P from fertilizers must be rationalized. This is especially true in the tropics where iron and aluminum oxides in Oxisols and Ultisols cause strong sorption of soluble fertilizer P and reduce its efficiency. To improve the efficiency of P applications, it is imperative to maximize the recycling of P from crop residues, and organic and mineral fertilizers. In highly weathered tropical soils, the availability of P may depend more on the turnover of easily decomposable soil organic matter than on the desorption of inorganic P (P_i). The immobilization of P_i by microbes and its gradual release by microbial turnover can protect P from physico-chemical adsorption reactions if this release is synchronized with the demand of growing plants and/or a subsequent generation of microorganisms. Furthermore, a significant part of the P held in soil microorganisms is an easily available P source for plants.

Microorganisms play a key role in soil organic P transformations through excretion of phosphatase enzymes, P mineralization from organic sources, and synthesis and release of organic P. In addition, the solubilization of sparingly soluble inorganic P forms by microorganisms has been documented. Soil microorganisms were found to be a major factor in controlling organic and inorganic P solution concentrations in temperate grassland topsoils.

In recent years, substantial progress has been made in the selection and breeding of crop and forage plants genetically adapted to low-P soils. Some of these cultivars have been shown to efficiently utilize low fertilizer P inputs. Besides root attributes such as size, distribution and P uptake efficiency, which affect the ability of plants to absorb P, rates of crop/forage residue decomposition differ among plant species. The decomposition of plant residues is biologically driven, with soil microorganisms making by far the most important contribution in mineralization. A linkage between vegetative cover, soil biological activity and P availability was suggested by previous studies where changes in the P status of native savanna soils replaced by introduced grass-only (*Brachiaria decumbens*) and grass-legume (*Brachiaria decumbens* and *Pueraria phaseoloides*) pastures were investigated. Grass-legume pastures had higher reserves of labile organic P compounds (phosphonates and diester P) assessed by liquid state ^{31}P nuclear magnetic resonance spectroscopy. The soils under grass-legume pasture maintained higher organic and available P levels with less temporal variation than grass-alone or native pastures. With comparable fertilizer inputs and greater product exports than in grass-alone pastures, improved P availability in grass-legume pastures could not be due to differences in P budgets. It was suggested that greater turnover of roots and above-ground litter in legume-based pastures could provide for steadier organic P inputs and, therefore, higher P cycling and availability. The soil organic P fraction most affected was NaOH extractable P. NaOH-P_o is known to be the primary source of plant available P in non-fertilized systems. Furthermore, a close relationship between resin extractable P_i and organic P was observed in Ultisols. These results suggest that organic P contributes to available P_i.

If this is correct, land use systems that increase soil organic P should enhance soil biological activity and increase P mineralization. To test this hypothesis, an Oxisol was studied after five years under contrasting agricultural land-use systems. The systems were grass legume pasture (GL), continuous rice (CR) and native savanna (SAV) as control. First, chemical sequential P extraction was used to evaluate whether a higher partitioning of fertilizer P into organic fractions occurred in GL than in CR and SAV systems. To investigate whether organic P was immobilized or turned over, biological soil parameters related to P transformations such as size of the soil microbial biomass, amount of microbially bound P, C mineralization and acid phosphatase activity were assessed. Given the central role of microorganisms in the soil P cycle, microbial P turnover was studied using ^{33}P isotopic labeling.

Materials and Methods:

Field Experiment: Soil samples were taken in a five year old field experiment established in 1993 to investigate the sustainability of crop rotation and ley farming systems for the acid soil savannas. The experiment was carried out at the CORPOICA-CIAT, Carimagua research station, Meta, Colombia, 150 m above sea level on the eastern plains of Colombia. The area is representative of the well-drained savannas. Rainfall averages 2240 mm annually, falling mainly from late March to mid-December. Mean annual temperature is 27°C. Soils are well-drained silty clay Oxisols (tropeptic haplustox, isohyperthermic).

The following treatments were included in the study:
Native savanna (SAV): native grassland, burned once per year in February, not grazed.
Grass-legume pasture (GL): pasture undersown with rice in 1993, since then grass-legume pasture including *Brachiaria humidicola* CIAT 679, *Arachis pintoi* CIAT 17434, *Stylosanthes capitata* CIAT 10280 and *Centrosema acutifolium* cv Vichada CIAT 5277; partly resown for renovation in June 1996 with legumes (the same *Arachis pintoi* and *Centrosema acutifolium*; additionally *Stylosanthes guianensis* CIAT 11833); on average grazed with 2.7 steers ha^{-1} during 15 d followed by a 15 d ley re-growth phase.
Continuous rice (CR) since 1993: *Oryza sativa* cv Oryzica Sabana 6, cv Oryzica Sabana 10 since 1996; fallow during second semester rains and dry season.

The experiment had a split-plot design with four replicates with treatment sub-plots of 0.36 ha size (200 x 18 m). Before establishing the treatments GL and CR on savanna, the soil was conventionally tilled after burning the native vegetation. The CR and GL plots were limed before starting the experiment in 1993 using 500 kg dolomitic lime ha^{-1}. Fertilization of rice was with 80 kg N (urea, split among three applications of 20, 30 and 30 kg N), 60 kg P (triple superphosphate), 100 kg K (KCl), 35 kg S (20 kg elemental, 15 kg as $MgSO_4.H_2O$) and 10 kg Zn ($ZnSO_4.6\ H_2O$) per ha. With exception of fertilizer P placement in rice, all fertilizers were broadcast. While the introduced pasture received an additional 20 kg P ha^{-1} only when renovated in 1996, rice was fertilized annually (60 kg P ha^{-1}), resulting in the P inputs shown in Table 23. Native savanna was not fertilized. The systems additionally differ in soil cultivation (frequent, rare or no cultivation in CR, GL and SAV treatments, respectively) and in the application of herbicides (frequent, rare or no application of herbicides for CR, GL and SAV treatments, respectively).

Phosphorus budgets were estimated by subtracting the P removed from the system by grain and/or with animals from the P applied in mineral fertilizers. Phosphorus exports in grain were calculated by multiplying weighed rice grain yields with measured P contents in the grain. Phosphorus 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}.
Soil Sampling: Sampling was carried out during the rainy season, in September 1998. For the sampling, 0.09 ha sub-plots (75 m x 12 m) were delimited in each treatment and replicated to avoid border effects

and disturbance by micro-plots laid out for special investigations. These 0.09 ha plots were divided into three 25 m x 12 m sampling sub-plots to ascertain that random cores (60) were taken over the complete area. Sampling in the 0-10 cm layer represented a precautionary method to avoid contamination with soil from deeper layers that was not affected by soil cultivation (usually to a maximum of 15 cm depth).

Soil Phosphorus Analyses: Soil P analyses were carried out on each field replicate using air dried, 2 mm sieved samples. Soil P was fractionated by applying the following extractants sequentially on 0.5 g soil sub-samples and quantitating inorganic P, total P and (by difference) organic P in the extracts: H_2O with anion exchange resin in HCO_3-form, 0.5 *M* $NaHCO_3$, 0.1 *M* NaOH, and hot (80°C for 10 min) concentrated HCl. Total P in the soil residue after extraction was determined by digestion with hot concentrated perchloric acid.

Changes in fractions in fertilized CR and GL soils were compared to non-fertilized SAV using:

$$\text{Increase}(\%) = 100\frac{(\text{size of fraction in fertilized treatment - size of fraction in SAV})}{(\text{Sum } P_t \text{ fertilized treatment - Sum } P_t \text{ SAV})} \quad [1]$$

where:

$$\text{Sum } P_t = \text{Resin } P_i + NaHCO_3\, P_t + NaOH\, P_t + HCl\, P_t + \text{Resid } P_t \quad [2]$$

Bray-2 P was extracted using dilute acid fluoride (*0.03 M* NH_4F, 0.1 M HCl) at a 1:7 soil:solution ratio using 2.85 g soil and 40 sec shaking time. Total soil P was determined by digestion with a mixture of 2 parts hot concentrated HNO_3 and 1 part concentrated $HClO_4$, using 5 ml per 0.5 g soil.

Particulate Organic Matter: Particulate organic matter (> 53 μm) was isolated by dispersing soil of each field replicate in 5% sodium hexametaphosphate and passing the suspension through a sequence of 2 mm, 250 μm and 53 μm sieves. The fraction > 2 mm was discarded while the 250 μm and 53 μm fractions were dried at 50°C in an oven, finely ground and analyzed for total C and N using a flash combustion element analyzer.

Biological and Biochemical Soil Analyses:

Microbial Biomass C, N and P: Field moist soil (4 mm sieved) was incubated at 26°C for 15 d at a water content of 50% of field capacity (280 g H_2O kg^{-1} soil dry wt.) before the size of microbial C, N and P was determined. Microbial C and N were determined in duplicate and microbial P in triplicate on each field replicate. Microbial C and N released during chloroform fumigation (C_{Chl}, N_{Chl}) were calculated from the difference in extractable C and N, respectively, before and after the fumigation. The portion of microbially bound P released during fumigation with chloroform (P_{Chl}) was determined.

Soil respiration, C mineralization and phosphatase activity: Carbon mineralized during soil respiration was determined for each field replicate by trapping and quantitating CO_2 evolved by 40 g sub-samples of humid soil (4 mm sieved) placed in sealed containers. The metabolic quotient qCO_2 was calculated as the rate of CO_2-C production (μg) per mg C_{Chl} per h. Acid soil-phosphatase activity at pH 6.5 was measured on each field replicate.

Isotopic composition of extracted microbial P: Microbial P turnover in the absence of fresh organic matter additions was investigated in an isotopic labeling experiment carried out under conditions of constant soil respiration.

Statistical Analysis: Statistical analysis was carried out using log transformed data in order to meet the assumptions of analysis of variance (i.e. additive effects, symmetric errors with equal variance). The effect of land-use system was tested by analysis of variance (ANOVA). If the F test was significant ($p < 0.05$), the means were compared using Tukey's multiple range test.

Results and Discussion:

Fate of Applied P: Inputs by fertilizers exceeded P exports in GL and CR, resulting in positive P balances (Table 29). Total P determined by perchloric acid digestion was not significantly different from the sum of fractions extracted by the sequential procedure (Table 30). The total P content measured in the 0-10 cm soil layer was 52 and 152 mg P kg^{-1} higher in the GL and CR, respectively, than in the SAV topsoil (Tables 29 and 30). The increases in total P content calculated from the P balance (Table 29), assuming the bulk densities shown in Table 29, were 56 and 241 mg P kg^{-1} for GL and CR, respectively. This shows full recovery of applied P in the 0-10 cm soil layer of GL while some P is unaccounted for in the CR soil. Due to soil cultivation in the CR treatment (usually to a maximum of 15 cm depth), part of the applied P may have been mixed into deeper soil layers or may have moved into the subsoil.

In agreement with the positive P balance, available inorganic P increased in the CR and GL soils in relation to the SAV control (Table 30). For tropical pasture species, Bray-2 P values from 2 to 5 mg kg^{-1} (i.e., the range within GL soils fall) are considered medium while they would be considered low for crops. For most tropical crops, Bray-2 P values of 11-15 are considered adequate and >15 high, indicating that in the investigated CR soils, P is not a yield limiting factor.

Resin, $NaHCO_3$ (0.5 *M*) and NaOH (0.1 *M*) extractable P_i were higher in CR than in GL, both in absolute and relative terms (Table 30). NaOH P_i is confirmed to be the main sink for applied P, as observed in earlier studies on Oxisols at Carimagua and on Ultisols in the Amazon basin.

Table 29. Estimated P budget over five years (1993-1997) for contrasting land-use systems, and resulting changes in total P contents in the 0-10 cm soil layer.

Treatment	Estimated P budget			Increase in soil total P content		
	Input	Export	Balance	Bulk density†	Calculated from P balance	Measured ‡
	kg P ha^{-1}			Mg m^{-3}	mg P kg^{-1}	mg P kg^{-1}
Savanna	0	0	0	1.24	0	
Grass-legume	80	10	+ 70	1.24	56	52 (11)
Continuous rice	300	23	+ 277	1.15	241	152 (8)

† source: PE-2 Annual Report (1999)
‡ see Table 2; mean and SEM of 4 field replicates; pairs of SAV and GL, and SAV and CR, respectively, were formed at random.

Organic P fractions were less affected by P inputs than inorganic P fractions. In addition, they were less affected in CR than in GL where especially NaOH P_o acted as a sink. Analysis of changes in fractions using equation [1] shows that more than 30% of the increase over SAV went into organic fractions in GL while the corresponding portion was less than 11% in CR soils (Table 30). Differences in the partitioning of P in the fertilized treatments indicate that P transformation processes in CR soils differ from those in GL soils. Though changes in absolute size of organic fractions are not statistically significant (Table 30), the organic fraction most affected was NaOH extractable P_o. This confirms a higher partitioning of P applied as fertilizer into organic fractions in GL soils. If NaOH P_o could contribute to plant available P_i, GL should be characterized by higher soil biological activity mediating P mineralization, than CR soils.

Biological Activity in Relation to P Transformations

Size and composition of the microbial biomass: The amount of extracted microbial C, N and P was affected by the agricultural land-use system in the order GL ~ SAV > CR (Table 31). This confirms that, in Colombian savanna soils, the replacement of the native vegetation by grass-legume pasture rather increases the soil microbial biomass, while rice monocropping leads to a decrease.

Although the fumigation extraction method is widely used to measure microbial biomass, there is still uncertainty about the conversion factors (k_{EC}, k_{EN}, k_P) to use in calculating the total soil microbial C, N and P contents. While techniques for k_{EC} and k_{EN} determinations are available, recent studies agree on not using k_P factors because to date, no precise technique for its determination is available that could account for all the variation among different organisms and different soils. If we convert C_{Chl} using a k_{EC} of 0.25, the estimated soil microbial biomass ranged from 289 (CR) to 689 (GL) mg microbial C kg^{-1} soil. This is less than reported for Oxisols under undisturbed tropical rain forest, but is in the range reported for temperate pastures and arable soils. The same applies for the percentage of total soil C held in the microbial biomass (1.2 – 2.4%, assuming k_{EC} of 0.25), which suggests that the soil microbial population has adapted to the severe chemical constraints of highly weathered tropical soils.

While N_{Chl} values are also in a similar range to temperate cropped soils, P_{Chl} is significantly lower. As a consequence, C_{Chl}/N_{chl} ratios were similar while C_{Chl}/P_{Chl} was significantly lower. Lower C_{Chl}/N_{Chl} ratios in GL and CR than SAV indicate higher N availability for microorganisms in CR and GL soils. While N fertilizers were applied in CR, N availability in GL was increased by biological nitrogen fixation. The P availability according to Bray-2 P contents varied among the soils and was adequate to high in CR soils. Despite that, the C_{Chl}/P_{chl} ratios were only slightly affected by the land-use system. Microbial C/P ratios from 12:1 under high to 45:1 under low available P conditions were reported before.

Because it had the highest total soil P content and lowest P_{Chl}, the P_{Chl}/Total P ratio was lowest in the CR soil (Table 31). The CR soil was also characterized by the lowest C_{Chl}/Total C and N_{Chl}/Total N ratios, indicating a lower significance of microorganisms as nutrient pools in the CR than in the SAV and GL soils. The P_{chl} was lowest in CR despite the fact that this treatment showed the highest content in Bray-2 and resin extractable P_i (Table 30), confirming results obtained in another experimental site on the Eastern Plains of Colombia. Higher P_{Chl} amounts under grass-legume pasture than savanna or grass-alone pasture were also observed before. Consequently, in low P Oxisols, the quantity of extractable microbial P is determined by factors other than available inorganic P. Pastures containing legumes seem to exert a positive effect on microbial P through the input of plant material of higher quality. In addition, pasture soils are subjected to much less cultivation and herbicide applications than CR soils.

The size and composition of the microbial biomass in the various land-use systems agree with the higher importance of organic P in GL than SAV than CR soils suggested by the P fractionation data. However, the changes in the size of the microbial nutrient pools or organic P fractions cannot distinguish whether higher organic P means P immobilization, or if the increases go along with higher mineralization. Previous results suggest that the higher litter quality of grass legume pastures may result in increased mineralization and nutrient turnover. While approaches to measure soil P mineralization are available for non-P limited soils with medium to low P sorption capacity, the P mineralization potential of low P acid Oxisols can be deduced only from indicators. We used C mineralization obtained from respiration measurements and acid phosphatase activity.

Indicators on Phosphorus Mineralization: Cumulative C mineralization was higher in both grassland systems than in the CR soil (Table 32). While mineralization during the first two weeks of incubation was only slightly higher in SAV than GL (Fig. 28, Table 32), GL maintained higher mineralization thereafter.

Results on C mineralization were related to substrate availability indicated by particulate organic matter (Fig. 29). Both size fractions contained more C and N in GL than CR soils (significant at P = 0.05 for all except N in the 250 µm – 2mm fraction), and contents in SAV took an intermediate position. Particulate organic matter (POM) was found to account for the majority of soil organic matter initially lost as a result of cultivation of North American grassland soils. The POM-N content in moist savanna soils of West-Africa was shown to be influenced by organic matter additions and to contribute significantly to the maize N supply. That POM-levels were highest in GL, therefore, indicates a higher input of mineralizable organic matter, while the decrease found when SAV is replaced by CR suggests a loss of organic nutrient reserves.

Table 30. Distribution of P in various fractions in fertilized land-use systems (continuous rice, grass-legume pasture) five years after establishment on native savanna as assessed from sequential extraction. Relative changes (% increase) describe which percentage of total P increase in fertilized systems over native savanna was found in a given fraction (formula see footnote †).

	Resin	$NaHCO_3$		NaOH		HCl		Resid		Sum	
Treatment	P_i	P_i	P_o	P_i	P_o	P_i	P_o	P_t	P_t‡	P_i§	P_o
Savanna											
Mean (mg kg^{-1})	2.6a	3.9a	11.3a	27.4a	45.3	35.6a	23.9	60.6	212a	69a	81.9
Grass-Legume											
Mean (mg kg^{-1})	4.8b	6.7b	14.6b	45.5b	51.0	46.5b	30.3	62.2	263b	103b	97.8
% Increase†	4.3	5.4	6.5	35.5	11.3	21.4	12.6	3.2	101	66.6	31.1
Continuous Rice											
Mean (mg kg^{-1})	14.3c	20.2c	17.1b	111.0c	42.7	54.3b	36.2	65.6	363c	200c	98.0
% Increase†	7.7	10.7	3.8	55.0	-1.7	12.3	8.1	3.3	100	85.8	10.6
F-Test	***	***	**	***	Ns	*	ns	ns	***	***	Ns

Means of 4 field replicates samples per treatment. Means within a column followed by the same letter are not significantly different ($p = 0.05$) by Tukey's multiple range test. F-test: ***$p < 0.001$, **$p = 0.001$-0.01, *$p = 0.01$-0.05, *ns* = not significant.

† Increase (%) = (size of fraction in fertilized treatment - size of fraction in SAV) /
(Sum P_t fertilized treatment – Sum P_t SAV) * 100

‡ Sum P_t = Resin P_i + $NaHCO_3$ P_t + NaOH P_t + HCl P_t + Resid P_t = Sum P_i + Sum P_o

§ Sum P_i = Resin P_i + $NaHCO_3$ P_i + NaOH P_i + HCl P_i

¶ Sum P_o = $NaHCO_3$ P_o + NaOH P_o + HCl P_o

Table 31. Size, composition and significance of the soil microbial biomass nutrient pool in an Oxisol under different land-use systems: amounts of extracted microbial C, N and P; microbial nutrient ratios and extracted microbial nutrients as percentage of the total nutrient content in the soil.†

Treatment	C_{Chl}	N_{Chl}	P_{Chl}	C_{Chl}/N_{Chl}	C_{Chl}/P_{Chl}	C_{Chl}/total C	N_{Chl}/ total N	P_{Chl}/ total P
	mg kg^{-1}						%	
Savanna	145.0b	26.4b	5.4b	5.4	27.4	0.6ab	1.6b	2.5b
Grass-legume	172.3b	35.3b	6.6b	4.9	25.9	0.6b	2.0b	2.4b
Continuous rice	72.2a	17.5a	2.6a	4.1	27.6	0.3a	1.1a	0.7a
F-Test	**	**	***	ns	Ns	*	**	***

Means followed by the same letter are not significantly different ($p = 0.05$) by Tukey's multiple range test. F-test: ***$p < 0.001$, **$p = 0.001$-0.01, *$p = 0.01$-0.05, *ns* = not significant.

† determined after a 15 d incubation period

Table 32. Carbon mineralization and specific respiratory quotient of two different incubation periods, and phosphatase activity in low P acid soils of different land-use systems.†

Treatment	Cumulated C mineralization d1 – 14	d 14 – 63	QcO_2 d 1 - 14	d 14 – 63	Phosphatase activity
	mg C kg^{-1} soil		µg CO_2-C mg^{-1} Cchl h^{-1}		*µg nitrophenol g^{-1} h^{-1}*
Savanna	274b	299.3b‡	5.8	1.8	270.4c
Grass-legume	251b	416.8b	4.6	2.1	223.3b
Continuous rice	114a	161.5a	4.5	1.8	145.5a
F-Test	**	***	ns	ns	***

Means followed by the same letter are not significantly different ($p = 0.05$) by Tukey's multiple range test. F-test: ***$p < 0.001$, **$p = 0.001$-0.01, *$p = 0.01$-0.05, *ns* = not significant.

† determined after a 15 d incubation period

‡ different from GL value at $P = 0.06$ for the Tukey test

Table 33. Reactivity of microorganisms towards added ^{33}P compared with Bray-1 extractable P: percentage of ^{33}P recovered in extractable microbial P (P_{Chl}) and percentage of ^{33}P in the Bray-1 extractant of the non-fumigated, non-P-amended sample ($Bray_0$-P) at two sampling dates.

Treatment	d since labeling†	$Bray_0$-P	P_{chl}	Percentage of ^{33}P found in $Bray_0$-P	P_{Chl}
		mg kg^{-1}			
Savanna	2	0.4 (0.01)	5.3 (0.31)	4.9 (0.21)	9.6 (0.90)
	8	0.2 (0.01)	4.4 (0.14)	2.0 (0.08)	9.5 (0.15)
Grass-legume	2	1.4 (0.09)	4.4 (0.56)	5.8 (0.49)	24.7 (2.36)
	8	0.9 (0.04)	3.3 (0.23)	3.4 (0.04)	20.5 (1.86)
Continuous rice	2	7.4 (0.24)	2.2 (0.63)	6.9 (0.24)	1.6 (0.70)
	8	6.6 (0.24)	1.1 (0.05)	5.6 (0.26)	1.8 (0.24)

Mean and SEM (in brackets) of 3 analytical replicates.

† Before labeling, soils were incubated during 3 wk.

In contrast to microbial biomass and soil respiration, the metabolic quotient qCO_2 did not differ among treatments, neither for the unsteady respiration phase from d 1 to d 14, nor during the phase of basal respiration (Table 32). Thus, no difference in organic substrate use efficiency is suggested.

The acid phosphatase activity, and in turn the potential to mineralize available phosphomonoesters, declined in the order SAV > GL > CR (Table 32). Soil acid phosphatases are exoenzymes of microbial and plant origin. They can keep their functionality through stabilization by sorption and association on soil compounds. Plant roots increase phosphatase secretion under conditions of P deficiency. In addition, acid phosphatase activity in soils is related to soil organic matter content. Higher phosphatase activities in SAV than GL and CR therefore present a composite result of greater overall biological activity, low P_i availability and higher organic substrate availability observed in these treatments.

In conclusion, results on C mineralization, substrate availability estimated by organic P fractions and POM, and phosphatase activity suggest that P mineralization is more important in delivering available P in GL soils than in SAV and CR soils.

Microbial P turnover

Two d after labeling the soil, 25, 10 and 2% of the added ^{33}P were recovered in extractable microbial P in GL, SAV and CR soils, respectively, with only slight changes occurring until d 8 (Table 33). Differences among the percentage of incorporated isotope were greater than among P_{Chl}. Extractable P_{Chl} was on similar levels in GL and SAV soils during the incubation experiment, and lower in CR. Comparison of the P_{Chl} value assessed at the end of the pre-incubation time before labeling the soil (Table 31) when it had reached basal soil respiration (Fig. 28) with P_{Chl} values measured during the incubation experiment (Table 33) shows that the size of P_{Chl} did not increase, but rather decreased during incubation (Table 31 and 33). Thus, incorporation of ^{33}P was not caused by an increase in P_{Chl} size, but shows that a part of P_{Chl} was renewed. More than 20% of the tracer found in P_{Chl} in the GL soil suggests that microorganisms had turned over significant amounts of P held in their biomass during the 2 d since labeling. This indicates a greater turnover of extractable microbial P in GL than in SAV and CR.

These high rates of ^{33}P incorporation into P_{Chl} suggest that microbes can assimilate large amounts of soluble P_i within a very short time. The exact mechanisms of P assimilation by and P release from specific soil microorganism species have received scant attention. The P regulation of a few microbes, especially *Escherichia coli* and *Saccharomyces cerevisiae*, is well known from laboratory studies. Inorganic orthophosphate is the preferred P source. To cope with low P concentrations, *E. coli* as well as other microorganisms have developed an emergency system induced by gene expression. It includes additional specific P_i transport mechanisms, increased phosphatase production, and uptake of glycerol and hexose phosphates and phosphonates. An increased rate of P recycling by organisms living in P deficient soils was suggested before. Substantial microbial P turnover can be deduced from other incubation studies as well.

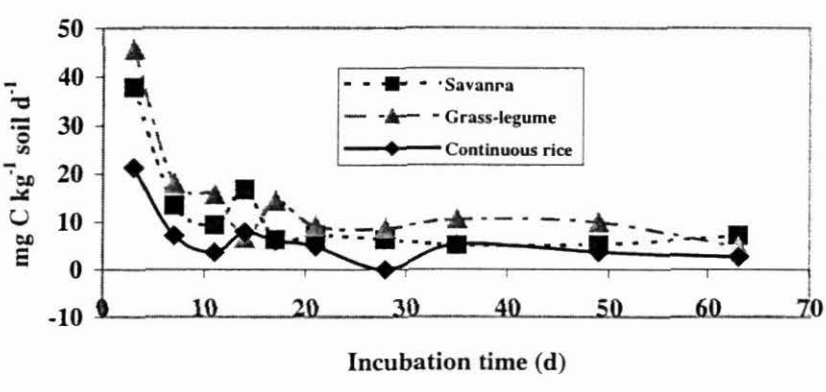

Figure 28. Changes in daily C mineralization rate during the incubation.

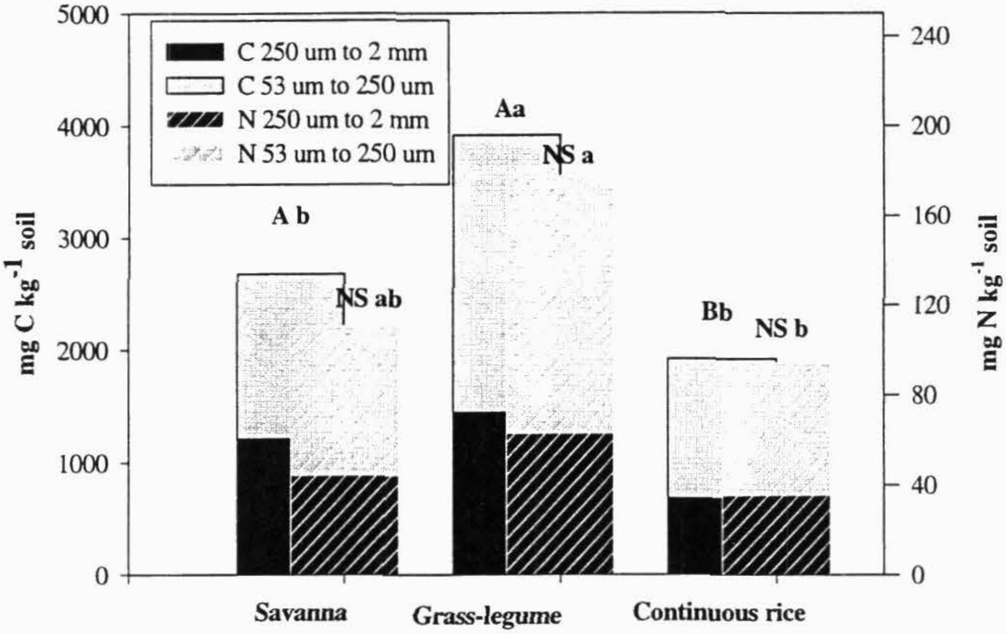

Figure 29. Particulate organic matter C and N in two size fractions in soils of contrasting land-use systems. Upper case letter denote significant differences among systems for the fraction with the size 250 µm – 2mm, lower case letters for the 53 µm – 250 µm fraction.

Application of the sequential P fractionation procedure described previously on ^{33}P labeled GL soils showed that, 2 d after labeling, up to 10% of the added isotope was recovered in NaOH-P_o (S. Bühler, unpublished results); this concurs with the fast turnover of extractable microbial P deduced from ^{33}P incorporation. These findings suggest a great significance and velocity of organic P turnover in low P acid Oxisols, and agree with recent results showing that soil organic matter turnover was much faster in highly weathered tropical than temperate soils.

While other studies carried out with C additions and wetting-drying cycles caused flush effects that were accompanied by significant changes in the size of microbial P, our work concerns microbial P turnover under conditions of basal respiration and nearly constant P_{Chl} size. Nevertheless, it cannot be completely excluded that soil microbial activity was stimulated by the thorough mixing that occurred when labeling the soil, even though the size of P_{Chl} was not increased (Table 33). Other factors that could result in overestimated turnover are the presence of labeled particulate or organic P since the calculation of ^{33}P found in P_{Chl} is based on specific activity determinations obtained by dividing total radioactivity by P_i in aliquots of the Bray-1 extracts.

Significance of microbial P and organic P cycling in contrasting land-use system: In our study, the highest ^{33}P incorporation (Table 33) suggesting fastest microbial turnover, was found in GL, which also had the highest biological activity (Table 32, 33) and low to medium available P content (Table 29, 30). The lowest turnover rate was found in the CR soil, which also had the lowest biological activity and highest P status. The intermediate microbial turnover rate in SAV was accompanied by low available P and intermediate biological activity. Thus, in the investigated soils, biological activity rather than soil inorganic P availability seems to determine microbial P uptake and release, and thus microbial P turnover. The higher the microbial activity, the greater is microbial P turnover.

In fertilized Ultisols, inorganic P was found to be the main source of plant available P. However, our results suggest that this applies only in the case of high fertilizer doses. In the case of the low P doses applied to GL, increases in biologically mediated, organic P related processes play an important role in the maintenance of P availability and the efficiency of P cycling. These low P doses are maintained in the P cycle by the standing plant biomass of introduced pasture germplasm adapted to low P conditions, which provide for steadier organic P inputs by root and above-ground litter than do crops. Through the decomposition process, plant litter P enters into the soil microbial biomass. The microbial biomass represents a rapidly cycling P pool whose turnover is affected by the agricultural land use system. Thus, in the case of low P doses, the failure of P to enter organic P pools, including plant biomass, living and dead soil organic matter, can be thought to indicate a degrading system due to low level of P cycling (PE-2 Annual Report, 1999).

The present study cannot provide a final statement on the impact of different microbial P turnover rates on soil P dynamics. The immobilization of P_i by microbes and its gradual release through microbial turnover protects P from physico-chemical adsorption reactions with soil particles if this release is synchronized with the demand of growing plants and/or of a next generation of microorganisms. If not, substantial competition between soil microbes and plants, on the one hand, and soil inorganic particles (adsorption surfaces) on the other, could occur for the scarce P resource. While inorganic P availability was increased more in CR than in GL, both absolute and relative to total P increases in soils, the organic P availability was increased more in GL. Introduced GL pastures, in which soil microbial P turnover is greatest, sustain a high productivity of high quality forage. This suggests that increased microbial P contents do not inhibit improved forage germplasm from acquiring the P needed.

Impact:

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 and cultivated soils while, in cultivated soils, much higher P fertilizer doses significantly increase available inorganic P contents with lesser impact of organic P pool sizes. The amount and turnover of P held in the soil microbial biomass is increased when native savanna is replaced by improved pasture while it was lowered when soils are cultivated and cropped continuously. Therefore, the study suggests an alternative strategy to cropping low P Oxisols through applications of high P fertilizer doses. The combination of low P fertilizer doses and grass-legume pastures composed of germplasm that is adapted to the chemical constraints of Oxisols promotes P cycling and efficient use of P inputs. Given the high productivity of grass-legume pastures, the soil microbial biomass cannot be seen as a pool competing with the plant but rather as an important part in the P cycle that supports a high P use efficiency of the non-renewable P resource. However, it remains to be investigated whether crops planted in pasture-crop rotations could benefit from the enhanced organic P dynamics in grass-legume pasture soils, and a direct method to quantify organic P mineralization should be developed and tested in these systems.

Contributors:

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3.1.2 Impact of different land uses and soil management practices on the physical, chemical, and biological changes of soils of the well-drained *Altillanura*

Highlight:

- A special project funded by PRONATTA was completed and the results contributed toward development of a number of recommendations for land use planning and soil management for the infertile Oxisols of the *Altillanura* of Colombia.

Purpose:

To determine the impact of different land uses and soil management practices on the physical, chemical, and biological changes of soils of the well-drained *Altillanura.*

Materials and Methods:

Study site: The present study was conducted in the municipalities of Puerto López and Puerto Gaitán, Department of Meta, Colombia, between 30° 55' and 40° 20' N latitude and between 72° 1' and 72° 55' W longitude. The area contains flat, undulated, and dissected *Altillanura* landscapes.

Climate and soil characteristics: The average annual precipitation in the area of influence of Puerto López is 2649 mm, with a standard deviation of 340 mm, and in the area of influence of Puerto Gaitán it reaches 2158 mm, with a standard deviation of 282 mm. The altitude ranges between 100 and 200 masl. Mean annual temperature was 26 °C, with 80% relative humidity. During the rainy season (April-November), potential evapo-transpiration was 112 mm/month (with a standard deviation of 3.4 mm) and solar radiation was 4.47 Kw-h/m^2 (with a standard deviation of 0.21). Soils are acid with low organic matter, calcium, magnesium, potassium, and phosphorus contents, and high aluminum saturation levels that limit plant growth. Light-textured soils generally show greater nutritional limitations than heavy soils, but have the advantage of presenting a lower percentage of aluminum saturation and greater available phosphorus. Altillanura soils are very old; in flat-convex areas, Oxisols (Haplustox, Haplortox, Acrorthox) are found in flat-convex areas, whereas Inceptisols (Andaquepts, Plinthaquepts, Tropaquepts) are found in concave areas that have accumulated materials from higher areas. In some areas Ultisols (Umbraquults) are found.

Sampling sites: Sixteen farms, distributed in three landscapes—flat, undulated, and dissected *Altillanura*—were selected. Sampling sites were selected on each farm regarding land use and compared with the check (undisturbed soil). Several farms were selected for in-depth studies of undisturbed soils regarding landscape and slope. Overall, 70 sites were selected that included savannas of different landscapes and different slopes within a specific landscape, as well as diverse land uses, for example established or traditionally renewed pastures (use of phosphoric rock or "Calfos" as only source of fertilizer at very low rates and with intensive harrowing), or established or renewed pastures planted with a crop (rice, maize), crop rotation, annual monocrops, and permanent crops (African oil palm, rubber, pine, mango, cashew, and citrus fruits). The respective samplings were carried out at each site from September to November in a 10-m radius of the target point. Measurements were carried out during the dry season to determine permanent wilting point (PWP) under field conditions as well as trials on response to rainfall in savanna soils. All sites selected did not present any physical impediment for tillage in terms of effective depth, stoniness, high moisture saturation or relief that allowed little access of machinery.

Sampling depth: Chemical variables were measured at three depths (0-5 cm, 5-20 cm, and 20-40). Texture, density, sand distribution, and soil microbiology were measured at two depths (0-5 cm and 5-20). Vertical tangential resistance (TVR) and distribution of soil aggregates were measured at 0-3 cm depth. Infiltration and hydraulic conductivity were evaluated at 0 to 10-cm depth. Resistance to penetration was measured at 0-60 cm depth.

Sampling methodology and sample size: Twelve samples were taken with auger at every sampling site or point, at the respective depths, to determine chemical, textural, and microbiological variables. Composite samples for each depth range were then sent to the lab. Four rings (5 cm × 5 cm) at each sampling depth were used to determine bulk and real density. To measure infiltration three pairs of infiltrometer rings arranged in an equilateral triangle were used at each sampling point. Measurements were taken at the following time intervals: 1, 2, 3, 4, 5, 10, 15, 20, 30, 45, 60, 90, and 120 minutes. Infiltration was measured in all cases after at least 2 dry days. To evaluate resistance to penetration (RP) and vertical tangential resistance (VTR), six readings were made for each variable under field capacity conditions. To successfully simulate field capacity conditions at each site, three rings, 30 cm in diameter, were buried saturated with water and covered with plastic and grass. After 2 days, the site was revisited and two measurements of resistance performed at each ring. A cone penetrograph, with maximum reading capacity of 25 kg/cm^2, was used to measure resistance to penetration. A metallic TURVANE, 1.9 cm in diameter and 3 cm long, was used to measure vertical resistance; its maximum capacity for reading was 140 kPa. Three dilutions were used for the microbiological count, with three readings per dilution, following the methodology established by the Tropical Soils Biology and Fertility Program (TSBF). Twenty frames were placed in two transects to determine plant composition and forage availability in savanna soils, using the BOTANAL methodology. Transects crossed at the center of the indicated point.

Evaluating productivity: Farm sampling sites included several of those used for CIAT-managed experiments to integrate and complement data on crop productivity and seasonal animal performance on soils of different textures.

Additional measurements taken during the project: The following additional measurements or activities were also performed during the course of the project

1) A satellite trial to test the effects of incorporating different rates of lime, at different depths, using maize Sikuani v-110 and *Panicum maximum* as test materials.
2) Determination of rainfall distribution and weekly frequency in the target area.
3) Study of vesicular-arbuscular mycorrhizae (Unillanos thesis).
4) Determination of field capacity and permanent wilting point in the field.
5) Soil processes of wetting and drying during the dry season.

Test indicators
Chemical: Organic matter, aluminum, phosphorus, calcium, magnesium, and potassium.

Physical: Sand, lime, clay, infiltration rate, hydraulic conductivity, bulk density, particle density, total porosity, distribution of aggregate size, distribution of sand particle size, resistance to penetration, vertical tangential resistance, field capacity, and permanent wilting point.

Biological: Populations of bacteria, fungi, actinomycetes, and number of spores of vesicular-arbuscular mycorrhizae.

Vegetation: Floristic composition of savannas, forage contribution of species, rate of occurrence of species, forage availability, and average height of vegetation.

Production: Crop yield and meat production per hectare in soils of different textures.

Climate: Distribution of days of uninterrupted rain or drought during the rainy season; rainfall distribution.

Information management and analysis: The data were stored in a database and organized in external files using SAS. For analysis of variance, farms were taken as replicates for each landscape, using the PROC GLM procedure and Duncan's multiple range test to separate averages. Descriptive analyses of frequencies, averages, and standard deviation were performed for several variables. Pearson's linear correlation analysis was applied to all variables and those showing high correlation coefficients and significance with well-defined distribution of points were then adjusted by the "curve expert" program.

Results and Discussion:

Results from this special project contributed toward development of the following recommendations for land use planning and soil management for the infertile Oxisols of the *Altillanura* of Colombia.

Rainfall distribution

1. From the viewpoint of water requirements of grasses and crops, rains begin as of week 16 (22 April) and stop during week 46 (19 November), which means that there are 7 months of rains in the area of influence of Puerto López up through Carimagua.
2. Rain distribution implies that initial soil preparation should begin in mid-November and be complemented in April so soil physical conditions are not affected, ants and weeds are controlled, and the destruction of earthworm population minimized.
3. If rain distribution is used properly, then crop rotation is possible, taking advantage of the short Indian summer in August to plant the second crop. However, in the *altillanura* of the Department of Vichada, between La Primavera and Venezuela's frontiers, precipitation is 56% lower than that of Puerto López and the weekly distribution of rains is unknown. Crop rotation is therefore restricted.

Soil chemical properties

1. Savanna soils present chemical differences in terms of slope and depth. The soil profile of lowland savannas show levels of DM, P, and total bases that are 70%, 68%, and 24% higher than those of the high plateaus. Nutrients tend to concentrate mainly in the 0-5 cm depth.
2. Land uses involving permanent crops (African oil palm, rubber, pine, citrus fruits) and crop rotations showed higher nutrient content than soils with improved pastures and annual monocultures.
3. Nutrient content in the soil profile was irregular for all land uses. The highest amount of nutrients was concentrated in the 0-5 cm depth, especially phosphorus and calcium and, to a lesser extent, potassium.
4. Maximum yields of *Panicum maximum* and maize Sikuani v-110 were obtained with tillage between 0-15 cm depth and application of dolomitic lime at 2000 and 3000 kg/ha; however, maximum efficiency in reducing the percentage of aluminum saturation occurred at 30 cm depth, with 3000 kg dolomitic lime/ha.
5. Potassium content in the soil profile was not affected by liming rate and tillage depth. Its distribution was more uniform compared with that of calcium and magnesium, indicating its greater mobility.
6. By using a rigid chisel, low values of resistance to penetration (<10 kg/cm^2) were obtained, on average, up to 22.5 cm; with the harrow low value were obtained up to 7.5 cm depth. The cumulative infiltration with the chisel was 2.7 times greater than that obtained with the harrow.

Soil physical properties

1. The water infiltration rate in savannas of the undulated *Altillanura* (uA) was higher than in the flat (fA) and dissected *Altillanura* (dA) because uA generally has high percentages of sand and low tangential resistance to surface cut. Lowland savannas generally show higher infiltration than highland plateaus.
2. Land use involving permanent crops allowed moderately fast infiltration rates, whereas infiltration was slow when land use involved annual monocultures. Pastures, in general, showed intermediate infiltration.

3. A positive exponential relationship (r = 0.96) was found between percentage of sand and cumulative water infiltration during two hours in highland savannas. Soils with less than 20% sand present slow infiltration, and those with more than 70% present fast infiltration.
4. A negative exponential relationship (r = -0.86) was found between tangential resistance to cut measured at 3 cm depth and cumulative infiltration; values lower than 20 kPa enhance infiltration and those higher than 45 kPa reduce it substantially.
5. The percentage available water (PAW), measured under field conditions in undisturbed highland savannas, changed depending on soil texture and depth. At 0-20 cm depth, the PAD was of 16% for clay soils, 14% for clay loam soils, and 9% for sandy loam soils; at 0-40 cm depth, these values were, accordingly, 9%, 9%, and 7%.
6. The percentage organic matter (OM) and bulk density (BD) changed with texture; heavy textures showed higher OM contents and lower BD, whereas light textures presented low DM contents and high BD. Furthermore, OM decreased with depth, whereas BD remained relatively constant.
7. Fine sands (< 0.25 mm) predominate in the highland savannas, representing between 60%-80% in all textures and depths up to 40 cm.
8. Trials involving wetting and drying of soil during the dry season in the fA indicate that heavy soils become wetter faster (24 hours) than light soils (96 hours). For both heavy and light soils, the complete drying phase takes 15 days during the summer.
9. Soil microaggregates (MAG) in undisturbed savanna soils increased with percentage organic matter (r = 0.96) and decreased with percentage sand (r = -0.94). In general, soils containing less than 3% OM or more than 50% sand are potentially vulnerable to degradation and loss of structure.
10. The use of harrows to renew pastures on light-textured soils increased the loss of OM (63%) and MAG (11%) compared with the use of chisels (losses of 41% and 3%, respectively). In heavy soils, the use of chisel keeps MAG stable and increases OM content, whereas the harrow reduces OM by 12% and MAG by 14% at the 0-5 cm depth.
11. Resistance to penetration (REPE) in soils of undisturbed highland savannas was lower in soils of sandy loam texture than in those of clayey texture.
12. REPE at 0-30 cm depth in the depressions of the dA was less than 10 kg/cm^2, whereas, in the uA, it was higher than 10 kg/cm^2 at all sites.
13. Land uses in clay loam soils of the fA, that involved pineapple, crop rotations, and rubber, showed low REPE values (< 10 kg/cm^2) in first 22 cm of depth. On the other hand, in sandy loam soils planted to yellow tobacco, African oil palm, and *Brachiaria dictyoneura*, REPE values were higher than 10 kg/cm^2, except for pine plantations.

Soil microbiological properties

1. Soils in general, regardless of use and landscape, showed low populations of bacteria and fungi and acceptable populations of actinomycetes and vesicular-arbuscular mycorrhizae (VAM). The greater presence of actinomycetes indicates poor OM quality and slow OM decomposition in these soils.
2. Dominant fungi included those of the genera *Penicillium* (76.8%) and *Trichoderma* (13.2%); in the case of bacteria, those of the genus *Pseudomona* (42.7%) dominated, and among VAM, those of the genera *Glomus* and *Acaulospora*.
3. The populations of fungi and actinomycetes was higher at 0-5 cm depth, whereas that of bacteria was higher at 5-20 cm depth, possibly attributable to the antibiotic production capacity of *Penicillium* and the role of actinomycetes as inhibitors of bacterial development.

Floristic composition and forage biomass of savannas

1. In the fA, clayey textures showed higher forage biomass (2,429 kg DM/ha) than sandy loam textures (1,732 kg DM/ha), attributable to the higher forage contribution (FC) of *Trachypogon vestitus* (68.5%) and *Schizachyrium hirtiflorum* (18.5%). The FC in sandy loam textures was attributable to

Trachypogon vestitus (35.5%), *Paspalum pectinatum* (34.5%), and *Thrasya petrosa* (9%).

2. Forage biomass and plant composition in the uA changed depending on the slope. Lowland sites showed higher forage biomass (1,440 kg DM/ha) than highland sites (836 kg DM/ha). The species contributing more forage in lowland sites were *T. vestitus* (80%) and *P. parviflorum* (17); in highland and intermediate-altitude sites, *T. vestitus* decreased to 56% and 66%, respectively, and *Rynchospora podoesperma* contributed 11.5% and 16% of the forage, respectively.
3. Forage biomass in the dA was higher in lowlands (4,494 kg DM/ha) than in the highlands (3,382 kg DM/ha), associated to changes in soil texture, in OM content, and in floristic composition. In lowland sites, the species that most contributed forage were *S. hirtiflorum* (44%) and *Andropogon selloanus* (18.5%); in the highlands and intermediate-altitude zones, *T. vestitus* contributed the most with 68.5% and 84%, respectively.
4. The highest forage biomass was found in the depressions of the dA and the lowest in uA. In general, changes are associated with soil moisture dynamics and OM contents.

Agricultural and livestock productivity

1. Pastures established with rice in heavy and light soils produced, over a 3-yr period, 4.5 and 1.8 times more meat/hectare than traditionally established pastures (121 kg meat/ha). Also, rice yields of 3,400 and 2,700 kg/ha were obtained in the savannas, covering 100% of pasture establishment costs.
2. The recovery of degraded *Brachiaria decumbens* pastures by sowing rice and maize allowed meat production/hectare to triple or double, respectively, during the rainy season and triple and quadruple, respectively, during the dry season, compared with traditional recovery with harrowing plus P fertilization. A total of 124 kg meat/ha was produced during the rainy season and 9 kg meat/ha during the dry season.

Impact:

The project achieved the specific objectives proposed. Additionally, measurements were taken that increased the understanding of soil characteristics of the *altillanura* regarding texture. A first approximation was made to determining critical levels. This information, together with institutional research, will help generate new concepts for decision making regarding soil use and management that will ultimately serve as tools to support planning, technology transfer, and extension agencies.

The funding provided by PRONATTA was fundamental to the achievement of the proposed objectives, as well as well organized inter-institutional and interdisciplinary work during project execution and development.

Project results were shared with stakeholders at three events:

1. Two scientific articles presented at the IX Colombian Congress of Soil Science, held in Paipa (Boyacá) on 23 October 1998:
   - Relaciones entre la infiltración de agua en el suelo y algunas propiedades físicas en las sabanas de la Altillanura Colombiana
     Phanor Hoyos, Edgar Amézquita, Richard J. Thomas, Raúl R. Vera, Diego L. Molina, and Edgar F. Almanza
   - Efecto del sistema y uso de la tierra en la distribución de los agregados en suelos de la Altillanura Colombiana
     Phanor Hoyos, Edgar Amézquita, Richard J. Thomas, Raúl R. Vera, and Diego L. Molina
2. Presentation of results at ICA-Puerto López on 31 July 1999, directed toward proudcers, individual technical assistants, guilds, and institutions.
3. A seminar was presented at CIAT-Palmira on 9 September 1999, directed toward scientific staff, research associates and assistants, university students (pre- and graduate level), and technical staff.

Results from this special project identified the following aspects for further research and analysis:

1. To design soil management strategies and uses of the *Altillanura* of the Department of Vichada, Colombia, we recommend an analysis of the weekly distribution of rains and the probabilities of continuous dry and rainy days.
2. We also need to know the water storage capacity of soils of Vichada's *Altillanura*, the bulk density and size distribution of sand particles, and their relationship to the dynamics of soil wetting and drying.
3. We recommend studies be conducted on waste management of savannas, pastures, and harvest residues, systems of incorporation regarding age of cutting, quality, length or size of brushwood, and effects on soil chemical, physical, and biological characteristics for different textures and depths.
4. Studies should be conducted on different types of simple and composite fertilizers of different concentrations, solubility, and refinement to evaluate fertilizer management and dynamics in soil profiles, when applied at different rates. The response in terms of root production, forage biomass, harvests, and soil chemical and physical characteristics for texture and depth should also be studied.
5. Studies to evaluate the water balance of savanna soils of the *Altillanura*, under different uses, regarding precipitation, intensity of rains, cumulative days of rain, cumulative dry days with volumetric amount of water held in profile, water lost by runoff, to determine models of hydrologic efficiency for different textures and slopes.
6. Initiate research strategies to implement other potential uses for soils of the fA that offer producers and new investors alternatives to diversify production, improve their income, and generate regional employment.

Contributors:
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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 Local soil quality indicators/soil quality monitoring system

Highlight:
- Soil quality indicators have been identified for the savannas and hillsides agroecosystems and have been incorporated into a guide that is being tested in Colombia, Central America and the East African Highlands as part of collaborative activities under the SWNM system-wide program.

Purpose:
To develop a user friendly soil quality monitoring system as a decision making aid for land users.

Rationale:
Soil degradation can occur rapidly with events such as severe storms and landslides. However the majority of degradation in farmers' fields occurs slowly, almost unnoticeably with the loss of topsoil organic matter and nutrients. The recuperation of degraded soil is always a slow and costly process with few exceptions such as nutrient depletion, soil surface crusting and sealing. Therefore land users and policy makers require sets of indicators to monitor the state of the land (soil and water) for use as early warning signals of degradation in order to make timely decisions on land management to reverse or prevent further degradation. Because soil is a multi-functional medium involved in the regulation of biogeochemical nutrient cycles, as a conditioner of the amounts and quality of water available to plants and as a

bioremediator of agrochemicals and other xenobiotic chemicals, indicators of soil quality should also reflect these different functions. However whilst indicators and standards for air and water quality are already in place, the soil has been neglected. This is partly because a definition of soil quality is not as simple as that for air and water and is often laden with value judgements. Despite the on-going debate concerning soil quality and indicators, farmers and other land users already employ their own local or indigenous indicators (e.g. soil color, presence/absence of weed species) that are often far removed from scientific or technical indicators.

Development of a soil quality indicator guide. Guidelines have been developed to help farmers and researchers recognize, understand and develop common sets of soil quality indicators (SQI's). Local knowledge is collated and new concepts and principles are added that incorporate scientific or technical indicators into a common language that can be of widespread value. This is especially important when the deterioration of soils is less evident to the land user e.g., invisible soil-borne pathogens, gradual erosion of the topsoil or acidification. The eventual aim is to develop a soil and water quality monitoring system that can be used by the land user for decision making over different temporal and spatial scales.

The development of local soil quality indicators starts with the application of a participatory method for identifying and classifying local soil quality indicators at the micro-watershed level. This process is included in a guide that promotes an understanding of soils through the different perceptions and experiences of the small-scale farmer. A theoretical framework is established using a simplified model of the origin of soils. Details of the guide have been published in Spanish and English as part of a set of nine guides for natural resource management (CIAT, 1999). Briefly the guide is in three sections. The first provides simple information on what soil is, how it is formed and indicators of soil quality. A series of practical exercises are outlined to enable an instructor to help participants develop skills for classifying soils. The exercises result in an understanding of the principal physical, biological and chemical properties of soils. The second section provides an explanation of soil quality indicators and how to identify and prioritize local indicators. Farmers are brought together in a meeting where they work in groups. Both a matrix and a classification system are used to prioritize their own indicators. The third section outlines how to organize a "Soils Fair" for farmers. This aims to help farmers develop skills in determining through simple methods, the physical, chemical and biological properties of soils and relate this to their knowledge of local soil management. A series of exercises and group work leads the participants through the identification and ranking of local soil quality indicators. During the training exercise local and technical indicators of soil quality were compared to technical assessment methodologies. An example of an outcome of this process is presented in Table 34.

Table 34. An example of the integration of local and technical soil quality indicators and their ranking by farmers.

Order of Importance	Indicator	
	Local	Technical
1	Good plants, good crops, healthy looking, thick/Bad plants, bad crop	Yield
2	Land with chichiguaste, malva/Land with zacate	Vegetation type
3	Loose soil, porous,, powdery	Soil structure
4	New land (land use change from pasture to crops), less than 10 years of use/more than 10 years of use	Length of time used
5	Soil depth (half machete, 12 inches), thick/thin soil less than 4 inches	Effective soil depth

The training tool has been developed for application by two groups. The first are professionals and technicians in private and public institutions and organizations working on NRM and sustainable development. They use the guide to support planning, follow up and evaluation of their initiatives. Some eventually become trainers in the use of the guides themselves. The second group consists of the inhabitants of watersheds or members of community-based organizations. They can work with NGO's and other organizations to use the methods and strategies and actively participate in the management of their natural resources. As part of the training in the use of the guide the participants should practice what they have learned. To facilitate this the development of "action plans" is encouraged. These are work plans orientated to the application of the decision-making guides by the participants in their particular sites. In Honduras for example there are five action plans that employ the soil quality indicator guide (Table 35). For Colombia, Honduras and Nicaragua over 50 institutions are participating in this process.

Table 35. Organizations and action plans that are utilizing the local soil quality indicator guide in Honduras.

Institution	Collaborating institutions/communities
Menonite Social Action Commission	Regional offices working with 3 communities (San Antonio, Limpia and Choloma
COHDEFOR Honduran Corporation for Forestry Development	Working with 10 community organizations in St. M. de Colon
AFE-COHDEFOR Watershed management section	Working with farmers in 5 critical conservation areas
Christian Commission for development	Working with technicians, agricultural facilitators, farmers and technical support committees
DICTA/SAG Science and Technology Division	Working with other institutions, technical personnel and farmer enterprises at country level

At the same time as the development of local soil quality indicators scientists conduct biophysical experiments under more controlled conditions either on- or off-farm to determine the most appropriate set of indicators for a particular agroecosystem. Ideally parameters should be identified that integrate physical, chemical and biological factors. For example and under certain circumstances, water infiltration can be used as an integrative factor as it is dependent on soil physical structure, particularly texture, soil chemistry (the relationship between soil surfaces) and soil porosity, all of which are affected by the activity of soil biota. To avoid the need to develop sets of critical values for each parameter and soil type work has been initiated using a native ecosystem such as the native savanna or forest for benchmark values and comparing values under different land management practices on similar soil types. For more widespread use it is recognized that critical values will need to be determined for different soil parameters.

To be useful to a variety of users including farmers, extension workers and policy makers, SQI's should be;

i) relatively easy and practical to use under field conditions by farmers, extension workers, specialists and scientists.
ii) relatively accurate, precise and easy to interpret.
iii) cost-effective to measure.
iv) sensitive to variations in management and climate.
v) able to integrate soil physical, chemical and biological properties and processes and serve as basic inputs for estimation of soil properties or functions that are more difficult to measure directly.
vi) correlate well with ecosystem processes, plant and animal productivity and soil health in a predictable way.
vii) components of existing soil data bases.

Table 36 shows an example developed from research undertaken in the savanna agroecosystem of Brazil and Colombia. In this environment the soil constraints are;
loss of organic matter, limited water availability during short dry periods in the wet season, compaction and surface sealing, wind and water erosion, depletion of soil nutrients and acidification and associated aluminum toxicity. Another example is from the East Africa highlands where loss of organic matter, wind and water erosion and depletion of soil nutrients are the main constraints (Table 37).

Table 36. Soil quality indicators for the savannas.

Indicator	Methodology	Easy of use	Sensitivity to land use change	Suitability for on-farm use	General suitability
Aggregate size distribution/stability	Aggregate stability	+	+++	-	+++
Extractable organic carbon	Lab extractions & colorimetry	+	++	-	+
Permanganate- Extractable N	Lab extractions & colorimetry	+	++	-	++
Microbial C/total C	Microbial biomass	+	++	-	+
Free/easily accessible POM	*Organic matter fractionation*	++	++	-	++
Water infiltration rate	Ring infiltrometer	+	+	-	++
Earthworm biomass	Soil sampling/hand sorting	++	+++	+	+++
Earthworm termite ratio	Soil sampling/hand sorting	+	+++	+	++
Soil pH	pH strips	+++	+	+	+
Porosity	Pore size analysis	+	++	-	++
Compaction	Hand held penetrometer	+++	++	++	++

- not easy/suitable/sensitive; + little suitability/sensitivity
++ moderately easy/suitable/sensitive
+++ good suitability/sensitivity
Data in Table 30 taken from Thomas and Ayarza (1999).

Table 37. Soil quality indicators for the East African Highlands.

Indicator		Methodology	Easy of use	Sensitivity to land use change	Suitability for on-farm use	**General suitability**
Local	Technical					
Presence of Earthworms	Biological activity	Soil sampling, hand sorting	+	+++	+	++
Good crop	Fertility	Lab extractions & colorimetry	+	++	-	++
Dark green plant colour	Leaf colour or nutrient status	Lab extractions & colorimetry	+	++	-	++
Deep soils	Effective depth	Soil sampling	++	+	+	+
Not salty/ salty i.e. visible at surface	Electrical conductivity and pH	Lab extractions & pH strips	++	+	-	+
Smell or rotting vegetation	Redox potential	Lab extractions	+	+	-	+
Black soil colour	OM content	Lab extractions, OM fractionation	++	++	+	++
Easy to cultivate	Texture or compaction	Hand held penetrometer	+++	++	++	++
Presence of good indicator weed species	Soil fertility or weed diversity	Farm surveys	+++	++	++	++
Good water retention-	Water holding capacity or infiltration	Ring infiltrometer	+	+	-	++

- not easy/suitable/sensitive
+ little suitability/sensitivity ; ++ moderately easy/suitable/sensitive; +++ good suitability/sensitivity
Data taken from Barrios et al,. (In preparation

The identified indicators are ranked according to their ease of use on-farm. Appropriate indicators can then be brought into the training exercises with farmers on the development of local soil quality indicators with the appropriate level of simplicity e.g. earthworm biomass from Table 36. Thus both scientific and local knowledge can be brought together into a user-friendly and user-devised soil quality monitoring system in order to build social capital and help land user decision making on the use of their natural capital.

Currently the soil quality indicators are being validated by additional on-farm and on-station trials in both the Colombian savannas and hillside agroecosystems of Colombia, Honduras and Nicaragua. At the same time the guideline for the identification of local soil quality indicators is being disseminated in Latin America and Eastern Africa. Training events for extension workers, researchers and farmers are being organized in Latin American and African countries. The guideline for local soil quality indicators is being adapted for African conditions by local organizations.

Contributors:
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Activity 3.3 Compile data bases to feed into simulation models and decision support systems

Highlight:

- Data from the long-term experiments on phosphorus cycling in the savannas have contributed to the development of an improved crop model (CERES) and have been made available to other groups via a multi-institutional collaborative project within the SWNM program.

Purpose:
To improve the phosphorus sub-model for the CERES and other simulation models, calibrate and test the new model.

Rationale:
Crop simulation models are increasingly being widely used to estimate crop yields as affected by nutrients and water inputs as well as management practices and climatic conditions. A group of models, CERES for cereal simulation growth and CROPGRO for legume simulation, have been used successfully around the world for various purposes. A computer model for the simulation of phosphorus (P) in the soil and plant atmosphere has been developed and added to the two above crop simulation models to enhance their capabilities especially in tropical areas where P deficiencies are common. The models have been tested using data on maize, soybeans and upland rice grown under acidic tropical conditions in the Colombian savannas.

The phosphorus model
There are three inorganic and two organic P pools that are represented in the model (Fig.30). In addition, there are two pools that represent rapid and slow cycling plant residues as well as a fertilizer pool. The labile pool is the most dynamic pool, and a soil solution pool is defined as a fraction of the available labile pool. Crops take up P from the soil solution pool. The fraction of labile P in solution depends on the type of soil and can be changed in the soil chemical parameter file. The active pools serve as medium to slow release pools that replenish the labile pool. Finally the stable pools are very slow release pools, but will increase or decrease in size depending on the rate and frequency of P fertilizer application.

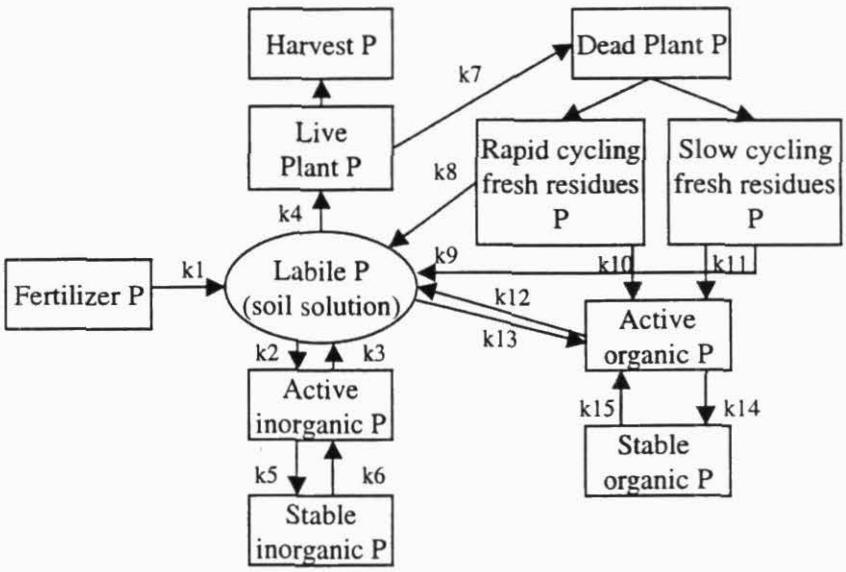

Figure 30. Phosphorus self-model for the CERES

Pools Initialization: To initialize the P pools, data on P fractions in the soil are needed. We used the sequential P fractions measured by the Hedley fractionation to initialize the pools. This sequential fractionation procedure extracts the different forms of P in the soil starting with labile forms and ending with the more stable forms. Both inorganic and organic forms of P are measured. We assigned the different fractions to corresponding P pools according to what is best described in the literature. The rates of transfer between pools are described in the chemical parameters file and the user can change those transfer rates when different soils are used.

Experiments and sites: Two separate experiments were used for the calibration and the testing of the P model with maize and soybean from Colombia. Both experiments were carried out at the CIAT-CORPOICA Experiment Station, Carimagua (4' 30''N, 71,19' 'W) on the eastern savannas of Colombia. Rainfall averages 2240 mm annually, falling mainly form late March to mid- December. Mean annual temperature is 27 ^{0}C. Soils are well-drained silty clay Oxisols (tropeptic haplustox, isohyperthermic). The data used for genetic coefficients calibration were from the Culticore experiment for the maize variety "Sikuani", and the soybean variety "Soyica Altillanura 2". For upland rice data from the variety Sabana 6 was used. The data available were from three years (1994-1996) with a maize / soybean rotation (2 crops/year). The Culticore experiment was established in 1993 to investigate crop rotation and ley farming systems for the acid- soil savannas. Triple super phosphate fertilizer was applied at 60 and 40 kg P ha^{-1} for the maize and soybean crops, respectively. Other nutrients were applied at adequate levels. The data used to calibrate and test the P-model for the upland rice variety Sabana 6 were obtained from the Culticore on-station experiment at Carimagua and the Matazul on-farm experiments.

Carimagua: CULTICORE experiment: Four years of data from 1993 till 1996 with the following treatments: Rice monoculture and Rice – Cowpea rotations. The Culticore experiment is a crop rotation experiment with an annual application of P fertilizers at 60 kg P ha^{-1}. Rice monocultures received 100 kg N ha^{-1}applied in 1994 as three split applications. No N fertilizer was applied for the other years. Rice-cowpea rotations had different amounts of residues leftover from the previous cowpea crop. The residues were broadcast and incorporated at 15 cm depth.

Matazul: RESIDUAL PHOSPHORUS (RP): Four years of data. The RP experiment consists of 16 treatments of annual and one-time applications of P fertilizers with maize, soybean and upland rice crops. The annual applications range from 5 to 50 kg P ha^{-1}. Other treatments had a one-time application in year one with rates ranging from 10 to 200 kg P ha^{-1}. Data for rice production as well as uptake of P by rice at harvest are available. Data on P fractions are available for four treatments. However, soil and weather files are not available for Matazul.

Testing of the model for maize and soybean: Data from the Residual Phopshorus (RP) experiment were used for testing the P model for both Maize and Soybean. The RP experiment included the annual application of P fertilizer at 0, 5, 10, 15, 20, 30, 40, and 50 kg ha^{-1} and the one time application of P at 10, 20, 30, 40, 60, 80, 120, 160, and 200 kg ha^{-1}applied in 1993. Sequential files for the Maize-Soybean rotation for all treatments were constructed and simulations run in sequence for 4 years. The P pools were initialized once at the beginning of the simulation in the first year. Phosphorus fractionation data were used to initialize the pools in the first year.

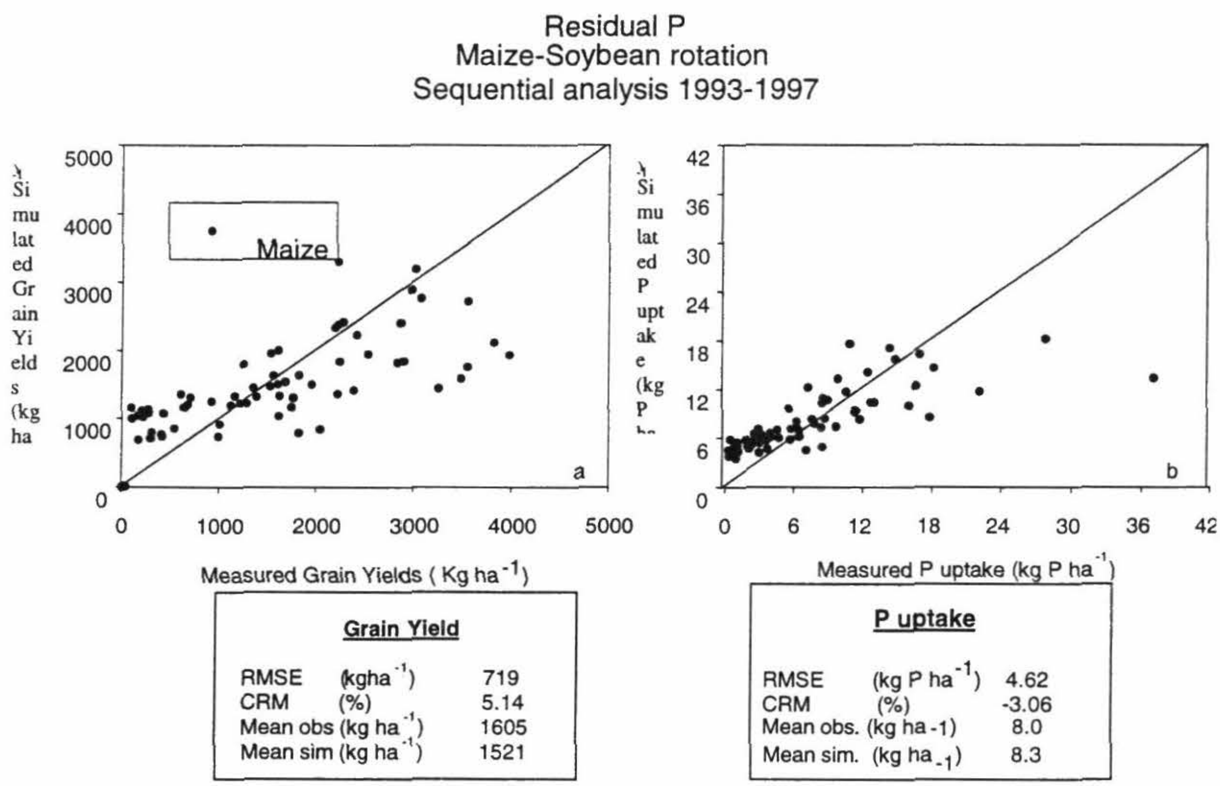

Figure 31. Measured and simulated Maize grain yield (a) and total P uptake (b) in a sequential analysis done on the maize-soybean rotation for all treatments.

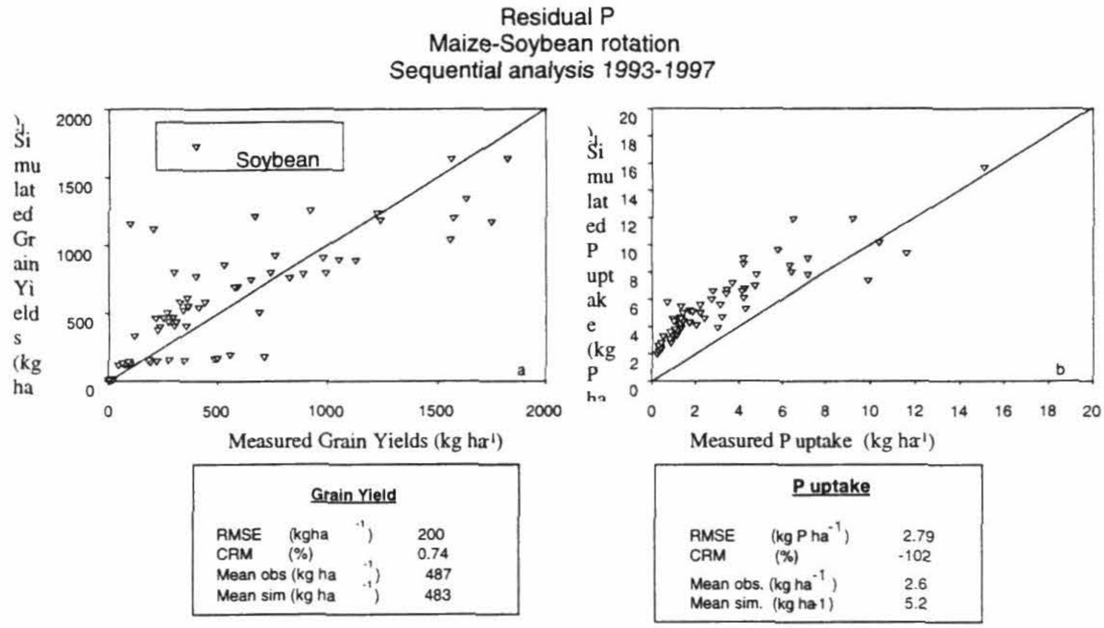

Figure 32. Measured and simulated Soybean grain yield (a) and total P uptake (b) in a sequential analysis done on the maize-soybean rotation for all treatments.

TESTING OF THE MODEL WITH MAIZE AND SOYBEAN

Parameters to test the model: The principal parameter used in the comparison of simulated to observed values is the root mean square error (RMSE) which estimates the variation, expressed in the same units as the data, between simulated and observed values. This parameter is defined by the following formula:

$$RMSE: = \left[\sum_{i=1}^{n} (S_i - O_i)^2 / n \right]^{1/2}$$

where O and S are observed and simulated values respectively. The RMSE can also be expressed as a coefficient of variation by dividing it by the mean of the observed values. The RMSE tests the accuracy of the model, which is defined as the extent to which simulated values approach a corresponding set of measured values.

The second parameter used is the coefficient of residual mass (CRM) which measures the tendency of the model towards overestimation. A negative CRM indicates a tendency of the model for overestimation. The CRM is defined by the following formula:

$$CRM = 100 * \left[\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i \right] / \sum O_i$$

Results and Discussion:

Results from the sequential analysis for maize is presented in Figure 31 and for soybean in Figure 32. In general the model does a good job in simulating grain yields for both maize and soybean and P uptake for maize (Fig. 31 & 32). Phosphorus uptake by soybean is however overestimated by 102%. It seems the model can not predict the extremely low amounts of P actually taken up by the soybean crop (mean observed P uptake is 2.6 kg P ha^{-1}). One of the important conclusions is that one annual application of P fertilization on the Maize crop is not enough to sustain the next crop in rotation (soybean) even at the higher rates. This may be due to the acidity of the soil and the adaptability of the variety to acidic conditions. The RMSE is, in general, high for both crops for both grain yields and P uptake. This reflects the variability of the measured data. Although this experiment is designed to be a P response experiment , it is suspected that other uncontrolled factors affected crop yields and P uptake. Weeds were not controlled in these experiments, and some of the variability could be explained by the weed biomass production. In its present form, the P model can be successfully used to answer 'What if' management type questions in the tropical acidic soils of Colombia. Management issues such as planting dates, rate and timing of P fertilizer addition can be tried out to achieve the best possible scenario.

Testing of the model with upland rice In order to calculate the P demand by the rice plant during different growth stages, data for uptake of P by rice at optimum growing conditions are needed. Data from the literature regarding P uptake by upland rice with growth stage were collected and were used to construct a graph of percent P uptake in the dry matter with growth stage (Figure 33). This graph was used to estimate the demand by the crop in the model.

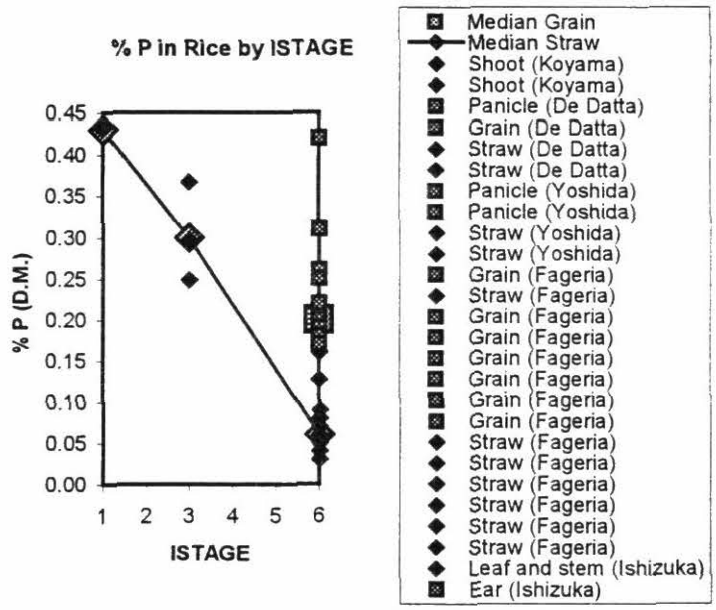

Figure 33. Percent P in dry matter with growth stage of rice. Data points are from the different cited references.

Genetic Coefficients calibration: The data from the culticore experiment were used to calibrate the genetic coefficients for Sabana 6. There are problems with the variability of the replications in the treatments and the variability among the different years. For example there was a difference of 20 days for date of maturity for the crop between the different years. The best values obtained for the genetic coefficients are listed in Table 38.

Table 38. Genetic coefficients for variety Sabana 6.

Genetic coefficient	Calibrated value for Sabana 6
P_1	500
P_2R	100
P_5	450
P_2O	13.0
G_1	36.6
G_2	0.027
G_3	0.50
G_4	1.00

The predictions from the various years for both treatments are presented in Tables 39a through 39c. The model gives good grain yield predictions for two years (1993 and 1995). Biomass yields are always over estimated by the model.

Table 39a. Some predicted and measured growth parameters from treatment 1, 1993

Variable	Predicted	Measured
Flowering date (dap)	74	63
Physiological maturity (dap)	110	109
Grain Yield (kg ha^{-1} at 14% moisture)	3015	3120
Grain number (grains m^{-2})	9602	9595
Panicle number (panicle m^{-2})	577	-
Maximum LAI (m^2 m^{-2})	2.17	
Biomass at harvest (kg ha^{-1})	8859	8100
Harvest Index	0.293	
Final leaf number	20	-

Table 39b. Some predicted and measured growth parameters from treatments 1 and 2, 1994

	Treatment 1		Treatment 2	
Variable	Predicted	Measured	Predicted	Measured
Flowering date (dap)	73	78	73	78
Physiological maturity (dap)	110	120	110	120
Grain Yield (kg ha^{-1} at 14% moisture)	5476	2458	5333	3213
Grain number (grains m^{-2})	17441	9595	16987	14508
Panicle number (panicle m^{-2})	600	-	600	-
Maximum LAI (m^2 m^{-2})	8.2		8.3	-
Biomass at harvest (kg ha^{-1})	16989	6528	16737	7473
Harvest Index	0.277		0.274	-
Final leaf number	20	-	20	-

Table 39c. Some predicted and measured growth parameters from treatments 1 and 2, 1995

	Treatment 1		Treatment 2	
Variable	Predicted	Measured	Predicted	Measured
Flowering date (dap)	73	78	73	78
Physiological maturity (dap)	107	103	107	103
Grain Yield (kg ha^{-1} at 14% moisture)	3180	3121	3772	3236
Grain number (grains m^{-2})	10129	14508	12015	9595
Panicle number (panicle m^{-2})	602		580	-
Maximum LAI (m^2 m^{-2})	3.55		3.08	-
Biomass at harvest (kg ha^{-1})	9955	6321	10696	6761
Harvest Index	0.275		0.303	-
Final leaf number	20		20	-

The RP data from Matazul was intended for use as a test for the P model for rice. However several data are needed to establish the necessary files to run simulations:

a. Weather files for Matazul.

b. Soil file from Matazul.

c. Initial conditions for moisture and nitrogen for each year.

Phosphorus data are available for these experiments including soil P fractionation data for the different dates as well as yield data and uptake of P by the rice crop at harvest . However many data are still missing to run the model for these data sets. As a result only sensitivity analyses were done to show the response to P stresses in the model using the Culticore data.

Sensitivity analysis Sensitivity analysis was performed on the Culticore data from 1994 and 1997. The analysis included testing the response of the model to different rates of P fertilizers as well as different initial condition of P.

Different rates of P application Three-year data sets (1994 to 1996) from the Culticore experiment were used to run the model with different rates of P application ranging from 0 to 60 kg ha^{-1}. The model responded well to the application of the different P rates showing increased response in terms of grain and biomass yields to the different rates of application. Figure 34 shows grain and biomass yield response to the different rates of P fertilizer application.

In 1994, simulations show a response due to P fertilizer application at all rates in comparison to the other years where the response flattens out at 20 kg P ha^{-1} in 1995 and at 40 kg P ha^{-1} in 1996. The model shows N stresses during these two years where no N fertilizers were applied. The increased response in 1994 shows the effect of adequate N fertilization on the P response of the crop. This however does not reflect accurately the measured values where in 1994 they were lower than predicted.

Different initial conditions for Labile P: Sensitivity analysis was also run for different initial conditions for labile P for rice monocultures in 1994. Labile P in the model is equated measurable resin P. Figure 35 shows results of selected growth parameters with different initial conditions. These simulations were done with no P fertilization applied. Again the model shows response at all levels of labile P tested.

Impact:

Improvement of the genetic coefficients calibration is needed to improve the predictions of the model. This could be done with the experiments from Matazul with the high yielding treatment (optimum growing conditions) when the soil and weather files are available.

The sensitivity analysis done on the model shows it is responsive to different rates of P fertilizer applications as well as to initial conditions of labile P. Several growth parameters respond to P additions. Some of the growth parameters that do not seem to be affected by P fertilization are: flowering and maturity dates, panicle number and leaf number.

The model still needs to be tested with P response experiments such as the Phosphorous Residual experiment from Matazul.

Internet: The P model software and documentation are published on the web. This will allow easy and rapid exchange of ideas and suggestions of users of the model. The model is published under the Nowlin chair web page at Michigan State University. The address is:

http://nowlin.css.msu.edu/software/P_model_form.html

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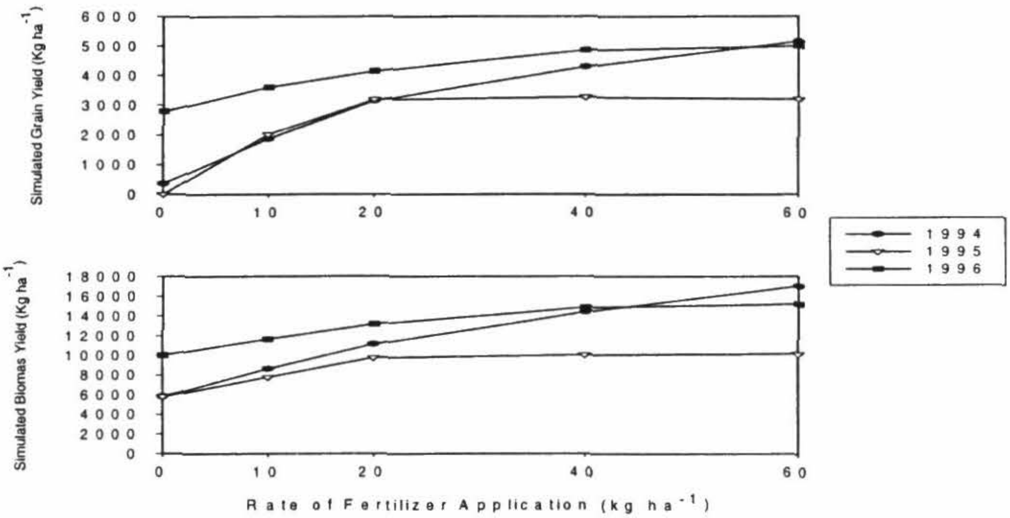

Figure 34. Sensitivity analysis with different rates of P fertilizer application done on the P version of CERES-Rice model using treatment 1 from the Culticore experiment.

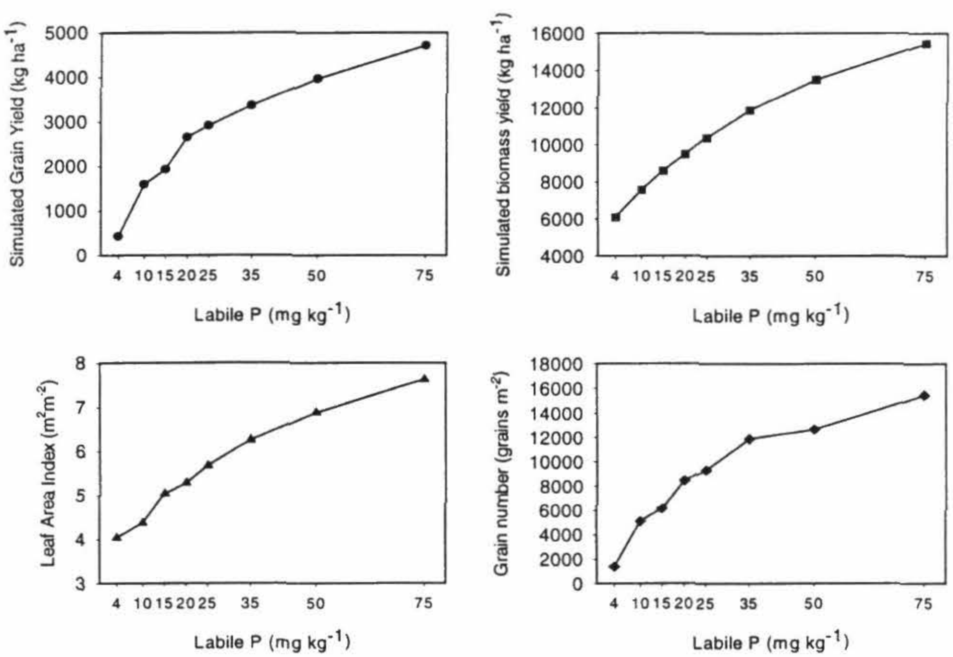

Figure 35. Sensitivity analysis done on treatment 1, 1994 Culticore experiment with different initial conditions of labile P.

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

3.4.1 Decision-making tree for the potential and productive use of soils in well-drained savanna flatlands *(first approximation)*

Highlight:

- Developed, as a first approximation, a decision-support tree for the well-drained savanna flatlands ecosystem, with pluviometric conditions of annual rainfall ranging from 2100 to 2600 mm.

Rationale:

In extensive, low-fertility areas that are prone to erosion and structural degradation such as the soils of the flat savannas, where land use practices alter biological, physical and chemical properties and texture, slope and depth better strategies for land use and management are required.

Thus we can developed a decision-making tree that links the results obtained in field experiments with geographical information systems (GIS). Figure 36 shows the linkages between strategic and applied research with GIS. The idea is to connect region with farm, lower scale (1:100000) with bigger scale (1:10000) to have a better approximation for sustainable soil and crop management systems. Research provides parameters and critical levels which could be used as indicators for either improvement or degradation of soils.

The findings needs to be produced in a user-friendly format for farmers and ideally should be measured with a single apparatus. The parameters and critical levels must be systematized in a data base through technical criteria for use in GIS. Monitoring and validation efforts will provide feedback to strategic and applied research.

We developed a scheme for land use with different potential production systems for the savanna flatlands (3,438,000 ha), taking into account the aforementioned criteria. It is assumed that the socioeconomic environment will be favorable for the agricultural and livestock sector at both the national and regional levels in the near future, thereby stimulating investments and adoption of technological innovations on the part of large- and medium-scale producers and permitting a significant generation of regional employment.

The soils of the savannas have traditionally been used for extensive operations of raising zebu cattle on natural grasslands managed with burning or on improved grasses with inadequate management. With the release of new annual crops and forage germplasm adapted to different levels of aluminum saturation, a new practices such as agropastoral, silvopastoral and agrosilvopastoral production systems become viable. Moreover, in the last ten years permanent crops such as rubber and African palm have appeared on a large scale. Both the current and the potential production systems that are proposed here are based on an implicit focus on integrated soil management that builds an arable layer over time, with a minimum of chemical, physical and biological constraints for the respective crops, taking into consideration the variables of texture, slope and depth of the soil profile. To the extent that the integrated improvement of the soil is accomplished, the intensity of soil use should be reduced gradually in order to change to conservationist systems that use less tillage, more mulching and consequently less dependency on agrochemicals. On the other hand, it is clear that there is a need to protect strategic areas of the savanna and of the native arboreal vegetation at the farm level so that they serve as corridors for protecting wild fauna, watersheds and controlling erosion. They also serve as biological regulators and for the phytosanitary protection of new crops and as a gene bank for future research and forms of development.

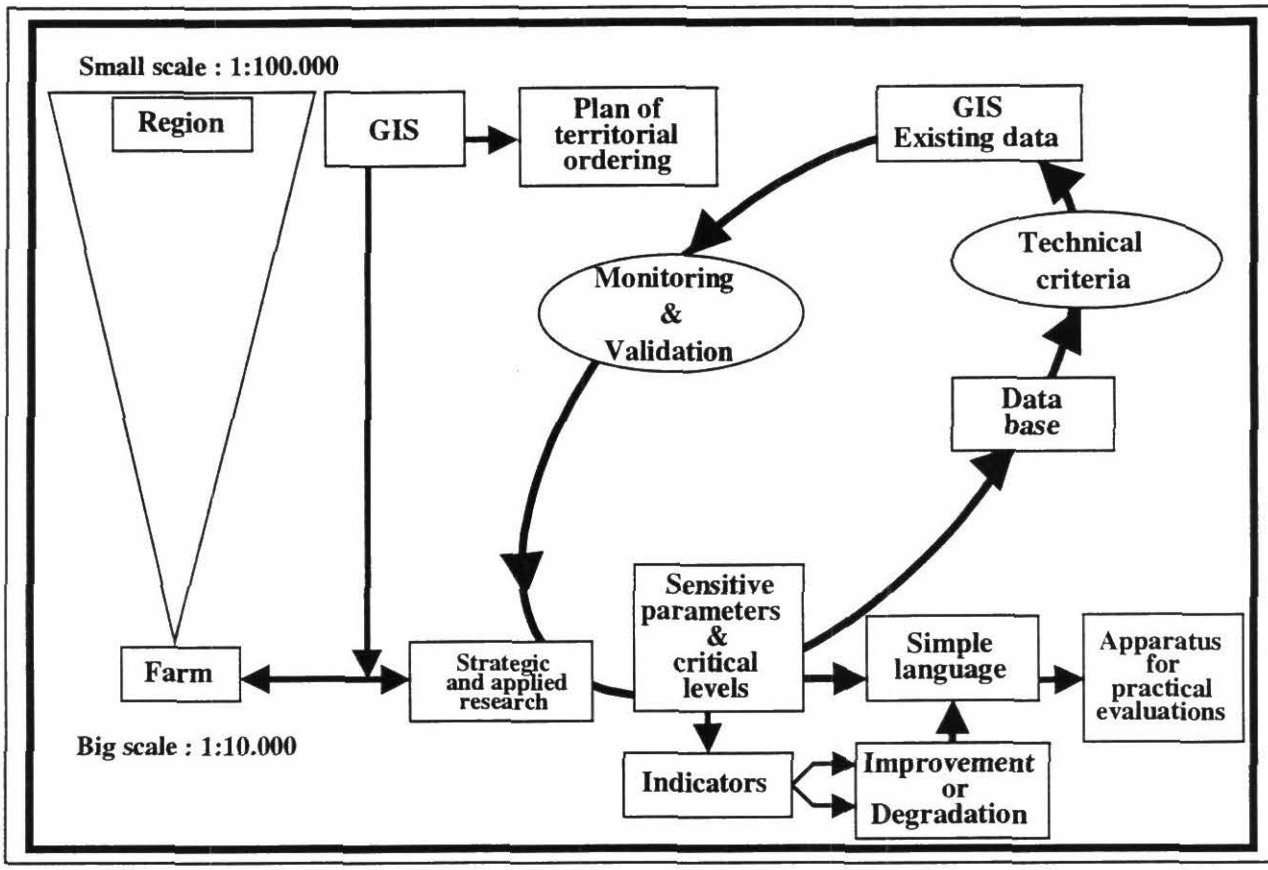

Figure 36. An approach developed by CIAT to integrate geographical information systems with strategic and applied biophysical research.

CLIMATIC COVERAGE

The proposed production systems apply to the area of the savanna flatlands between Puerto López and Carimagua (Province of Meta) with an annual rainfall ranging from 2100-2600 mm. The distribution of these rains indicates that from weeks 16 to 43 the water requirements of grasses and crops can be met.

SCHEME FOR THE DECISION-MAKING TREE ON THE USE OF THE SOILS IN THE SAVANNA FLAITLANDS.

Figure 37 presents the scheme of a general tree that includes two climatic regimes, three broad landscapes, three landscapes of the savannas, two levels of drainage, three soil texture groups and within each textural group, different degrees of slope. For each one of the slopes, three levels of the effective depth of the soil profile are considered.

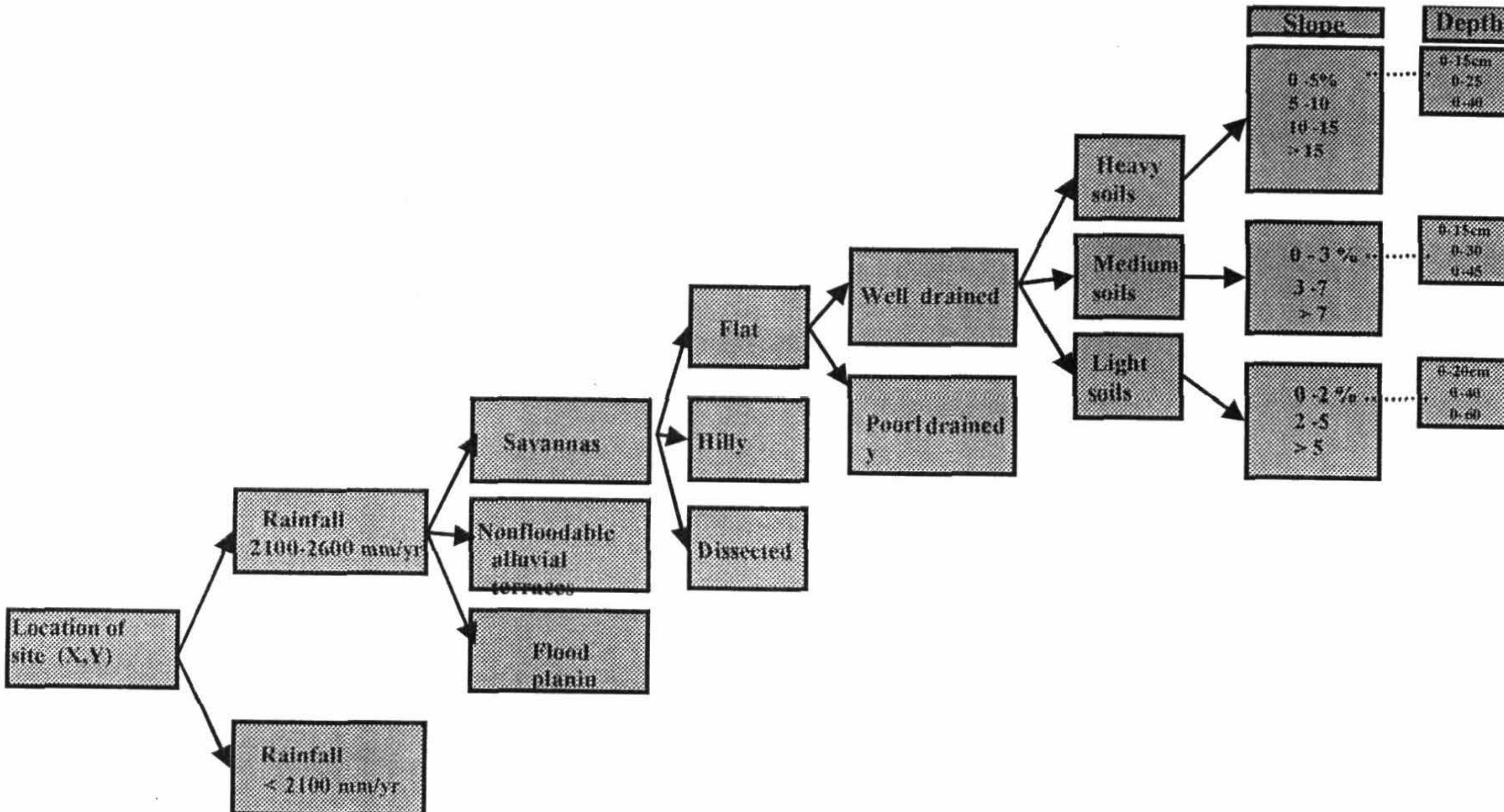

Figure 37. Scheme of a a decision-making tree for the potential productive use of soils in well-drained savanna flatlands (first approximation).

This paper makes reference only to the landscape of the well-drained savanna flatlands with its respective divisions. The textures for each soil group are as follows:

HEAVY SOILS: Clay, sandy clay and clay loam.
MEDIUM SOILS: Sandy clay loam and loam.
LIGHT SOILS: Sandy loam and sandy.

INFLUENCE OF SOIL TEXTURE AND SLOPE ON DECISION-MAKING RELATED TO AGRICULTURAL PRODUCTION SYSTEMS FOR THE WELL-DRAINED SAVANNA FLATLANDS.

Based on the codification and symbols defined in next pages, the decisions to be made about the production systems to be used when dealing with the effect of slope within each group texture are presented. In the column "Condition," the indispensable requirements for implementing the production system are also specified. For that purpose the following abbreviations are used:

OM = organic matter (%)
C-Ph-B = chemical, physical, biological
RC = rigid chisel
VC = vibrating chisel
FP = furrow planter
TDP = tiller-direct planter
GCH = grain combine harvester with attachment for chopping and spreading residue
LCE = land-clearing equipment
CTS = shade-tolerant crop
ASR = adjustment of stocking rate according to forage supply
OSQ = optimum seed quality
AG = adapted germplasm

For the soils that present different degrees of slope, the use of "banked terraces" at different distances in accordance with the degree of the slope are proposed. Banked terraces are raised soil barriers constructed on the contour to diminish the strength of the runoff and to act as traps to capture the eroded soil. For the conditions of the Eastern Plains, characterized by superficial soils, a disk plow should be used to construct them. Heavy machinery should not be used in order to prevent degradation of the soils. Preferably, they should be constructed 4-8 m apart so that they can be planted and from 0.6-0.8 m high so that they fulfill their function of decreasing the speed of the runoff water. They should be constructed with a minimum slope so that they gradually evacuate the water that they retain.

PRODUCTION SYSTEMS

The following is a brief description of the agricultural production systems and their potential use based on soil texture.

1. ***TECHNICALLY ESTABLISHED or RENOVATED PASTURES - TERP (renovated every n years)***. This concept refers to the establishment or renovation of pure grasslands or associated with legumes, using chisels for the preparation and early incorporation of lime and rock phosphate, tillage with parallel passes against the slope, planting in furrows, and fertilization with nitrogen and potassium one month after seedling emergence; and maintenance fertilization broadcast, based on soil analyses and texture. The light soil textures require N and K fertilization yearly. Management of rotations is required with adjustments for stocking rate in accordance with the availability of forage. Under this management system, it is estimated that the grass and legume components require renovations in the longer term, depending on the soil texture:

   TERP (R-3) renovation every 3 years in light textures

TERP (R-4) renovation every 4 years in medium textures
TERP (R-5) renovation every 5 years in heavy textures

2. ***SIMULTANEOUS AGROPASTORAL - Sim-AgP (1s × years).*** Indicates the simultaneous planting of annual crops and grasses and also includes the renovation of grasslands with annual crops. This system has been successful in the savannas because it not only results in good establishment of the grasslands, but the crop also finances the costs in the short term. The value in parentheses indicates one semester of an annual crop with renovation of the grassland every 'n' years in accordance with the soil texture:

    Sim-AgP (1s × 3) in light textures
    Sim-AgP (1s × 4) in medium textures
    Sim-AgP (1s × 5) in heavy textures

3. ***ROTATIONAL AGROPASTORAL - Rot-AgP (n years of annual crop × n years of grasses).*** Under this system different rotations of annual crops are alternated with grasses in sequential form. The first number indicates the number of years that the rotation of annual crops lasts; the second number, the number of years used for grasses. In this case the role of the grasses is to stabilize the physical conditions of the soil for maintaining the crop yields. The different combinations indicate the intensity of use for the annual crops and grasses, respectively, by soil texture:

    Rot-AgP (1×3) for light textures
    Rot-AgP (2×3) for medium textures
    Rot-AgP (3×3) (4×3) (5×3) for heavy textures

4. ***AGROSILVOPASTORAL - (AgSvP) or SILVOPASTORAL (SvP).*** These are simultaneous agroforestry associations of timber trees or fruit trees with animals, with or without the presence of crops, in a search for diversifying the production and providing a source of income in the short and long term. In all cases the timber trees (tre) or fruit trees (frt) should be protected from the animals during their establishment. The system can be initiated with the simultaneous establishment of annual crops (ac) and timber trees (tre), and later the grasslands (gr) are established when the trees reach sufficient height where they will not be damaged by the animals. Given that the silvopastoral systems form part of this system, their symbols are expressed as a separate set.

    AgSvP (ac/tre/gr) or (ac/frt/gr) for medium and heavy textures
    SvP (tre/gr) or (frt/gr) for light textures

5. ***AGROFORESTRY with PERENNIAL or MULTISTRATA CROPS - MS (pc/sht/tt).*** These associations seek to optimize the use of resources to increase productivity per unit of area. These systems are adequate for those perennial species that tolerate the shade from the trees and are not susceptible to diseases in this environment. They are more successful in more fertile soils, with good roads and access to the markets. The typical structure of these systems includes three strata: In the first stratum a permanent crop (pc), in the second, a shade tree (sht) and in the third, a timber tree (tt).

    MS (pc/sht/tt) heavy textures and OM >5%

6. ***AGROFORESTRY WITH ANNUAL CROPS - AgFAn (ac/tre).*** In this association the interaction of the annual crops with the trees is similar to the previous case; however, the possibility exists of establishing the associations in strips or alleys for intercropping the species of annual crops that do not tolerate shade.

AgFAn (ac/tre) medium and heavy textures

7. ***MIXED DOMESTIC GARDENS (MDG)***. These are very old agroforestry systems that are used for supplying the basic needs of families or small communities and are characterized by the high diversity of species in production throughout the year. The garden can produce food and cash crops including fruits, nuts, vegetables, fibers, wood, medicinal and ornamental plants, farm animals and fish from ponds.

   MDG for heavy textures and OM >5%

8. ***PERMANENT CROPS WITH MULCHING (PC+M)***. Monoculture systems of perennial species (pc) are planted on a large scale and generally managed with mulching with legumes (lg) to keep the weeds under control and maintain a constant supply of nitrogen for the system. Some annual crops can also be used during the establishment of the permanent crop, depending on the latter's root system.

   PC+M for medium and heavy textures

9. ***LIVE FENCES AND WINDBREAKS (LFWB)***. The live fence consists of a row of trees or bushes that mark the boundaries of a property, while the windbreaks can consist of several rows of trees that protect a grassfield, crops or bushes from the wind. These systems also provide forage, firewood, medicinal products and poles; however, they require a lot of labor. One of the major difficulties of the system lies in the durability of the tree trunks and in the difficulty of eliminating the live fence.

   LFWB (ac/tre), (frt/tre) for all textures

10. ***FORESTRY - F (conservation or commercial)***. This implies the planting of arboreal systems for purposes of conservation (cons), as well as for commercial (com) purposes (firewood, wood, medicinal, industrial). In sandy soils and on slopes, reforestation for conservation acquires great importance for regulating the water system. In the flat and clayey parts, commercial forestry production is possible.

    F (cons) for soils of all textures with greater slopes
    F (com, ind) for medium and heavy textures, flat areas

11. ***ANNUAL INTERCROPS - AIC (ce/lg)***. Annual intercrops (cereals and grain legumes) are planted in different combinations of spatial horizontal distribution according to the compatibility of the associating species for light, water and nutrients. The purpose is not only to optimize the resources per unit of area, but also to decrease pest and disease pressure and the use of agrochemicals. This system requires use of appropriate machinery and soils with better chemical, physical and biological conditions. In this scheme the different systems of conservationist tillage should be used.

    AIC (ce/lg) for heavy textures without chemical, physical and biological constraints.

12. ***CONSTRUCTIVE TILLAGE - ConstTil***. This system involves a sequence of rotating annual crops with the purpose of constructing an arable layer (in accordance with the soil texture and depth) with a minimum of chemical, physical and biological constraints, ending with a given production system: pastoral (P), silvopastoral (SvP), forestry (F), permanent crop (PC+M) or intercrops (AIC). The sequence of improvement can include a rest period or fallow after the rotations and prior to the establishment of the target production system. The proposals by soil texture are:

    ConstTil (1ac/P), (2ac/SvP) in light textures

ConstTil (2ac/P), (2ac/SvP), (2ac-F) in medium textures
ConstTil (3ac-P), (3ac-P+C) (3ac-AIC) in heavy textures

CODIFICATION AND DESCRIPTION OF THE AGRICULTURAL PRODUCTION SYSTEMS FOR THE SAVANNA FLATLANDS BASED ON TEXTURE.

For purposes of representing the production systems in function of the texture in the decision-making tree, an identification code, a description of its component, indicating the arrangements over time in some cases, and the symbol that represents the production system and its respective arrangement.

1. TECHNICALLY ESTABLISHED or RENOVATED PASTIRES- TERP (renovated every/n years)

CODE	ANNUAL CROP	PASTURES	TEXTURE	SYMBOL
1a	None	R-3	Light	TERP (R-3)
1b	None	R-4 years	Medium	TERP (R-4)
1c	None	R-5 years	Heavy	TERP (R-5)

2. SIMULTANEOUS AGROPASTORAL - Sim-AgP (simultaneous planting of crop with pastures)

CODE	ANNUAL CROP	PASTURES	TEXTURE	SYMBOL
2a	1 Semester	R-3	Light	Sim-AgP (1s×3)
2b	1 Semester	R-4 years	Medium	Sim-AgP (1s×4)
2c	1 Semester	R-5 years	Heavy	Sim-AgP (1s×5)

3. AGROPASTORAL ROTATIONAL - Rot-AgP (n years of crop x n years of pastures)

CODE	ANNUAL CROP	PASTURES	TEXTURE	SYMBOL
3a	1 year	3 years	Light	Rot-AgP (1×3)
3b	2 year	3 years	Medium	Rot-AgP (2×3)
3c	3 years	3 years	Heavy	Rot-AgP (3×3)

4. AGROSILVOPASTORAL (AgSvP) and SILVOPASTORAL (SvP)

CODE	DESCRIPTION	TEXTURE	SYMBOL
4a	Annual crops+trees+grasses	Medium & Heavy	AgSvP (ac/tre/gr)
4b	Trees+grasses or trees+fruit trees	Light	SvP (tre,frt/gr)

5. AGROFORESTRY WITH PERENNIAL CROPS or MULTISTRATA (MS)

CODE	DESCRIPTION	TEXTURE	SYMBOL
5	Perennial crops+shade trees+timber trees	Heavy (OM >5%)	MS (pc/sht/tt)

6. AGROFORESTRY WITH ANNUAL CROPS (AgFAn)

CODE	DESCRIPTION	TEXTURE	SYMBOL
6	Annual crops+trees associated or in intercropped alleys	Medium & Heavy	AgFAn (ac/tre)

7. MIXED DOMESTIC GARDENS (MDG)

CODE	DESCRIPTION	TEXTURE	SYMBOL
7	Annual crops, fruit and timber trees, medicinal and ornamentals plants, fish from ponds and farm animals	Heavy (OM >5%)	MDG

8. PERMANENT WITH MULCHING (PC+M)

CODE	DESCRIPTION	TEXTURE	SYMBOL
8	Perennial commercial or industrial crops with legumes for mulching	Medium & Heavy	PC+M

9. LIVE FENCES AND WINDBREAKS (LFWB)

CODE	DESCRIPTION	TEXTURE	SYMBOL
9	Live fence or windbreak that protects grasses (gr), annual crops(ac) or fruit trees (frt)	Light Medium & Heavy	LFWB (gr/tre), (ac/tre) or (frt/tre)

10. FORESTRY - F (conservation or commercial)

CODE	DESCRIPTION	TEXTURE	SYMBOL
10a	Planting trees for conservation in soils with greater slopes	Light Medium & Heavy	F (cons)
10b	Planting trees on flatlands for commercial or industrial purposes	Medium & Heavy	F (com, ind)

11. ANNUAL INTERCROPS (AIC)

CODE	DESCRIPTION	TEXTURE	SYMBOL
11	Annual crops intercropped with cereals (ce) and grain legumes (lg) in soils with few or minimal chemical, physical and biological constraints, managed with conservationist tillage systems	Medium & Heavy	AIC (ce/lg)

12. CONSTRUCTIVE TILLAGE (ConstTil)

CODE	INITIATING WITH ANNUAL CROP	ENDING WITH SYSTEM	TEXTURE	SYMBOL
12a	1 year	Pastoral	Light	ConstTil (1ac/P)
12b	2 years	Silvopastoral	Light & Medium	ConstTil (2ac/SvP)
12c	2 years	Pastoral		ConstTil (2ac/P)
12d	2 years	Forestry (commercial or industrial)	Medium	ConstTil (2ac/F(com,ind)
12e	3 years	Pastoral	Heavy	ConstTil (3ac/P)
12f	3 years	Permanent + mulching		ConstTil (3ac/PC+M)
12g	3 years	Intercrops		ConstTil (3ac/AIC)

HEAVY TEXTURES

SLOPE OF 0 to 5%

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1c	Technically established grasses	TERP (R-5)	RC, FP, ASR
2c	Simultaneous agropastoral	Sim-AgP(1s×5)	RC, FP, ASR, GCH
3c	Rotational agropastoral	Rot-AgP (3×3)	RC, FP, ASR, LCE, GCH
4a	Agrosilvopastoral	AgSvP (ac/tre/p)	RC, FP, ASR, LCE, GCH
5	Multistrata	MS (pc/sht/tt)	STC
6	Agroforestry with annual crop	AgFAn (ac/tre)	STC
7	Mixed home gardens	MDG	OM >5 %
8	Permanent+mulching with legumes	PC+M	AG, OSQ
9	Live fence – windbreakers	LFWB (p, ac, frt/tre)	
10b	Forestry (commercial or industrial)	F(com, ind)	AG, OSQ
11	Annual crops intercropped with cereals and grain legumes with different planting patterns	AIC (ce+lg)	Only for soils where it has been possible to build arable layer; management with TDP.
12e	Constructive tillage (begins with annual crops and ends with pastoral)	ConstTil (3ac/P)	Initially RC, FP, LCE, GCH; at the end, RC, FP, ASR
12f	Constructive tillage (begins with annual crops and ends with permanent+mulch)	ConstTil (3ac/PC+M	Initially RC, FP, LCE, GCH; at the end, maintain mulches
12g	Constructive tillage (begins with annual crops and ends with intercrops)	ConstTil (3ac/AIC)	Initially RC, FP, GCH; at the en management with TDP.

SLOPE OF 5 to 10% (BANKED TERRACES EVERY 100m)

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1c	Technically established grasses	TERP (R-5)	RC, FP, ASR
2c	Simultaneous agropastoral	Sim-AgP(1s×5)	RC, FP, ASR, GCH
4a	Agrosilvopastoral	AgSvP (ac/tre/p)	RC, FP, ASR, LCE, GCH
4b	Silvopastoral	SvP (tre,frt/p)	RC, FP, ASR
6	Agroforestry with annual crop	AgFAn (ac/tre)	STC
8	Permanent+mulch with legume	PC+M	AG, OSQ
9	Live fence – windbreaker	LFWB (p, ac, frt/tre)	
10b	Forestry (commercial or industrial)	F(com, ind)	AG, OSQ

SLOPE OF 10 to 15% (BANKED TERRACES EVERY 50 m)

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1c	Technically established grasses	TERP (R-5)	RC, FP, ASR
2c	Simultaneous agropastoral	Sim-AgP(1s×5)	RC, FP, ASR, GCH
4b	Silvopastoral	SvP (tre,frt/p)	RC, FP, ASR
5	Multistrata	MS (pc/sht/tt)	STC
7	Mixed home gardens	MDG	OM >5
10a	Forestry (reforest. and conserv.)	F (conserv.)	AG, OSQ

SLOPES >15% (BANKED TERRACES EVERY 30 m)

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1c	Technically established grasses	TERP (R-5)	RC, FP, ASR
2c	Simultaneous agropastoral	Sim-AgP(1s×5)	RC, FP, ASR, GCH
7	Mixed home gardens	MDG	OM >5
10a	Forestry (reforest. and conserv.)	F (conserv.)	AG, OSQ

MEDIUM TEXTURES

SLOPE OF 0 to 3%

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1b	Technically established grasses	TERP (R-4)	RC, FP, ASR
2b	Simultaneous agropastoral	Sim-AgP(1s×4)	RC,FP,ASR, GCH
3b	Rotational agropastoral	Rot-AgP (2×3)	RC, FP, ASR, LCE, GCH
4a	Agrosilvopastoral	AgSvP (ac/tre/p)	RC, FP, ASR, LCE, GCH
6	Agroforestry with annual crop	AgFAn (ac/tre)	STC
8	Permanent+mulching with legumes	PC+M	AG, OSQ
9	Live fence – windbreaker	LFWB (gr, ac, frt/tre)	
10b	Forestry (commercial or industrial)	F(com, ind)	AG, OSQ
11	Annual crops intercropped with cereals and grain legumes with different planting patterns.	AIC (ce+lg)	Only for soils where it has been possible to build arable layer; management with TDP.
12b	Constructive tillage (begins with annual crops and ends with silvopastoral system)	ConstTil (2ac/SvP)	Initially RC, FP, LCE, GCH; at the end, RC, FP, ASR.
12c	Constructive tillage (begins with annual crops and ends with pastoral system)	ConstTil (2ac/P)	Initially RC, FP, LCE, GCH; at the end, RC, FP, ASR.
12d	Constructive tillage (begins with annual crops and ends with forestry (commercial or industrial)	ConstTil (2ac/F(com, ind)	Initially RC, FP, LCE, GCH; at the end, good management of tł plantation

SLOPE OF 3 to 7% (BANKED TERRACES EVERY 50 m)

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1b	Technically established grasses	TERP (R-4)	RC, FP, ASR
2b	Simultaneous agropastoral	Sim-AgP(1s×4)	RC,FP,ASR, GCH
3b	Rotational agropastoral	Rot-AgP (2×3)	RC, FP, ASR, LCE, GCH
4a	Agrosilvopastoral	AgSvP (ac/tre/gr)	RC, FP, ASR, LCE, GCH
4b	Silvopastoral	SvP (tre,frt/gr)	RC, FP, ASR
6	Agroforestry with annual crop	AgFAn (ac/tre)	STC
8	Permanent+mulch with legume	PC+M	AG, OSQ
9	Live fence – windbreaker	LFWB (gr, ac, frt/tre)	
10a	Forestry (reforest. and conserv.)	F (conserv.)	AG, OSQ
12b	Constructive tillage (begins with annual crops and ends with silvopastoral system)	ConstTil (2ac/SvP)	Initially RC, FP, LCE, GCH; at the end, RC, FP, ASR.
12c	Constructive tillage (begins with annual crops and ends with pastoral system)	ConstTil (2ac/P)	Initially RC, FP, LCE, GCH; at the end, good management of the plantation

SLOPES >7% (BANKED TERRACES EVERY 30 m)

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1b	Technically established grasses	TERP (R-4)	RC, FP, ASR
2b	Simultaneous agropastoral	Sim-AgP(1s×4)	RC,FP,ASR, GCH
4a	Agrosilvopastoral	AgSvP (ac/tre/gr)	RC, FP, ASR, LCE, GCH
4b	Silvopastoral	SvP (tre,frt/gr)	RC, FP, ASR
9	Live fence – windbreaker	LFWB (gr, ac, frt/tre)	
10a	Forestry (reforest. and conserv.)	F (conserv.)	AG, OSQ

LIGHT TEXTURES

SLOPE OF 0 to 2%

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1a	Technically established grasses	TERP (R-3)	RC,FP, ASR
2a	Simultaneous agropastoral	Sim-AgP(1s×3)	RC, FP, ASR, GCH
3a	Rotational agropastoral	Rot-AgP (1×3)	RC, FP, ASR, LCE, GCH
4b	Silvopastoral	SvP (tre,frt/gr)	RC,FP, ASR
9	Live fence – windbreaker	LFWB (gr, ac, frt/tre)	
12a	Constructive tillage (begins with annual crops and ends with pastoral system)	ConstTil (1ac/P)	Initially RC, FP, LCE, GCH; a the end, RC, FP, ASR.
12b	Constructive tillage (begins with annual crops and ends with silvopastoral system)	ConstTil (2ac/SvP)	Initially RC, FP, LCE, GCH; a the end, RC, FP, ASR.

SLOPE OF 2 to 5% (BANKED TERRACES EVERY 50 m)

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1a	Technically established grasses	TERP (R-3)	RC,FP, ASR
2a	Simultaneous agropastoral	Sim-AgP(1s×3)	RC, FP, ASR, GCH
3a	Rotational agropastoral	Rot-AgP (1×3)	RC, FP, ASR, LCE, GCH
4b	Silvopastoral	SvP (tre,frt/gr)	RC,FP, ASR
9	Live fence – windbreaker	LFWB (gr, ac, frt/tre)	
10a	Forestry (reforest. and conserv.)	F (conserv.)	AG, OSQ
12a	Constructive tillage (begins with annual crops and ends with pastoral system)	ConstTil (1ac/P)	Initially RC, FP, LCE, GCH; a the end, RC, FP, ASR.
12b	Constructive tillage (begins with annual crops and ends with silvopastoral system)	ConstTil (2ac/SvP)	Initially RC, FP, LCE, GCH; a the end, RC, FP, ASR.
12d	Constructive tillage (begins with annual crops and ends with forestry (commercial or industrial)	ConstTil (2ac/F(com, ind)	Initially RC, FP, LCE, GCH; a the end, good management of the plantation

SLOPES >5% (BANKED TERRACES EVERY 30 m)

CODE	PRODUCTION SYSTEM	SYMBOL	CONDITION
1a	Technically established grasses	TERP (R-3)	RC,FP, ASR
2a	Simultaneous agropastoral	Sim-AgP(1s×3)	RC, FP, ASR, GCH
3a	Rotational agropastoral	Rot-AgP (1×3)	RC, FP, ASR, LCE, GCH
4b	Silvopastoral	SvP (tre,frt/gr)	RC,FP, ASR
9	Live fence - windbreaker	LFWB (gr, ac, frt/tre)	
10a	Forestry (reforest. and conserv.)	F (conserv.)	AG, OSQ
12a	Constructive tillage (begins with annual crops and ends with pastoral system)	ConstTil (1ac/P)	Initially RC, FP, LCE, GCH; at tl end, RC, FP, ASR.
12b	Constructive tillage (begins with annual crops and ends with silvopastoral system)	ConstTil (2ac/SvP)	Initially RC, FP, LCE, GCH; at tl end, RC, FP, ASR.

INFLUENCE OF SLOPES AND EFFECTIVE DEPTH IN DECISION-MAKING ON PRODUCTION SYSTEMS

HEAVY TEXTURES

SLOPE OF 0 to 5%

CODE	SYMBOL	*EFFECTIVE DEPTH (cm)*		
		0 – 40	0 - 25	0 - 15
1c	TERP (R-5)	*	*	*
2c	Sim-AgP(1s×5)	*	*	*
3c	Rot-AgP (3×3)	*	*	*
4a	AgSvP (ac/tre/gr)	*		
5	MS (pc/sht/tt)	*		
6	AgFAn (ac/tre)	*		
7	MDG	*	*	
8	PC+M	*	*	
9	LFWB (gr, ac, frt/tre)	*	*	
10b	F(com, ind)	*		
11	AIC (ce+lg)	*	*	
12e	ConstTil (3ac/P)	*	*	
12f	ConstTil (3ac/PC+M)	*	*	
12g	ConstTil (3ac/AIC)	*	*	

SLOPE OF 5 to 10% (BANKED TERRACES EVERY 100m)

CODE	SYMBOL	*EFFECTIVE DEPTH (cm)*		
		0 – 40	0 - 25	0 - 15
1c	TERP (R-5)	*	*	*
2c	Sim-AgP(1s×5)	*	*	*
4a	AgSvP (ac/tre/gr)	*	*	
4b	SvP (tre,frt/gr)	*	*	
6	AgFAn (ac/tre)	*		
8	PC+M	*	*	
9	LFWB (gr, ac, frt/tre)	*		
10b	F(com, ind)	*		

SLOPE OF 10 to 15% (BANKED TERRACES EVERY 50 m)

CODE	SYMBOL	*EFFECTIVE DEPTH (cm)*		
		0 – 40	0 - 25	0 – 15
1c	TERP (R-5)	*	*	*
2c	Sim-AgP(1s×5)	*	*	*
4b	SvP (tre,frt/gr)	*	*	
5	MS (pc/sht/tt)	*		
7	MDG	*	*	*
10a	F (conserv.)	*	*	

SLOPES >15% (BANKED TERRACES EVERY 30 m)

CODE	SYMBOL	*EFFECTIVE DEPTH (cm)* 0 – 40	0 - 25	0 - 15
1c	TERP (R-5)	*	*	*
2c	Sim-AgP(1s×5)	*	*	*
7	MDG	*		
10a	F (conserv.)	*	*	

MEDIUM TEXTURES

SLOPE OF 0 to 3%

CODE	SYMBOL	*EFFECTIVE DEPTH (cm)* 0 – 45	0 - 30	0 - 15
1b	TERP (R-4)	*	*	*
2b	Sim-AgP(1s×4)	*	*	*
3b	Rot-AgP (2×3)	*	*	*
4a	AgSvP (ac/tre/gr)	*	*	
6	AgFAn (ac/tre)	*		
8	PC+M	*	*	
9	LFWB (gr, ac, frt/tre)	*		
10b	F(com, ind)	*	*	
11	AIC (ce+lg)	*	*	
12b	ConstTil (2ac/SvP)	*	*	
12c	ConstTil (2ac/P)	*	*	*
12d	ConstTil (2ac/F(com, ind)	*		

SLOPE OF 3 to 7% (BANKED TERRACES EVERY 50 m)

CODE	SYMBOL	*EFFECTIVE DEPTH (cm)* 0 - 45	0 - 30	0 - 15
1b	TERP (R-4)	*	*	*
2b	Sim-AgP(1s×4)	*	*	*
3b	Rot-AgP (2×3)	*	*	
4a	AgSvP (ac/tre/gr)	*	*	
4b	SvP (tre,frt/gr)	*	*	
6	AgFAn (ac/tre)	*	*	
8	PC+M	*	*	
9	LFWB (gr, ac, frt/tre)	*		
10a	F (conserv.)	*	*	
12b	ConstTil (2ac/SvP)	*	*	
12c	ConstTil (2ac/P)	*		*

SLOPES >7% (BANKED TERRACES EVERY 30 m)

CODE	SYMBOL	EFFECTIVE DEPTH (cm) 0 - 45	0 - 30	0 - 15
1b	TERP (R-4)	*	*	*
2b	Sim-AgP(1s×4)	*	*	*
4a	AgSvP (ac/tre/gr)	*	*	
4b	SvP (tre,frt/gr)	*	*	
9	LFWB (gr, ac, frt/tre)	*		
10a	F (conserv.)	*	*	

LIGHT TEXTURES

SLOPE OF 0 to 2%

CODE	SYMBOL	EFFECTIVE DEPTH (cm) 0 – 60	0 – 40	0 - 20
1a	TERP (R-3)	*	*	*
2a	Sim-AgP(1s×3)	*	*	*
3a	Rot-AgP (1×3)	*	*	*
4b	SvP (tre,frt/gr)	*	*	
9	LFWB (gr, ac, frt/tre)	*		
12a	ConstTil (1ac/P)	*	*	*
12b	ConstTil (2ac/SvP)	*	*	

SLOPE OF 2 to 5% (BANKED TERRACES EVERY 50 m)

CODE	SYMBOL	EFFECTIVE DEPTH (cm) 0 - 60	0 - 40	0 - 20
1a	TERP (R-3)	*	*	*
2a	Sim-AgP(1s×3)	*	*	*
3a	Rot-AgP (1×3)	*	*	*
4b	SvP (tre,frt/gr)	*	*	
9	LFWB (gr, ac, frt/tre)	*		
10a	F (conserv.)	*	*	
12a	ConstTil (1ac/P)	*	*	
12b	ConstTil (2ac/SvP)	*	*	
12d	ConstTil (2ac/F(com, industrial)	*	*	

SLOPES >5% (BANKED TERRACES EVERY 30 m)

CODE	SYMBOL	*EFFECTIVE DEPTH (cm)*		
		0 – 60	0 - 40	0 - 20
1a	TERP (R-3)	*	*	*
2a	Sim-AgP(1s×3)	*	*	*
3a	Rot-AgP (1×3)	*	*	
4b	SvP (tre,frt/gr)	*	*	
9	LFWB (gr, ac, frt/tre)	*		
10a	F (conserv.)	*	*	
12a	ConstTil (1ac/P)	*		
12b	ConstTil (2ac/SvP)	*	*	*

Impact:
One of the great difficulties in defining cartographic units for soil use and management is the use of scales because even at the farm level, there is extensive variability in the chemical, physical and biological properties of the soils. At the same time, the satellite technology that can separate soils by variables such as texture, slope and depth of the profile do not yet exist. In extensive areas characterized by low fertility and susceptibility to erosion and structural degradation, such as the soils of the tropical savannas known as the *Altillanura*, it is necessary to develop tools that help technical assistants and producers make sound decisions as to their use and management. We propose, as a first approximation, the use of a decision-making tree for the well-drained savanna flatlands ecosystem, with pluviometric conditions of annual rainfall ranging from 2100 to 2600 mm. This tree takes into consideration aspects of climate, landscape and textural characteristics of the soils at three degrees of slope and three soil profile depths as macro criteria for determining their use and management. Different options for land use and management are developed for each one of the foregoing combinations. The potential production systems for each one of the combinations and the conditions necessary for their implementation are presented schematically. The proposed production systems range from areas of protection to constructive tillage systems that involve integrated soil management for developing arable layers at different levels of depth. These production systems are based on the concept of gradually improving the soil in all its characteristics, while controlling the risks of erosion and degradation through rational management of the resources in each specific situation. Then once the integrated improvement of the soil has been accomplished, it will be necessary to maintain its health through soil conservation practices with less dependency on tillage, fertilizers and agrochemicals in order to achieve efficient, sustainable production systems.

Contributors:
P. Hoyos, E. Amézquita, R. Thomas, N. Beaulieu and Y. Rubiano

3.4.2 Preliminary version of a simple database tool for soil diagnosis in the flat high plains (*altillanura plana*) of the Colombian *Llanos*

Highlights:

- A preliminary version of a simple tool is available to farmers and those who assist them to diagnose the health of their soils and to establish their limitations for specific crops
- The tool allows the storage of soil data for a series of georeferenced observation points that can be linked to a GIS and then analyzed with geostatistical or interpolation methods.

Results

The field component of the tool consists of a form to fill in with the characteristics of the soils that are measured in the field: Geographic coordinates, tangential resistance to cutting, penetrability, effective depth, pH, texture, color, and apparent density. If resources allow laboratory tests, then additional fields can be filled: effective density, organic matter content, and hydraulic conductivity. In the office of the agriculture extension service, the farmer has access to the database tool, which has been programmed in Microsoft Access, a very commonly used database management system. The farmer or an extension agent fills the electronic version of the field form using the computer and automatically fills a database table with the field data. The values in the resulting fields are compared with critical and optimal values for the type of soil being considered, which are stored in a separate table. These critical values are based on experimental data obtained in CIAT and CORPOICA test plots in the Colombian *altillanura plana*, in Carimagua (Culticor experiment), Matazul, and others. After this comparison is made, a report is generated, indicating how the measured values fall within the critical and optimal ranges, or if they fall outside. The tool will later be improved so that the report also interprets these results in terms of possible causes, possible solutions, and level of degradation.

The user then has the option of evaluating the level of restriction that the studied soil shows for specific crops. The soil requirements for these crops are still in development and stored in a separate database, which is linked to the tool. The user chooses the crop, and the soil properties are compared with the crop's soil requirement. As before, a report is generated with a diagnosis of how the measured soil properties fall within the optimal and critical values for the chosen crop. The user can generate as many crop reports as wanted and can save them in a text file.

Soil properties for many points, as well as their corresponding diagnosis, can be entered in a single table. Because the table also stores the geographic coordinates of each point, it can be exported to text format and imported in the MapMaker software. The resulting coverage can be overlaid onto digitized aerial photographs or satellite images. Soil properties can then be queried on screen. Soil property values can be interpolated from the ones in the database to form a grid surface.

Impact:

The use of this tool should lead to better soil management by farmers and to choosing the most suitable portions of land for intensification efforts. This should result in a decrease in soil losses and an increase in agricultural productivity. This tool makes available to farmers and agriculture extension agents the results of years of scientific research on soil physics in CIAT.

Contributors:

Yolanda Rubiano, Edgar Amezquita, Nathalie Beaulieu, Arturo Franco

3.4.3 Testing and refining coefficients of the P module NuMaSS and PDSS2

Highlight:

- Testing of NuMaSS (nutrient management decision support system) decision support system using the data from field experiments 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.

Purpose:

To perform a comparison of decision-aid predictions of fertilizer requirement (level 0 comparisons) and to perform a comparison of coefficients used in PDSS2 (phosphorus decision support system) and the P module of NuMaSS (nutrient management decision support system) to predict P fertilizer requirement (level 1 comparisons and testing).

Rationale:
A series of experiments have been carried out in the Llanos of Colombia. The purpose of these experiments was to determine the nutrient P requirements for several annual crops including maize, cowpea, and upland rice. Two of the experimental sites and three crops were selected to test the predictions of the PDSS2 and P module of NuMaSS with estimates of P requirements from factorial response curve experiments conducted in the field.

Results and Discussion:
Predictions of P fertilizer requirement:
Carimagua maize. As indicated in Figure 38, the PDSS2 prediction of P requirement for maize on this soil was slightly more than that estimated from the field-experiment, although the differences were not great. The experimental response curve is also shown in the Figure 38 and indicates a relation between the prediction and the field estimates. The predictions from PDSS2 are based on coefficients developed largely from experiments from the Brazilian Cerrado and from North Carolina.

Matazul cowpea and upland rice. A comparison was also made between the field estimates of P requirement for cowpea and upland rice Matazul and the PDSS2 predictions. As in the case of the Carimagua, this site is also located in the Eastern Llanos of Colombia (Figs. 39 and 40). The results were somewhat different than for the Carimagua site. PDSS2 predictions for cowpea tended to be somewhat less than that estimated from factorial response curve experiments conducted in the field. Results for the upland rice also suggest a slight underprediction of P requirements. This underprediction in the case of upland rice might have been related to the fact that the applied P was either applied before the former crop of cowpea or all applied before the previous crop. Estimates of 0.5*M* $NaHCO_3$ - P were made from a relationship with Bray P 2. As indicated in Chen et al., 1997, estimating critical levels is also one of the major sources of error in the PDSS system. It may be that the critical levels for 0.5*M* $NaHCO_3$ were from the Olsen while field measurements were from modified Olsen extractant. Critical levels and buffer coefficients for Olsen P for the EDTA modified method are higher than for the method that does not use EDTA.

Further results from PDSS2 analysis were included an economic analysis of the predicted P fertilizer estimates and the corresponding benefit / cost estimates and how the economic results vary with residual assessments of P applications. The results indicate that 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. A simple summary is given in Table 40.

Table 40. Economic results of the calculation of benefit / cost ratios for three crops. Data from Matazul for the rice and cowpea, Carimagua for the maize.

Factors	Crop		
	Rice	Maize	Cowpea
Market Price ($/tonne)	400	357	516
Expected Yield (tonnes)	3.26	2.95	0.993
P requirement (kg P ha^{-1})	21	44	31
Benefit/Cost ratio	3.9	2.5	1.4

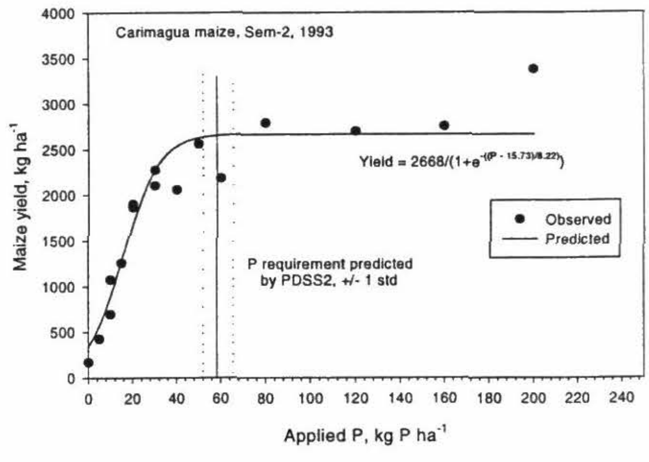

Figure 38. Comparison of P requirement estimated by PDSS2 with the experimentally determined P response curve. Carimagua maize, Semester 2, 1993. Conditions assumed in PDSS2, Initial P: 5.2, critical level 15, 42% clay.

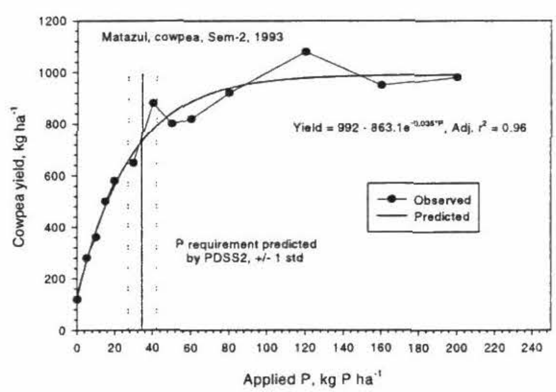

Figure 39. Comparison of the P requirement estimated by PDSS2 with the experimentally determined P response curve. Matazul cowpea, second semester, 1993.

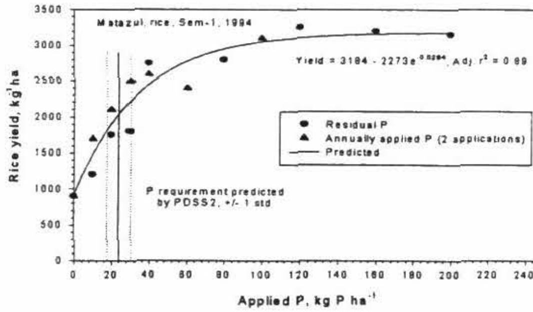

Figure 40. Comparison of P requirement predictions of PDSS2 with the experimentally determined response curve, Matazul, rice, 1994.

Likely one of the main reasons for the higher benefit / cost ratio for rice was the relatively high yield, good price at the market, and the lower P requirement. Maize yields seem very low and this together with the higher P requirements probably explain the predicted lower benefit / cost ratio. Cowpea yields were so low that the higher price did not compensate resulting in the lowest overall benefit / cost ratio. One caution seems important, however, and that is that in subsistence economies the market prices do not necessarily reflect the values, pride, and security of producing one's own food.

Impact:

Testing of NuMaSS using the data from the field experiments in the Llanos of Colombia indicated that in the Llanos of Colombia 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. As a result of this testing, buffer coefficients and critical levels of Bray-2 P were subsequently included in PDSS2. Further studies are underway for level 1 testing, in which we will compare field estimates of the coefficients used in PDSS2 predictions with those generated by PDSS2: P critical levels for Bray P2 for maize, cowpea, and upland rice, P buffer coefficients for Bray P2 and 0.5*M* $NaHCO_3$, coefficients for the slow reaction of fertilizer P with the soils at Carimagua and Matazul, and coefficients for the desorption of extractable P.

Contributors:

R.S. Yost (University of Hawaii, Hawaii, USA); D. K. Friesen (IFDC-CIMMYT, Nairobi, Kenya); J. I. Sanz, M. Rivera, and I.M. Rao (CIAT).

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

This activity is reported under project SW-2 (SWNM system-wide program).

Activity 3.6 Develop soil degradation risk assessment maps with PE-4

This activity was completed in 1999 for the Rio Cabuyal watershed in Colombia. Similar work is planned for Central America.

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

Activity 4.1 Organize and coordinate field days/ workshops

Highlight:

- Twelve field days were held in Pescador (January-September/2000), Cauca, Colombia with the participation of 276 visitors mainly farmers, extensionists and students from universities and schools; and one field day for Swedish Agricultural University (SLU) researchers was held in San Dionisio, Nicaragua.

Activity 4.2 Prepare guidelines/pamphlets on SWNM concepts

Highlight:

- A methodological guide entitled "Indentifying and Classifying Local Indicators of Soil Quality. East African Version. Participatory Methods for Decision Making in Natural Resource Management." Was preapred in collaboration with project SW-2 and the African Highlands Initiative.

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

Highlight:

- Coordinated a training course entitled: "Local Indicators of Soil Quality", held in Mukono, Uganda and sponsored by the CIAT, SWNM and AHI .

Activity 4.4 Publish research results in refereed journals and other publications

Highlight:

- The project team published 39 refereed journal articles, 7 refereed book chapters, 3 non-refereed book chapters, and 30 articles in conference proceedings.

Activity 4.5 Supervise postdoctoral research, graduate and undergraduate theses

Highlight:

- The project supervised 19 BSc, 1 Special, 5 MSc and 8 Ph.D theses.

The following is a list of undergraduate and graduate students who received training with the project scientists (Table 41).

Table 41. Training supported by PE-2 and MAS consortium of SWNM Program.

Name	Nationality	Education	Institution	Research theme
M.A. Rondon	Colombia	Ph.D.	Cornell Univ.	Greenhouse gas fluxes
W. Trujillo	Colombia	Ph.D.	Ohio State Univ.	Carbon sequestration
S. Buehler	Switzerland	Ph.D.	ETH, Zurich	Phosphorus acquisition/cycling
S. Phiri	Zambia	Ph.D.	Norway Agric. Univ.	Phosphorus acquisition/cycling
N. Castañeda	Colombia	Ph.D.	Univ. of Gottingen	Genotypic variation in P acquisition & utilization in *A. pintoi*
K. Tscherning	German	Ph.D.	Univ. of Hohenheim	Integration of soil and feed quality indicators for crop-livestock sytems including multipurpose legumes.
C. Thierfelder	Germany	Ph.D.	Univ. of Hohenhein	Development of soil preserving land use systems in the tropics.
Y. Rubiano	Colombia	Ph.D.	Univ. Nacional, Palmira	Soil degradation indicators fot the Llanos.
I. Valenzuela	Colombia	M.Sc.	Univ. Nacional, Palmira	Relationship between free soil water and its composition in Vertisols.
M. Rivera	Colombia	M.Sc.	Univ. Nacional, Palmira	Chemistry of tropical soil
P. Cerón	Colombia	M.Sc.	Univ. Nacional, Palmira	Local knowledge about soils and their management in the Potrerillo watershed, Cauca
R. Torres	Colombia	M.Sc.	Univ. Nacional, Palmira	Biological indicators of soil quality in improved fallow systems, Cauca.
J.T. Reyes	Honduras	MSc.	Univ. Nacional, Palmira	Biological indicators of soil quality in improved fallow systems, Cauca.
L.F. Chávez	Colombia	Special	Universidad de Brasilia	Specialization in direct- Drilling
C. Zamorano	Colombia	BSc.	Univ.Nacional, Palmira	Biological indicators of soil quality in improved fallow systems, Cauca
L.X. Salamanca	Colombia	BSc.	Univ. Nacional, Palmira	Biological indicators of soil quality in improved fallow systems, Cauca
C.L. Herrera	Colombia	BSc.	Univ. Nacional, Palmira	Floristic characterization of the Potrerillo watershed, Cauca.
E. Claros	Colombia	BSc.	Univ. Nacional, Palmira	Evaluation of yields from different double-purpose live barriers systems, Cauca
J.A. Rizo	Colombia	BSc.	Ùniversidad San Buenaventura	Economic analysis of double purpose live barrier systems, Cauca.

Name	Nationality	Education	Institution	Research theme
A. Suárez	Colombia	B.Sc.	Universidad Tecnológica del Llano.	Influence of depth of compaction in maize yields.
C.A. Cabrera	Colombia	B.Sc.	Universidad Tecnológica del Llano.	Characterization of degraded and non-degraded pastures in Altillanura.
E. Torres	Colombia	B.Sc.	Univ. del Valle	Evaluation of rainfall Simulation
C. García	Colombia	BSc.	ICESI, Cali	Data compilation
L. Bejarano	Colombia	B.Sc.	Univ. Nacional, Palmira	Erodability in Hillside
E. Ruíz	Colombia	B.Sc.	Univ. del Valle	Relationship between compaction and electrical conductivity.
A. Salamanca	Colombia	B.Sc.	Univ. Nacional, Palmira	Soil physical characterization under *Desmodium*
J. Barragán	Colombia	B.Sc.	Univ. Tecnológica del Llano.	Influence of the compaction maize yields.
M. Banguero	Colombia	B.Sc.	Univ. Nacional, Palmira	Erodability in hillsides
L.A. Charris	Colombia	B.Sc.	Universidad Tecnológica del Llano.	Collection soil chemical data from the Llanos.
L.D. Ayala	Colombia	B.Sc.	Univ. Nacional, Bogotá	Carimagua-Culticore
P.A. Pinto	Colombia	B.Sc.	ITA, Buga	Technician, working on soil physical determinations.
A.R. Parrado	Colombia	B.Sc.	Univ. del Llano	Pastures and soil degradation – Llanos.
X. Pernett	Colombia	B.Sc.	Univ. Nacional, Palmira	Climate studies in the llanos

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

Highlight:

- Established and maintained collaborative links with 50 institutional partners.

NARS:

CORPOICA – Popayán, Colombia; R. Torres
CORPOICA – Montería, Colombia; S. Cajas
CORPOICA – La Libertad, Colombia; A. Rincón, R. Valencia, D. Aristizábal, E. García, J.H. Bernal.
CORPOICA – Macagual, Colombia, C. Escobar
EMBRAPA-CPAC, Brazil: L. Vilela, D. Resck, C. Magno da Rocha, A.G. de Araujo, J.E. da Silva.
EMBRAPA-CNPAB, Brazil; R. Boddey, S. Urquiaga, B. Alves
APDC (Associaçao de Plantio Direto No Cerrado), Brasil: Prof. Ronaldo Trecenti

NGO'o:
CIPASLA, R. Rivas
CENIPALMA, P.L. Gómez, F. Munevar
CENICAFE, H. Rivera, S. Suárez
CORPOTUNIA, W. Cifuentes
CRC (Corporación Regional del Cauca), J. Chavez
FEDEARROZ, G. Preciado, A. Castilla, A. Salive
CIPAV, E. Murgueitio, S. Siadieagien
CIDIAT, Venezuela – R. Lopez
COLCIENCIAS, G. Urrego
INPOFOS, Ecuador – J. Espinosa
MONOMEROS COLOMBO-VENEZOLANO, R. Guerrero
CENIPALMA, P.L. Gómez, F. Munevar

Regional Universities:
Lavras, Brazil; Prof. A.S. Lopes
Uberlandia, Brazil; M. do Schneider, R.S. do Carmo Lima
UNELLEZ/CIELAT, Venezuela; L. Sarmiento, G. Sarmiento

Specialized Institutions:
Bayreuth University; Prof. W. Zech, W. Wilcke, J. Lilienfein, A. Freibauer, H. Neufeldt, R. Westerhoof, T. Renz, T. Thile, S. Fuhrmann, V. Laabs, W. Amelung.
Cornell University, USA; Prof. J. Duxbury, F. Fernandes
Ohio State University, USA; Prof. R. Lal
Michigan State University, USA; Prof. J. Ritchie, S. Daroub
University of Paris/ORSTOM, France, Prof. P. Lavelle
Macaulay Land Use Research Institute, UK; Prof. J. Wilson
University Bangor, Wales, UK; F. Sinclair
Technical High School, Univ. of Zurich, Switzerland; A. Oberson, M. Frossard
Agricultural University of Norway, Norway; Prof. B.R. Singh
University of Gottingen, Germany, Prof. N. Claassen
University of Hohenhein, Prof. R. Schultze-Kraft, D. Leihner
ETH, Zurich, Switzerland
Universidade de Brasilia, Brasil, Prof. Carlos Alberto da Silva Oliveira, Prof. Dr. Ricardo Carmona.
Universidade Federal de Santa Maria, Brasil, Prof. Telmo Jorge Carneiro
Univesidad Federal de Viçosa, Brasil, Prof. Dr. Ernani Luiz Agnes

International Agricultural Research Centers:
CATIE, Costa Rica; D. Kass, J. Beer
ICRAF, Kenya; P. Smithson
IBSRAM, Thailand; R. Lefroy
IFDC, USA; D. Friesen

National Universities:
Universidad Nacional de Colombia, A. García, E. Madero, E. Escobar, M. Sánchez, M. Prager.
Universidad de Nariño, Hugo Ruíz
Universidad del Cauca, Popayán, P.Cerón
Universidad de los Llanos, G. Romero
Universidad del Tolima, H.F. Libreros
Universidad de Caldas, W. Chavarriaga

Universidad Distrital de Bogotá, G. de las Casas
Universidad Centro Americana, Managua, Nicaragua, A. Grijalba
Universidad Nacional Agraria, Managua Nicaragua, M. Somarriba
Escuela Agrícola Panamericana Zamorano – Honduras, M. Andrews

Complementary and Special Projects

Research activities reported have been supported from a number of donors (Table 42).

Table 42. List of donors of Complementary and Special Projects:

Donor/Project	Duration	Total Pledge (US$)
ETHZ, Zurich, Switzerland Assessing the impact of adapted germplasm on the phosphorus fertility of low phosphorus -supplying tropical soils	1998 – 2001	140,000
DFID – UK Carbon-nitrogen Relations of Soil Organic Matter from Deep-Rooted Grasses in the South American Tropics	1996 – 1999	303,395
PRONATTA, Colombia Impacto de diferentes usos y manejos del suelo en los cambios físicos, químicos y biológicos de los suelos de la Altillanura bien drenada de los Llanos de Colombia	1996 – 1999	51,480
COLCIENCIAS, Colombia Sostenibilidad del Recurso Tierra de la Orinoquía en Realción a su Uso Actual y Potencial	1996 – 1999	172,800
DFID – UK Confronting Soil Erosion and Nutrient Depletion in the Humid/Subhumid Tropics	1998 – 1999	156,037
DFID – UK Potential of Thitonia diversifolia to enhance phosphorus mineralization and cycling	1998 - 2000	20,000
SWNM Managing Acid Soils: Water and Nutrient Fluxes as Indicators of Sustainable Land Use in the Brazilian Savanna	1996 – 1999	360,000
ACIAR Integrated nutrient management in tropical cropping systems: Improved capabilities in modelling and recommendations.	1999-2002	434,130

List of Staff

Senior Staff
Project Manager - Richard J. Thomas
Soil Microbiology
I.M. Rao – Plant Nutrition
Edgar Amézquita – Soil Physics
Edmundo Barrios – Agronomy/Soil Biology
José I. Sanz - Agronomy
Miguel A. Ayarza – Agronomy/ Soil Chemistry

Postdoctoral Fellow
Juan José Jiménez – Soil Macrofauna
Robert Delve - Àgronomist
W. Wilcke – Soil Chemist
J. Lilienfein – Soil chemist

Consultants
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Samira Daroub - Modeller
Phanor Hoyos - Agronomy

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Mariela Rivera
Gloria Marcela Rodríguez
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Workers
Josefa Salamanca
Héctor Unda
Luis Soto
Jaime Romero
Nixon Betancourt
Joaquin Cayapú
Dayro Franco
Jahir Cayapú
Adolfo Messu

List of Publications

Refereed journal articles:

[redacted] Barrios E., J.G. Cobo, I.M.Rao, R. Thomas, E. Amézquita, J.J. Jiménez (2000) Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia. Agriculture, Ecosystems and Environment (submitted)

2. Castillo, J.A., Amézquita, E., Müller, K. 2000. La turbidimetría una metodología promisoria para caracterizar la estabilidad estructural de los suelos. *Revista Suelos Ecuatoriales* 30 (1 y 2), *in press.*

[redacted] Cobo J.G., Barrios E., Kass D. and Thomas R.J. (2000) Decomposition and N and P release by green manures in a hillside tropical soil. Soil Biol. Biochem. (in press)

4. Decaëns, T., 2000. Degradation dynamics of surface earthworm casts in grasslands of the Eastern Plains of Colombia. Biology and Fertility of Soils, 32: 149-156.

5. Decaëns, T., Rossi, J.-P. 2000. Spatio-temporal structure of earthworm community and soil heterogeneity in a tropical pasture (Carimagua, Colombia). Ecography (in press).

6. Decaëns, T., Galvis, J.H., Amézquita, E. 2000. Propriétés de quelques structures produites par les ingénieurs écologiques du sol dans une savane colombienne. Comptes Rendus de l'Académie des Sciences, (in press).

7. Decaëns, T., Jiménez, J.J., Lavelle, P. 1999. Effects of exclusion of the anecic earthworm *Martiodrilus carimaguensis* Jiménez and Moreno on soil properties and plant growth in grasslands of the Eastern Plains of Colombia. Pedobiologia, 43: 835-841.

8. Decaëns T., Mariani L. , Betancourt N., Jiménez J.J. Earthworm effects on permanent soil seed banks in Colombian grasslands. Submitted to Ecography.

9. Decaëns T., Asakawa N., Galvis J.H., Thomas R.J., Amézquita E. Surface activity of ecosystem engineers and soil structure in contrasting land use systems of Colombia. Submitted to European Journal of Soil Biology.

10. Decaëns T., Jiménez J.J., Barros E., Chauvel A., Blanchart E., Fragoso C., Lavelle P. Soil macrofaunal communities in permanent pastures derived from tropical forest or savanna. Submitted to Acta Oecologica.

11. Feijoo, A., Knapp, E.B., Amézquita, E., Lavelle, P. 2000. Dinámica de poblaciones de lombrices de tierra en áreas de laderas del Departamento del Cauca,Colombia. *Revista Suelos Ecuatoriales* 30 (1 y 2), *in press*

12. Hoyos, P., Amézquita, E., Thomas, R.J., Vera, R.R., Molina, D.L. 2000. Efecto del sistema y uso de la tierra en la distribución de los agregados en suelos de la Altillanura Colombiana (Effect the land use system in aggregate size distribution of soil from the Eastern Plains of Colombia). *Revista Suelos Ecuatoriales* 29(1):61-65.

13. Hoyos, P., Amézquita, E., Thomas, R.J., Vera, R.R., Molina, D.L., Almanza, E.F. 2000. Relaciones entre la infiltración de agua en el suelo y algunas propiedades físicas en las sabanas de la Altillanura Colombiana (Relationships between infiltration and some soil physical characteristics in the Colombian savannas). *Revista Suelos Ecuatoriales* 29(1):55-60.

[redacted]. Jiménez, J.J., Decaëns, T., 2000. Vertical distribution of earthworms in grasslands of the Eastern Plains of Colombia. Biology and Fertility of Soils (in press).

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List of Acronyms

ACIAR	Ausralian Centre for International Agricultural Research, Australia
AUN	Agricultural University of Norway, Norway.
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
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
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
INPOFOS	Instituto Internacional de Fósforo y Potasio, Ecuador
LAC	Latin American and the Caribbean
MAS	Management of Acid Soils (*of* SWNM *of the* CGIAR), CIAT Colombia.
NARS	National Agricultural Research Systems
NGO	Non-Governmental Organization
ORSTOM	Institut français de recherche sicentifique pour le developpement en coopération, France.
PRONATTA	Programa Nacional de Transferencia de Tecnología, Colombia
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
UNELLEZ	Universidad Nacional Experimental de los Llanos Orientales Exequiel Zamora, Venezuela