The Soil Management Collaborative Research Support Program

TropSoils

Technical Report, 1988–1989

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TropSoils Technical Report, 1988–1989

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Introduction

Approach

TropSoils' goal is to develop and adopt improved soil-management technology that will reduce constraints to plant growth; TropSoils also seeks to ensure that this technology is agronomically, economically, and ecologically sound for developing countries in the tropics. The research effort, previously partitioned into agroecological zones assigned to lead universities, has now been consolidated into two global thrusts: *natural-resource management* and *sustainable agriculture*. A third global thrust, *outreach*, links research networks, training, decision-support systems, and communications. The research projects described in this report were developed after identifying and prioritizing the constraints and research problems detailed below.

Global Thrust 1: Natural-Resource Management

Sustainable development requires the management, conservation, and enhancement of those natural resources which are most critical to meeting food, fiber, fuel, and shelter requirements, as well as to preserving genetic diversity and attenuating climatic change. TropSoils identifies five constraints to sound management of the natural-resource base: 1) land-clearing pressure, 2) landscape restrictions, 3) climatic variability, 4) inadequate resource information, and 5) production-demand pressures.

Land-Clearing Pressure

Population growth in the tropics places extreme pressure on the soil resources. As farm numbers increase, the soil recovery period shortens, and soils rapidly degrade to nonproductive levels. Farmers must clear more land to grow the same amount of food.

Landscape Restrictions

The effects of climate pose serious problems to soil conservation in the tropics. Even on rolling or gently sloping tropical landscapes, wind or water erosion may be common. Without reliable information about natural processes, it is impossible to formulate sound management practices. There are few good baseline studies about hydrology and erosion in tropical rainforests.

Climatic Variability

In regions where rainfall or temperature are extreme, climate can exert an important influence on soil management. Climate influences the physical, chemical, and biological properties of soils, as well as the choice of cropping system. The pronounced regional variability of rainfall and temperature in the tropics makes climate an important consideration in any soil-management system.

Inadequate Resource Information

Policies to achieve sustainable agricultural production must be based on an adequate technical assessment of natural-resource inventories. In many developing countries, these inventories are not available. Almost no reliable information exists on how forest conversion affects soil dynamics.

Production-Demand Pressure

Population growth, accompanied by increased demand for food, fiber, fuel, and shelter materials, places extreme pressure on the soil resources. Because many countries lack a strong industrial base, their economies depend on the production and export of agricultural commodities. Larger and larger areas must be brought into production to meet the demand for food and exports. These two demands, while not reversible, can be eased with the development of soil-management technologies that conserve natural resources while increasing production.

Global Thrust 2: Sustainable Agricultural Production

TropSoil's concept of sustainable agriculture is consistent with the definition proposed by USAID (1990):

> Sustainable agriculture is a management system for renewable natural resources that provides food, income, and livelihood for present and future generations and that maintains or improves the economic

productivity and ecosystem services of these resources.

The benefits of developing sustainable agriculture include reduced tropical deforestation and desertification, increased soil productivity, and increased soil stability. In short, sustainable agriculture will enhance the environment while providing food, fiber, and fuel at affordable prices. Tropsoils identifies five constraints to sustainable agriculture: 1) soil acidity, 2) nutrient deficiencies and losses, 3) soil physical limitations, 4) topographic limitations, and 5) water stress.

Soil Acidity

Many soils common in the tropics are very acid, low in exchangeable bases, and high in exchangeable aluminum. Soil acidity is also a major constraint in the Sahel. The acidity and toxicity in these soils constrain agricultural production in several ways. Sensitivity of plant species and cultivars to soil acidity and associated soil problems limits crop selection. Phosphorus fixation associated with soil acidity reduces the crop's ability to take up nutrients and use them efficiently. Because soil acidity is a barrier to root development, plants cannot reach moisture stored in acid subsoils. Therefore, water stress is common, and crop yields are reduced. Soil acidity and associated problems lead to land abandonment and the perpetuation of slash-and-burn agriculture in the humid tropics. In the semiarid tropics, soil acidity causes uneven growth of food crops and contributes to desertification.

Nutrient Deficiencies and Losses

Soils of the tropics, in addition to acidity constraints, are often low or deficient in one or more primary and secondary nutrients. Low crop yields attributable to poor nutrition and accelerating soil degradation are major contributors to rainforest destruction and land abandonment in the humid tropics, and of desert encroachment in the semiarid tropics.

Soil Physical Limitations

Soils of the tropics are characteristically highly weathered, and because of climate and other natural factors, they vary in the amount of organic matter they contain. The overuse of traditional management systems and heavy implements often leads to soil physical degradation. Specifically, the productivity limitations imposed by improper management include the development of subsurface root-restricting pans in savanna soils; surface hardening; excessive water runoff; soil loss by erosion in the humid tropics; and crust formation resulting in low water infiltration, runoff, and poor moisture harvesting in semiarid regions. The consequences of inappropriate management are the destruction of rainforests with slash-and-burn clearing, land abandonment, and desertification.

Topographic Limitations

Landscape configurations impose special challenges in the development of appropriate soil-management technologies. Tropical soils of the steeplands are especially vulnerable to degradation as a result of water erosion, even in the semiarid tropics. Selection of crops, cultivars, cropping sequences, and crop mixtures without considering landscape configuration often results in losses of food and fuel production capabilities.

Water Stress

Moisture stress, natural or imposed, may result from either excessive or inadequate amounts of water. The consequence of water stress is often a loss of crop yield. Selection of the best ecologically adaptable and socially acceptable combinations of crop, plant species, cultivars, and cropping sequences is a necessary production-management decision tempered by experience, financial constraints, and risk assessment.

Global Thrust 3: Outreach

Achieving sustainable agriculture and natural-resource conservation requires the effective validation, extrapolation, and communication of scientific information and user-oriented technologies. In the TropSoils approach, outreach includes those extrapolation, communication, training, networking, and decision-support activities that translate into useful knowledge.

TropSoils identifies four constraints to the extrapolation and adoption of improved technologies: 1) the number and diversity of potential users, 2) the site-specificity of soil-management practices, 3) the lack of local expertise and communications channels, and 4) the gap between new information and useable knowledge.

Number and Diversity of Potential Users

People throughout the tropics lack appropriate soil-management technologies. They are diverse in their needs, languages, and cultures. Extension and communication channels in developing countries are rudimentary; ethnic, cultural, and linguistic barriers are common.

Constraint: Site-Specificity of Management Practices

To be effective, soil-management practices must accommodate a range of conditions, including soil chemical and physical processes, crop and cultivar, climate and landscape, and social and economic conditions. While certain soil-management problems are common to many sites, solutions appropriate for one location may be inappropriate for another. Recommendations must therefore be specific to sites or regions.

Lack of Local Expertise and Communication Channels
The sophisticated, broad-based programs of extension and education that helped give rise to modern agriculture in developed countries are rare in developing countries. The lack of trained soil scientists, agronomists, educators, and communicators in developing countries impedes the transfer and adoption of new agricultural technologies.

Gap Between New Information and Useable Knowledge
Traditionally, research results become scientific knowledge through a lengthy process of consensus-building that includes peer review, publishing, public comment, and application. In agriculture and natural-resource conservation, responsibility for interpreting and applying this knowledge for practical use has for the most part been assigned to highly trained specialists in industry or in university extension services. Simply publishing and disseminating experimental results to developing countries are not in themselves sufficient to achieve the widespread adoption of appropriate soil-management technologies.

Lack of Education, Training, and Research Capability
A constraint to natural-resource management in developing countries is the lack of trained professionals to implement appropriate policies and programs. Research is constrained by a lack of trained scientists, by inadequate research infrastructures, and by a shortage of financial resources.

Additional Information
This document details the progress of TropSoils' research in each of the three thrusts outlined above. For more information about administrative matters and opportunites for collaboration contact:

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1.

Natural-Resource Management

Hydraulic Processes in a Steepland Primary Forest: NC-5

In the humid tropics, the increased conversion of forests to agroecosystems has caused concerns about environmental quality and land productivity, particularly in steep areas subject to erosion. To assess the consequences of such conversions in a quantitative and comparative fashion, researchers need benchmark data on hydrologic and erosion processes in an undisturbed forest ecosystem. This study begins an extensive investigation into the suitability of various agroecosystems to maintain productivity and to allay the environmental impact of forest conversion.

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Approach and Strategy: Y-800

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Objectives

The objectives of this study are 1) to monitor catchment inputs (rainfall and solutes) and outputs (streamflow, solutes, and sediments) and 2) to define source areas of runoff, sediments, and solutes within the catchment as a function of topographic and pedologic conditions.

Procedures

A catchment called *La Cuenca* was selected in a forest reserve at the La Esperanza station. The catchment is representative of the dissected uplands between the Pichis River and the San Matias Cordillera. Rainfall is measured with an automatic recording rain gauge; solute input is analyzed in weekly samples collected outside and within the forest. Streamflow is monitored at the catchment outlet by an automatic water-level recorder; stream water is collected on a weekly and a within-event basis and analyzed for solutes and sediments. On two topographically different hillslopes, tensiometers, piezometers, pressure-vacuum soil water samplers, and runoff-collecting devices were installed to monitor water, solute, and sediment fluxes. The spatial distribution of the surface runoff is defined by a large number of surface-runoff detectors. A system of plankways ensures that human traffic does not distort watershed measurement

Summary

A first-order catchment in the primary rainforest was monitored to identify the hillslope's dominant hydrological processes and to explain them as a function of the prevailing environmental controls. The research site is located in the Subandean region of the Western Amazon Basin (75° 5'W, 10° 13'S) on an old, dissected Ultisol surface.

Three continuous monitoring sites for overland flow, and one for pipeflow, and 72 overland flow detectors were employed to assess the temporal and spatial frequency of these near-surface flow processes. Overland flow is a common phenomenon: one-third of 187 rainfall events evaluated led to a response in at least 50% of the detectors. At the continuous monitoring sites, one out of four rainfall events in 1987 and 1988 resulted in overland flow in a convex upslope position, and three out of four events in a straight downslope position. Overland flow was found in concentrated-flow lines, many of which were traced to pipe outlets on the hillslopes. In the one pipe monitored, flow occurred only in the rainy season, and then only in response to sustained high-intensity rainfall events.

These near-surface hydrological processes were a consequence of the interaction between rainfall characteristics on the one hand, and the soil hydraulic conductivity-depth function and its spatial variability on the other hand. This interaction was evaluated on the basis of nearly 1400 undisturbed soil cores. A hydraulic discontinuity was found at a depth of 0.1 to 0.2 m, corresponding to a decrease in Ksat of four to five orders of magnitude throughout the catchment, except for the sideslopes, where the decrease was only two orders of magnitude. The medians of the maximum rainfall intensities are smaller than the surface Ksat everywhere but on the sideslopes, but they exceed the Ksat below a depth of 0.1m.

Three overland flow-generating mechanisms can be inferred: 1) localized Horton overland flow on steep sideslopes; 2) saturation overland flow when a temporary water table perched where the shallow hydraulic discontinuity reaches the soil surface; 3) return flow from soil pipes and macropores whose extensive network drains the perched water table.

Soil Hydraulic Conductivity and Landscape Position: Y-810A

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The complex soilscape at *La Cuenca* reflects an adjustment to regional fluvial rejuvenation. Soil hydraulic conductivity (Ksat) integrates various other soil properties which, in turn, are time-dependent. This time dependency is expressed as spatial dependency, on the premise that different landscape positions have a different history. Ksat, then, might vary in a predictable fashion with landscape position.

Objective

The objective of this study was to compare the Ksat of different landscape positions and depths.

Procedure

Ksat was determined by using the constant-head method on undisturbed soil cores. These were sampled according to landscape position (Figure 1). Each batch representing one combination of depth/landscape position was analyzed to decide on the appropriate estimator of location and scale.

Results

Table 1 summarizes the dependency of Ksat on depth and landscape position. Ksat at a depth of 0 to 0.1 m varied considerably among landscape positions. Most striking is the low estimate for the steep lower sideslope (B) compared to the more gentle upper sideslope (D) and the two geomorphologically stable surfaces (C and E). The estimates for the three stable surfaces were not significantly different. Although the differences among the topographic positions tend to diminish with depth, the Ksat-depth functions are distinct. The decrease was sharpest on the interfluve (E), comparatively gradual on the intermediate terrace (C), and intermediate on the upper

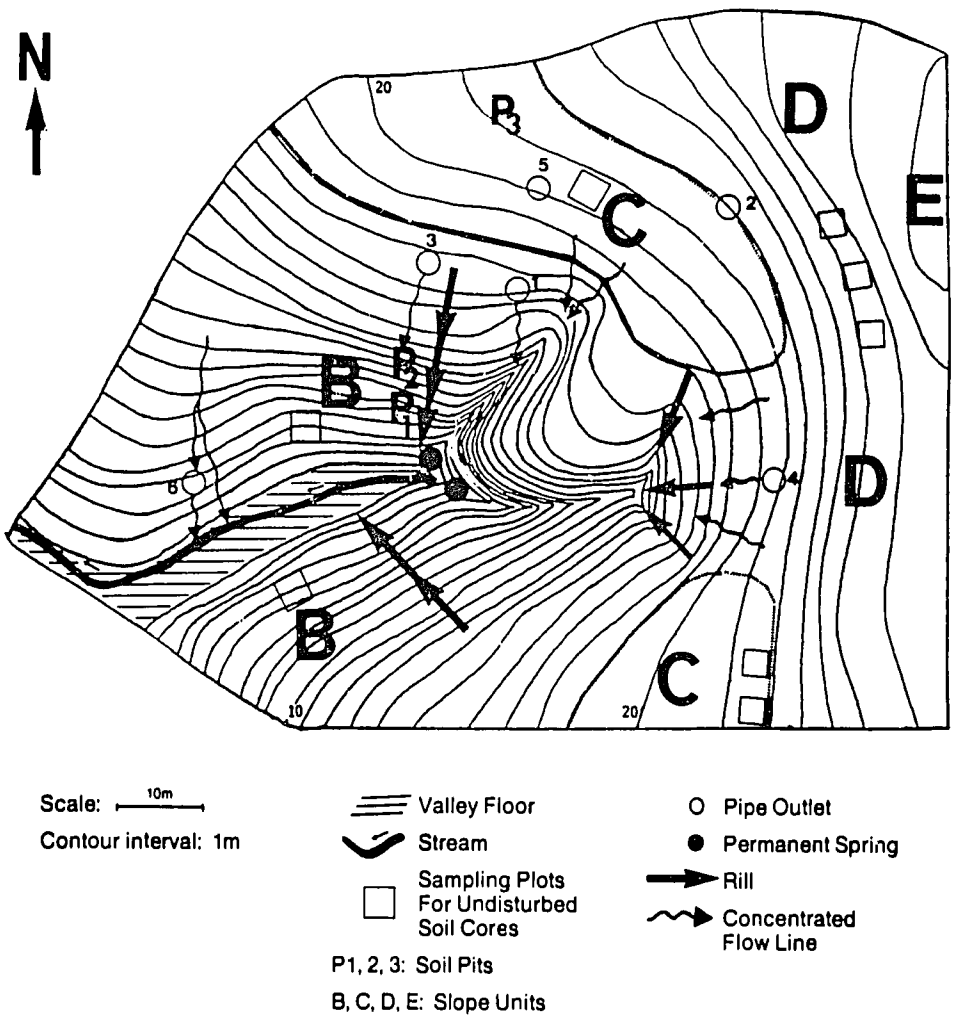

Figure 1. The research cachment at *La Cuenca*.

sideslope (D). The decrease in Ksat with depth on the lower sideslope (B) was of the same magnitude as that of slope-units C and D, but it was restricted to the upper 0.3 m.

In absolute terms, the decrease in Ksat with depth was very sharp, regardless of landscape position. This finding is due mainly to the shallowness of the surface layer affected by biological activity. On the steep lower sideslope (B), this activity seems to be even more reduced as a result of active surficial processes such as overland flow and rill formation.

Conclusions

The relationship between soil hydraulic conductivity and landscape position is clearly established. The Ksat-depth function, in particular, is characteristic for each landscape position.

Implications

The results support the formulation of hypotheses whose testing would require regional sampling (e.g. Pichis Valley, lower Pachitea, or Huallaga Basin).

Validation of the *La Cuenca* results at the regional scale would encourage the use of geographical information in extrapolating site-specific soil information to other areas.

Table 1. Saturated soil hydraulic conductivity as a function of depth and landscape position.

Slope unit	n	Depth	Lower confidence limits*	T_b§	Upper confidence limits
		— m —		mm/hour	
Lower sideslope (B)	50	0.0–0.1	27	45	71
	50	0.1–0.2	0.22	0.40	0.76
	50	0.2–0.3	0.054	0.097	0.16
	10	0.3–0.4	0.047	0.144	0.45
Intermediate terrace (C)	75	0.0–0.1	375	462	562
	75	0.1–0.2	2.23	3.74	6.19
	50	0.2–0.3	0.47	0.83	1.48
	10	0.3–0.4	0.04	0.10	0.26
Upper sideslope (D)	75	0.0–0.1	256	334	429
	75	0.1–0.2	0.58	1.08	2.12
	50	0.2–0.3	0.036	0.054	0.076
	10	0.3–0.4	0.007	0.014	0.025
Interfluve (E)	50	0.0–0.1	413	549	703
	50	0.1–0.2	0.11	0.20	0.36
	50	0.2–0.3	0.015	0.019	0.024
	10	0.3–0.4	0.007	0.015	0.032

* The confidence limits are based on a significance level of 0.05.
§ The location estimates (T_b) are based on Tukey's biweight.

Frequency of Overland Flow and Pipeflow: Y-810B

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Microtopographic expressions of surficial processes, such as rills and gullies, are conspicuous features of the primary rainforest soilscape in the Pichis Valley. These features suggest that water moves laterally near the soil's surface. The almost instantaneous catchment response to rainfall events suggests a rapid hydrological pathway, which would be consistent with the previous suggestion.

Objective

The objective of this study was to assess the spatial and temporal frequency of overland flow (OF) and the temporal frequency of outflow from one soil pipe (PF).

Procedure

Seventy-two OF detectors were installed throughout the catchment to cover all possible configurations of slope profile and contour curvature (Figure 1). They were checked after a total of 187 rainfall events. For nearly two years, the temporal frequency was determined in detail at three continuous monitoring sites for OF and one for PF.

Results

Table 1 summarizes the qualitative assessment of OF occurrence. Overland flow is a common occurrence temporally as well as spatially. A spatial frequency of at least 50% in one of three events might be considered *widespread*. However, that term is not to be equated with spatially continuous OF in the sense of sheetflow. Table 2 clarifies the discontinuous nature of OF in this environment. The degree of variability, and thus the discontinuity of hillslope flowpaths, is best appreciated by comparing the frequencies of detectors 4, 11, 12, and 16 in the left-hand gully. They are located within a few meters of each

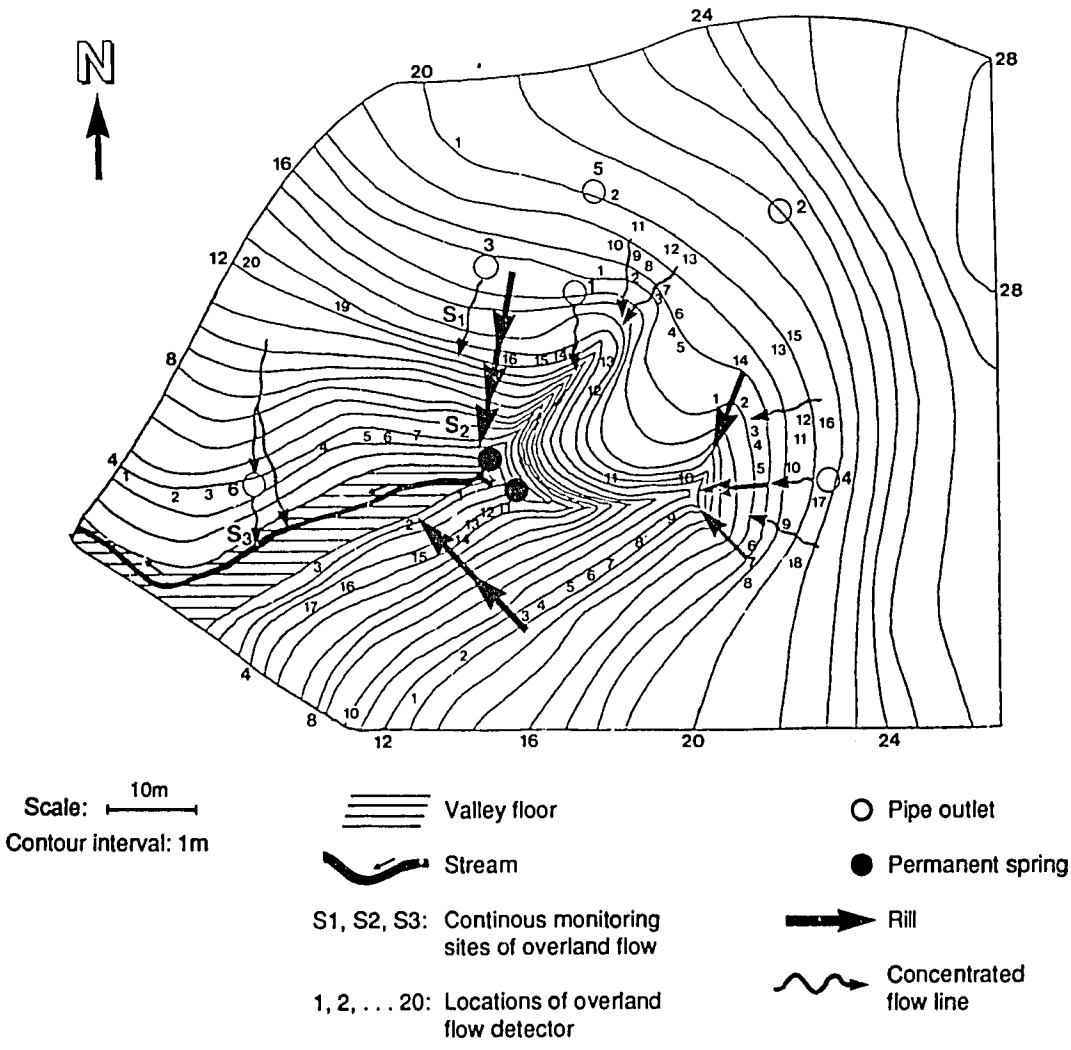

Figure 1. Locations of overland-flow monitoring sites and flow detectors.

Table 1. Frequency of overland flow, based on 187 storms between September 1986 and January 1988.

Spatial frequency	Temporal frequency
(% of sites)	(% of events)
≥ 25	74
≥ 50	33
≥ 75	4

other, and all are in an area of converging flow. And yet, OF occurs 16 times as frequently at one site as at the site a few meters away. Similar examples can be found elsewhere in the catchment. These findings imply that OF occurs in concentrated-flow lines.

The continuous monitoring of OF at sites S1, S2, and S3 confirms the above results (Table 3). The highest frequency was observed on the lower sideslope at site S2, and the lowest on the convex upper sideslope at site S1 (Figure 1). This suggests a topographic control of OF generation. The high frequency of OF observed at site S3, however, was attributed mainly to the interception of an active concentrated-flow line. This line could be traced upslope for a considerable distance; it was also fed by outflow from pipe 6 (Figure 1).

Outflow seldom occurred from the continuously monitored pipe 1. A complete record of rainfall characteristics of PF-generating events is given in Table 4. Most such events occur in the rainy season, none in the dry season, and few (of minor volumetric importance) during the transition periods. It would be premature to conclude from this one example that pipeflow rarely occurs, since field observations, including the contribution of outflow from pipe 6 to OF at S3, suggest otherwise.

Conclusions

Overland flow is a frequent and widespread phenomenon in this primary rainforest. One out of three rainfall events generated OF at 50% or more of the sites. The temporal frequency of OF occurrence at the continuous monitoring sites varied between 25 and 85% of all rainfall events.

Table 2. Frequency of overland flow in individual detectors.

Detector no.	Sampling unit§					
	CLO	CL1	CL2	CL3	Gully 1	Gully 2
	Number of storms					
1	10	8	22	3	40	23
2	23	8	87	42	37	13
3	2	74	59		35	28
4		81	69		23	160
5		14¶	25		77	143
6		28¶	7		58	103
7		53¶	35		22	40
8		108	15		65	39
9		64	43		81	102
10		57	26		6	36
11		17	50		37	26
12		2	13		15	10
13		55	57		6	53
14		81	53			26
15		4	89			22
16		8	112			24
17		29	—			38
18			—			32
19			25			
20			60			

§ CLO: along 1-m contour line.
CL1: along 4-m contour line.
CL2: along 12-m contour line.
CL3: along 20-m contour line.
Gully 1: in source area of orographically right-side gully.
Gully 2: in source area of orographically left-side gully.
¶ Incomplete record.

Table 3. Frequency of overland flow at three continuously monitored sites in 1987 and 1988.

Site	Number of events[§] 291 (1987)	270 (1988)
I	84	71
II	244	221
III	150	146

[§] Only events with magnitudes > 0.2 mm were considered.

Implications

The widely accepted notion that overland flow does not occur in tropical rainforest environments deserves a careful revision. The existence of near-surface lateral flow, as documented for *La Cuenca*, has its bearing on sediment and solute transport, especially on estimates of nutrient recycling.

Table 4. Characteristics of pipeflow-generating events, antecedent soil moisture conditions, and total volume of pipeflow.

Date	MAG[§]	I_{60}	I_{30}	I_{10}	h_{10}	h_{p30}	V_t
	mm	mm/h			(mb)		l
18-04-87	40.0	40.0	60.0	61.2	-31	-19	34
18-04-87	25.0	16.0	25.6	31.2	—	—	66
05-05-87	37.5	21.2	39.4	60.0	10	13	12
06-05-87	30.7	24.9	32.4	48.0	-24	-14	40
28-10-87	47.6	28.0	36.0	60.0	-18	-16	6
09-11-87	41.6	33.0	37.0	38.4	-20	-11	44
24-12-87	78.9	49.0	54.0	60.0	-13	-14	¶
29-12-87	34.2	23.8	49.2	54.0	-22	-20	¶
30-12-87	83.4	47.0	64.0	78.0	2	12	¶
13-01-88	68.1	34.8	44.0	48.0	-5	-4	22
04-02-88	18.6	18.5	33.0	44.4	-28	-23	43
12-03-88	58.7	34.7	50.0	52.0	-1	-6	202
20-05-88	40.9	28.2	36.0	42.0	-42	-31	37
31-05-88	42.7	20.6	24.4	38.4	-15	-11	26
09-02-89	103.0	33.0	35.0	60.0	—	—	¶
12-03-89	49.5	25.0	31.0	48.0	—	—	54
27-03-89	77.2	45.8	70.0	82.8	—	—	¶

[§] MAG: rainfall amount; I_{60}, I_{30}, I_{10}: 60-min, 30-min, 10-min maximum intensities; h_{p10}, h_{30}: soil water matrix potential at depths of 0.1 and 0.3 m; V_t: total volume.
[¶] Total volume exceeds storage capacity of container.

Descriptive Statistics of Precipitation Events: Y-810C

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Information about rainfall variables in Western Amazonia is very scarce. The few and functioning meteorological stations report only daily rainfall totals. As a consequence, researchers have little information about such variables as rainfall intensities. Information of this sort is indispensable for the correct interpretation of various hydrological processes. During 2.5 years of continuous operation, a recording rain gauge at *La Cuenca* has provided information about many rainfall variables.

Objective

The objective of this study was provide descriptive statistics of precipitation events.

Procedure

A tipping-bucket rain gauge was installed in a clearing adjacent to the research catchment; its output was recorded continuously with a resolution of 0.1 mm of rainfall. The following variables were extracted from daily charts for each event: amount (mm), duration (min), antecedent dry period (h), average rainfall intensity, and maximum intensities at 60, 30, 20, 15, 10, and 5 minutes. The rain had to stop for one hour before a new event could begin. Events separated by less than one hour were considered one event. During the study period, 842 events occurred.

Results

Table 1 summarizes the descriptive statistics on rainfall-event variables. Exploratory data analysis suggested that transforming all variables would promote symmetry; hence, the means are re-expressed means. Rainfall amount (mag) is based on logarithmic transformation. All other cases are based on fourth-root transformation.

Table 1. Descriptive statistics or rainfall-event variables.

Variable	Mean	Q25[§]	Median	Q75	Max
mag (mm)	3.2	0.8	3.3	13.2	121.2
dur (min)	87	30	80	190	970
I_{60}	6.3	2.3	6.2	14.0	50
I_{30}	7.2	2.2	6.4	17.4	76
I_{20}	7.8	2.1	7.5	19.8	90
I_{15} (mm/h)	8.8	2.4	8.0	21.6	92
I_{10}	9.5	2.4	9.0	24.0	120
I_5	11.5	3.6	10.8	26.4	120
I_{av}	3.0	1.2	2.9	5.6	37.2
adp	13	9	13	28	347

[§] Q25: 25% quantile; Q75: 75%.

Mechanisms of Overland Flow Generation: Y-810D

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Three mechanisms of overland flow generation are generally distinguished: 1) Horton overland flow, HOF (rainfall intensity exceeds infiltration rate); 2) saturation overland flow, SOF (rainfall on saturated soil, regardless of intensity); and 3) return flow, RF (subsurface flow forced to the surface).

These processes have been classified according to an environmental scheme which essentially rules out overland flow, generated by whatever mechanism, in the humid tropics. Common prejudices concerning the permeability of rainforest soils and the effect of the rainforest canopy on rainfall intensity may have contributed to this popular idea.

Objective

The objective of this study was to seek a causal explanation of overland flow based on the available information about soilscape and rainfall variables.

Procedure

Rainfall intensities of various durations were compared with soil-saturated hydraulic conductivity at various depths. Soil water-pressure potential was used as a proxy for soil moisture to assess antecedent moisture conditions throughout the year. Soil water-pressure potential was measured at 15 sites and four depths at 24 h intervals for two years.

Results

Table 1 shows how frequently, in the temporal and spatial sense, selected maximum rainfall intensities exceed soil saturated hydraulic conductivity (Ksat) at four depths. For HOF to occur, rainfall intensity must exceed surface Ksat. The results for soil depth 0 to 0.1 m show that HOF may occur at least in a localized fashion. For example, Table 1 reveals that 50% of all rainfall events evaluated have a 30-minute maximum intensity, which exceeds the Ksat of 13% for all undisturbed samples from that depth interval.

Table 1 also suggests that surface saturation, and thus SOF, may be achieved as a consequence of a perched water table: the spatial frequency with which rainfall intensity exceeds Ksat increases drastically at the shallow depth of 0.1 to 0.2 m. This postulated perched water table forms solely as a consequence of the ratio of rainfall intensity to Ksat at this depth increment, regardless of preceding moisture conditions.

Figure 1 summarizes the seasonal changes in soil water-pressure potential at 0.1, 0.3, 0.6, and 0.9 m, based on the median of 15 observations per depth. Except for a two-month period during the dry season, the soil profile is at near-saturation regardless of depth. It is therefore conceivable that complete surface saturation is achieved rapidly during the early stage of an event. As a consequence, surface saturation, and thus SOF, may occur as a result of the permanently high antecedent soil moisture conditions on account of frequent rainfall and/or the interaction of rainfall intensity and Ksat-depth function. In practice, intensity and frequency cannot be separated. Field evidence points to a dense network of pipes and

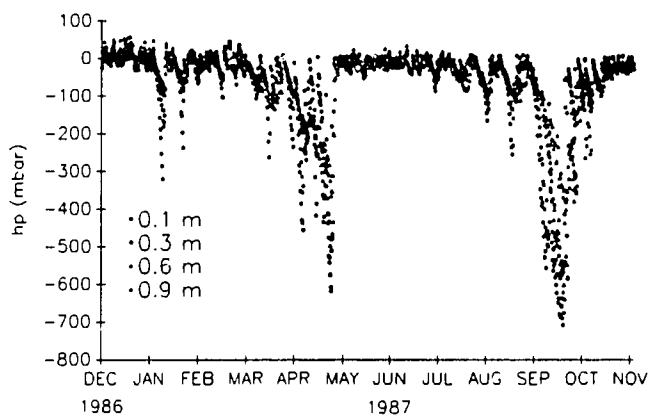

Figure 1. Soil water-pressure potential versus time at four soil depths.

Table 1. Comparison of soil saturated hydraulic conductivities and maximum rainfall intensities.

Soil depth quartiles:	I_{60} 25	I_{60} 50	I_{60} 75	I_{30} 25	I_{30} 50	I_{30} 75	I_{15} 25	I_{15} 50	I_{15} 75
—m—	Exceedance probability								
0–0.1	15	13	9	16	13	9	16	13	9
0.1–0.2	56	49	39	60	49	38	63	54	39
0.2–0.3	71	59	55	76	61	55	80	63	55
0.3–0.4	93	89	85	93	89	81	93	89	85

macropores associated with the surface soil, here defined by the 0- to 0.1-m depth interval. This network may drain a perched water table, which forms in response to a precipitation event, before it reaches the soil surface. Overland flow, in the form of RF, is generated where pipe and macropore outlets of this network occur on the hillslopes. The close association of pipe outlets with concentrated-flow lines observed in the field and the results from pipeflow monitoring support this interpretation.

Conclusions

The environmental controls at *La Cuenca* account for any of the above-mentioned mechanisms (i.e. they are potential pathways). The actual mechanism may change from event to event and, furthermore, from place to place within the catchment during the same event. Both the interaction between rainfall intensity and Ksat, and the prevailing antecedent soil moisture conditions favor saturation overland flow as the generating mechanism. Return flow from pipe and macropore outlets appears to be an equally important mechanism.

Implications

The results are at variance with the common environmental classification of the mechanisms that generate overland flow. The results suggest a redefinition of these mechanisms on the basis of the controlling soilscape and meteorological variables.

Soil Physical Properties: CU-108

Physical characteristics of medium- and fine-textured Cerrado Oxisols generally have been considered excellent for mechanized agriculture because of the very stable but weakly coherent microaggregate structure. However, evidence is mounting that deleterious soil physical conditions are developing in areas subjected to continuous annual cropping. In some fields in the Sao Gotardo region of Minas Gerais State, a decade of intensive cultivation has resulted in the formation of an extremely hard compacted layer 10 to 15 cm deep. Shallow rooting of the predominant crop in this region, soybeans, has been attributed to increased soil strength, reduced macroporosity, and poor aeration rather than to aluminum toxicity or low nutrient status of the subsoil. As a consequence of the shallow rooting of annual crops, the relatively costly investments in lime and fertilizer in Cerrado soils may not be utilized to maximum extent. Tillage pans reduce water capture from the frequently brief, intense storms, thus limiting replenishment of subsoil moisture. Reduced infiltration and increased runoff associated with subsoil compaction increase the severity of erosion under these circumstances.

Several factors are suspected of contributing to the formation of compacted layers in Cerrado soils. Normal farm traffic with heavy tractors and harvesters contributes to wheel-track packing, while the traditional practice of soil tillage with heavy disk harrows is almost certainly a major aggravating factor. Once compacted, Cerrado soils may have no natural correction mechanisms since there are no cycles of shrink and swell or freeze and thaw. The presence of tree roots in cleared Cerrado soils has discouraged any form of deep tillage in the initial years of cultivation. Also, because many of the region's farms are cash-grain operations with no cattle, there is almost no use of crop rotation or grass legume leys—either of which would help maintain soil physical properties.

Characterization of Structure Stability and Root-Restricting Pans in Cerrado Soils

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Objectives

The objectives of this study are 1) to diagnose soil and management conditions that result in the development of root-restricting zones in Cerrado soils subjected to continuous annual cropping, 2) to determine the effects of root-restricting zones on soil water dynamics in the field and the resulting implications for crop yields and soil erosion, and 3) to identify management practices that limit the formation of root-restricting zones.

Procedure

Laboratory, greenhouse, and field studies will be conducted to assess the interactions between soil bulk density, water content, matric potential and mechanical impedance, and the effects of these interactions on root growth in Cerrado Oxisols. Mineralogical and micromorphological work on these soils will be conducted at Cornell to aid in the interpretation of results. The studies will be coordinated with similar work on U.S. soils being conducted at Cornell University.

Soil-management factors responsible for the formation of root-restricting zones will be evaluated and, if possible, ranked in order of importance. The effects of different tillage operations and traffic patterns at various levels of soil moisture will be studied. Paired comparisons between virgin soils and adjacent fields that have been cultivated for different periods of time will be made to assess cultivation-induced changes in soil structure, organic-matter content, chemical properties, and clay migration in the soil profile.

The effects of tillage and traffic pans on the field soil water regime and resulting crop yields will be evaluated. Factors to be considered are rainfall runoff, infiltration and redistribution, root growth and corresponding water extraction patterns, and the onset of water stress in plants.

Results

Controlled growth chamber studies indicate that the high clay (80% clay content), Red-Yellow Latosol (Typic Acrustox) is susceptible to compaction. Soil mechanical impedance as measured by cone penetrometer was the single parameter best correlated with root length density of soybeans ($r = -0.914$). This is encouraging because the penetrometer is easy to read in the field compared with bulk density and aggregate stability measurements. A threshold level representing 70% of the maximum root length density for soybean (cultivar IAC 8) was attained at a mechanical impedance of 1.6 MPa. Precise characterization of root-impeding layers is necessary to understand the influence of mechanical resistance on root growth. With the difficulty of measuring total root length density in the field, certain anatomical signs of root response to compacted conditions serve as diagnostic tools for evaluating root penetration and radial expansion for comparison with micromorphological evidence of soil structural degradation.

To verify root growth restriction in the field, bulk and undisturbed soil samples were collected in soybean fields in the Federal District with disc-harrow tillage histories, as well as from adjacent native savanna vegetation sites. Soil thin sections were prepared for the 7- to 15-cm layer, where mechanical impedance was highest in the cultivated soils. Soil chemical status would not be expected to represent a barrier to soybean root penetration in these corrected soils (Table 1). At the time of soybean flowering, roots were sampled at 1-m intervals in 10 m of two adjoining rows after measuring penetration resistance with a penetrograph, 5 cm to either side of each plant.

A Root Deformation Index (RDI) was formulated to qualify morphological evidence of lateral deviation, constriction, and thinning of the axial soybean root. RDI values of 0 to 1 represent unimpeded root development, while RDI values of 2 to 3 indicate seasonally compacted conditions exist (roots still penetrate when moisture conditions are optimum), and RDI values of 4 to 5 signal severe compaction conditions with little penetration of high-strength soil layers. Index levels are as follows:

RDI-0, vertical axial root development with no evidence of strangulation or thinning;

RDI-1, axial root with slight deflection from vertical but no strangulation or thinning;

RDI-2, axial root with 90-degree deflection but still no sign of strangulation or thinning;

RDI-3, axial root with multiple deflections in corkscrew fashion as root seeks path of least resistance, but still no strangulation or thinning;

RDI-4, vertical axial root development, but with defined strangulation point, root thickening and fissuring above this point and marked thinning beneath it indicating restricted radial root expansion; and

RDI-5, axial root with 180-degree deflection with defined strangulation point and marked thinning.

In a field cultivated for 17 years (Fazenda Verda), high mechanical impedance (0.9 MPa) was encountered under field capacity at the extremely shallow depth of 5 cm, the point of first lateral deviation in the axial root. Root growth terminated at 16.5 cm length at a resistance of 1.6 MPa. Fifty-two percent of the roots were severely deformed (RDI-4–5).

Micromorphological analysis of the cultivated soils showed more evidence of structural degradation, rounding of aggregates, partial coalescence of primary particles, and packing of the ultrafine granular structure with pseudo-silt granules than was present in native soils. This finding strengthens the hypothesis that root growth is obstructed by physical clogging of soil macropores. Thin section studies corroborate laboratory-measured reduction in macroporosity and aggregate size distribution (Table 2). Structural degradation and consequent root impedance is evident in the midst of the pulverized layer of traditional disc tillage, and not immediately beneath the zone of tool engagement as might be expected.

Conclusions

On-farm sampling of soil physical and chemical properties in a field with a long-term history (16 years) of monoculture soybean cultivation and primary tillage only with disc harrows revealed a surprisingly shallow zone of root restriction. In spite of relatively low bulk densities, at times not exceeding 1.05 Mg/m^3, mechanical resistance, permeability, and macroporosity are severely altered in the shallow 7- to 15-cm layer. High aluminum saturation, low pH, low Ca, Mg, and P content (comparable to native soils) just below this hardened layer at a depth of 15 cm confirm the lack of effective tillage below this depth. Growth-chamber studies at CPAC have confirmed severe root restrictions under conditions found in these fields.

Aggregate stability tests show the 0- to 15-cm soil layer to be highly altered compared to soils in the native state or even to fields with reduced disc-harrow tillage. Analyses of thin sections show that movement of dispensable clay into microaggregates effectively clogs pore space, causes pore discontinuities, and causes smearing of clay particles by disc surface contact at the interface between the loosened soil layer and the hardened soil itself.

Field sampling of soybean root deformation, along with penetrometer measurements taken in January 1989, has further confirmed the relationship between high soil mechanical impedance and root growth. An index has been developed to describe the extent of root deformation in morphological terms related to simple lateral deviation, multiple deviations, strangulation and thickening, and cessation of axial root development.

Implications

A major area of emphasis of the TropSoils Acid Savanna program is increasing the use of biologically fixed nitrogen in organic residues for sustained crop production and maintenance of soil productivity. Production systems utilizing legume green-manure crops, which may be developed as part of this program, are likely to help alleviate some of the effects of mechanical impedance for succeeding crops. Management techniques to avoid serious soil compaction must be an integral part of any system for sustained crop production and maintenance of soil productivity. Understanding soil-management interactions leading to soil compaction in Cerrado soils should help identify the best management techniques. Management practices developed under this project should have wide applicability to many other soil conditions, including those found in U.S. agriculture.

Table 1. Chemical properties of the 7- to 15-cm layer in native soil and at Fazenda Vereda.

Site	pH	Al	Ca	Ca + Mg	P	K	O.M.
Native	5.4	0.68	0.12	0.40	0.4	29	3.37
Vereda	5.1	0.56	0.90	1.22	4.0	13	3.13

Table 2. Physical properties of the 7- to 15-cm layer in native soil and at Fazenda Vereda.

Site	Bulk density	Penetr. resist.	Permeab.	Poros.	Macropor.	Aggregates 2mm	Aggregates 1mm	Aggregates 0.5 mm
Native	0.88	0.4	425.1	66.0	24.9	82	8	6
Vereda	1.05	1.5	17.2	59.3	17.3	32	18	21

Land Resources Characterization and Evaluation in the Semiarid Tropics: TAMU-406

Most soil resources in semiarid Africa are highly fragile, droughty, and commonly exhibit chemical toxicities or nutrient deficiencies. Soil and climatic constraints pose the major limitations to agricultural development. Soil physical, chemical, and mineralogical conditions control soil/water/fertility interactions, which in turn are closely interlinked to topography/geomorphology/hydrology.

A knowledge of soil resources is fundamental for selection and operation of target sites for research design, interpretation of research results, and technology transfer. Soil resource inventories and characterization databases serve as the only meaningful basis for linkage among IARCs, NARS and specific TropSoils target research sites. Further, such research is necessary to determine which of the various technology packages, research innovations, and farmer experiences can appropriately be transferred among soil regions of the tropics. Principles of soil management are universal, but applications are site-specific and depend on soil resource knowledge. This project continues with the characterization of research sites. Representative soils from N'Dounga, Kala Pate, and Chikal Institut National de la Recherche Agronomique du Niger (INRAN) centers have been already described in previous reports (see *TropSoils Technical Report, 1986-1987*, p. 349).

Most of the grain production in sub-Saharan Africa is on sandy and loamy Ustalfs, Ustults, and Psamments. Major constraints of these soils are low water-holding capacity, restrictive subsurface layers (plinthite iron pans and laterite), weak structural stability (soil compaction and surface crusting), infertility (low organic-matter content, low cation-exchange capacity, few weatherable minerals, and low available P and N contents), soil acidity (Al and Mn toxicities), and susceptibility to wind and water erosion. Vertisols, while not extensive in Niger or Mali, are extensive in semiarid tropics. Potential productivity of Vertisols is high, but management is extremely difficult under traditional technology because of the high energy demands and unique soil-water interactions that result in a narrow soil-moisture workability range and highly critical timing of operations, particularly under low-input farming systems.

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Characterization of Research Sites in Niger and the Interactive Effect of Rainfall and Soils in Three Agroecological Zones

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The intricate relationship between climate and soils can be a major determinant in the agricultural development of any given region. It is a well-documented fact that different cropping systems are possible under the same climatic regimes because of differences in soil types. It is thus imperative to establish baseline conditions for soils and climate for better comprehension and analysis of research results.

Three research sites have been established in three different rainfall zones in Niger (Figure 1). These sites will allow scientists to observe the effect of soil and climatic interactions on crop growth, which will lead to better extension and adaptation of new management technologies to areas with similar climate and soil combinations within the Sahel.

Objectives

The objectives of this study were 1) to undertake physico-chemical characterization of the three TropSoils' research sites of western Niger; 2) to obtain climatic baseline data at the sites; and 3) to evaluate the effect of soil-water interaction on millet production at each site.

Procedures

Two pedons were characterized and sampled at each research site. Field observations were made of horizonation, color, texture, consistence, and structure. Samples taken to the laboratory were analyzed for the following: texture, pH, cation-exchange capacity (CEC), exchangeable bases, total nitrogen, organic carbon, available P, and exchangeable acidity. Rainfall was monitored using nonrecording rain gauges.

Results

Soils

Soil textures at Malgorou and Ounditan were loamy sands and sands, respectively, throughout the entire profile. At Tyeleda, a sandy topsoil graded into a loamy sand subsoil (Table 1). Average clay contents for Malgorou, Tyeleda, and Ounditan were 10, 9, and 5%, respectively. At Malgorou, fine sands constituted the dominant sand fraction, while coarser sands dominated the sand fraction at Ounditan. However, almost equal proportions of fine and coarse sands were obtained at Tyeleda (Table 1).

The soils at each site were acidic throughout the profiles. Only two horizons (out of seven) at Tyeleda contained any measurable amounts of exchangeable Al. However, exchangeable Al occurred in all horizons at both Ounditan and Malgorou.

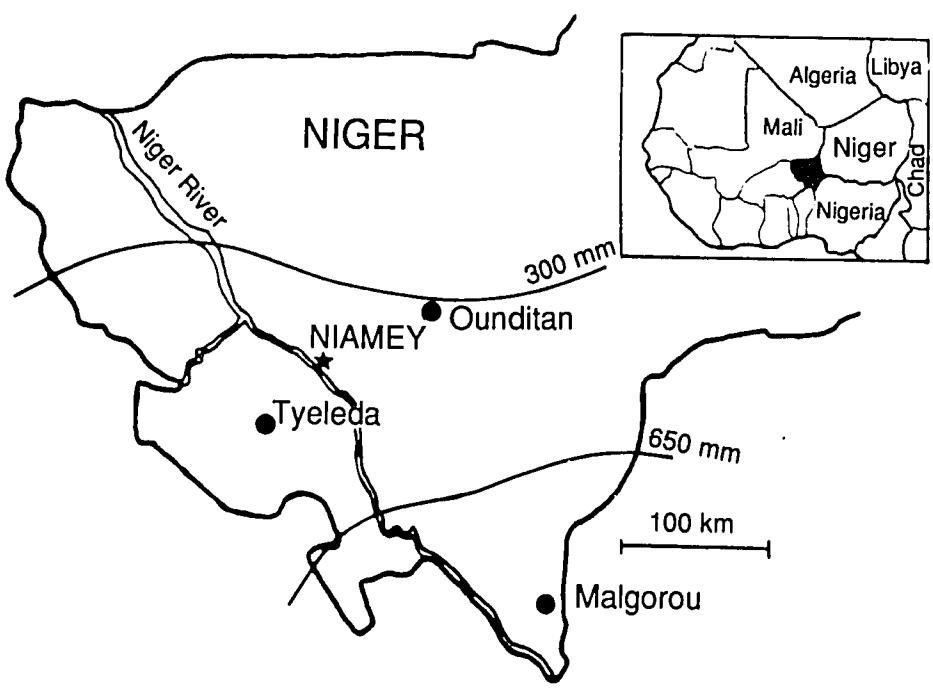

Figure 1. Location of three TropSoils' experimental sites.

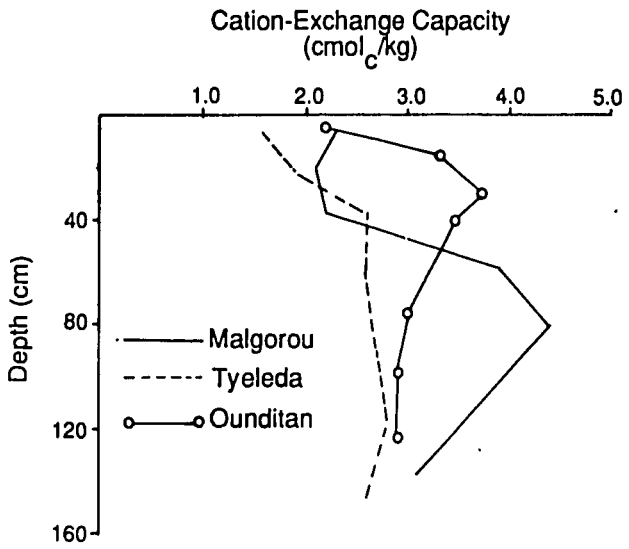

Figure 2. Depth of distribution of cation-exchange capacity.

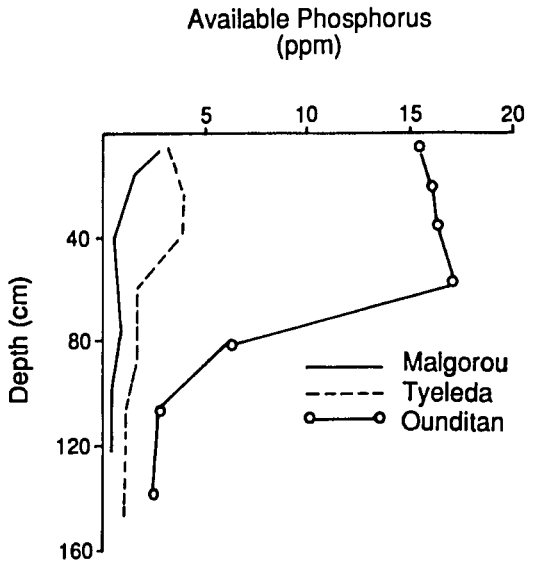

Figure 3. Depth of distribution of available phosphorus.

Table 1. Selected physical and chemical data of soils at Malgorou, Tyeleda, and Ounditan.

Horizon	Depth	pH H_2O	Sand	Clay	P	CEC	Exch. Al	Base sat.	Tot. C	Tot. N
	cm		—— % ——		ppm	— cmol/kg —		%		
Malgorou (Typic Kanhaplustults)										
Al	0–9	5.8	84.9	4.0	3.17	2.18	0.12	36	0.23	0.026
A2	9–22	5.0	84.5	9.1	1.6	3.34	0.74	16	0.21	0.026
Bt1	22–37	5.1	81.9	12.0	1.1	3.73	0.66	25	0.16	0.021
Bt2	37–65	5.2	81.7	11.5	0.5	3.35	0.46	25	0.10	0.015
Bt3	65–87	5.4	81.8	10.2	0.9	2.99	0.46	18	0.00	0.000
BC1	87–109	5.2	80.3	10.6	0.5	2.87	0.47	26	0.00	0.000
BC2	109–135	5.1	81.3	10.7	0.5	2.94	0.32	30	0.00	0.000
Tyeleda (Typic Kanhaplustalfs)										
Ap	0–14	6.2	93.0	2.8	15.3	2.30	0.00	97	0.26	0.016
Bt1	14–27	5.9	92.5	4.1	16.0	2.10	0.00	91	0.19	0.015
Bt2	27–47	5.4	91.4	5.0	16.4	2.2	0.00	91	0.14	0.012
Bt3	47–68	6.1	86.4	9.5	17.3	3.9	0.00	67	0.13	0.015
Bt4	68–93	6.3	82.2	12.8	6.3	4.4	0.00	64	0.00	0.000
Bt5	93–120	6.2	84.5	12.7	3.7	3.8	0.00	69	0.00	0.000
Bt6	120–153	6.4	85.0	11.9	2.8	3.1	0.00	78	0.00	0.000
Ounditan (Typic Kanhaplustalfs)										
A1	0–14	5.9	95.2	2.6	3.4	1.6	0.00	61	0.22	0.008
A2	14–28	5.5	94.5	3.8	3.8	1.9	0.11	47	0.20	0.007
Bt1	28–46	5.3	91.4	6.2	3.7	2.6	0.39	33	0.20	0.009
Bt2	46–73	5.0	90.0	7.5	1.9	2.6	0.72	24	0.14	0.009
Bt3	73–103	5.0	91.5	6.7	1.7	2.7	0.64	30	0.00	0.000
Bt4	103–129	5.0	91.8	5.9	1.2	2.8	0.27	40	0.00	0.000
Bt5	129–150	5.2	92.2	5.3	1.1	2.6	0.17	38	0.00	0.000

Soil fertility was generally low at all sites, as indicated by the low CEC values of the A and Bt1 horizons of each profile (Figure 2). Cation-exchange capacities appeared to be controlled by the clay fraction, with organic carbon playing only a minor role (Table 2). While base saturations were less than 35% throughout the profiles at Malgorou, high-percentage base saturations were obtained at both Tyeleda and Ounditan (Table 1). At all sites, Ca was the dominant exchangeable cation.

Organic carbon contents were very low in all soils (Table 1), and no significant differences between sites were observed. Barely measurable amounts of total N were obtained, which was probably a consequence of low organic-carbon contents. Available P was low at Malgorou and Ounditan. However, unusually high amounts of available P were obtained at the Tyeleda site (Figure 3). In terms of depth distribution, P at the surface was generally higher, possibly as an effect of nutrient recycling from crop plants and animal manure. While there was a sharp decline in available P with depth at Malgorou, both Tyeleda and Ounditan soils contained considerable amounts of available P in the subsoil.

Free Fe oxides were found in all pedons (Table 1). Depth distribution of the Fe oxides followed the distribution of the soil's clay fraction, which could indicate the presence of Fe oxide coatings around clay particles.

Amount and Distribution of Rainfall

Rainfall distribution for 1987 at the three sites is shown in Figure 4. Malgorou, the southernmost site, received the highest rainfall (550 mm), followed by Tyeleda (320 mm), and Ounditan (210 mm). Although distribution of rainfall during the growing season was excellent, all three sites received below-average rainfall in 1987 (Table 3).

In 1988 (Figure 5), three early rains occurred well before the growing season at Malgorou. If the cumulative rainfall curve was adjusted to remove this rainfall, (which most likely did not contribute to seed germination or seedling establishment due to loss by evaporation), Tyeleda actually received a greater amount of "available" rainfall for the first 70 days of the cropping season than did Malgorou. Ounditan, the northernmost site, received a greater or equal amount as Malgorou for the first 50 days of the growing season. However, 1988 proved to be an excellent year in terms of the amount and distribution of rainfall at all sites.

Total rainfall during 1989 was 769 mm, 615 mm, and 439 mm for Malgorou, Tyeleda, and Ounditan, respectively. The distributions presented in Figure 6 show three distinctive dry spells during the season. An early season drought had an adverse effect on germination and seedling establishment. Rainfall was also scarce for a considerable length of time between the tillering and flowering stages. For Tyeleda and Ounditan, there was also a drought spell toward the end of the growing season.

Interaction between Rainfall and Soil Properties on Millet Yields

General yield results of the experimental sites and other on-farm field trials demonstrated the interactive effect of rainfall and soil properties on millet yields. Available P (Bray 1) was used to assess soil fertility, as it has been documented that P is probably the most limiting nutrient to millet production in the Sahel. Available P contents were low at Malgorou and Ounditan. At Malgorou, this reading could be related to increased quantities of ex-

Table 2. Regression relationships relating soil CEC to the soil clay and organic carbon fraction (n = 14).

Site	Relationship	r^2
Malgorou	CEC = 0.35 + 0.3 Clay	0.65***
	CEC = 0.24 + 1.59 Organic carbon	0.01 ns
Tyeleda	CEC = 1.21 + 0.18 Clay	0.66***
	CEC = 3.27 – 4.75 Organic carbon	0.23 ns
Ounditan	CEC = 0.94 + 0.27 Clay	0.86***
	CEC = 2.51 – 1.76 Organic carbon	0.17 ns

*** = r^2 significant at P=0.0001.
ns = r^2 nonsignificant at P = 0.05.

Table 3. Cumulative rainfall for each of the three TropSoils experimental sites for 1987, 1988, and 1989.

Site	°N latitude	Rainfall zone§	Cumulative rainfall 1987	1988	1989
		mm			
Malgorou	12°10'	600-700	550	696	769
Tyeleda	13°12'	400-500	320	501	615
Ounditan	13°50'	250-300	210	406	439

§ Mean annual rainfall for the last 20 years.

Table 4. Biomass yield of HKP millet variety in 1988 and 1989 with the addition of N and P fertilizers at the three TropSoils experimental sites.

Site	1988	1989
	kg/ha	
Malgorou	2250	1429
Tyeleda	4153	2143
Ounditan	2178	696

changeable Al and free iron oxides that fix both native and applied phosphorus. At Ounditan, the sandy parent material of low nutrient reserves could account for the low P levels. However, unusually high levels of P were obtained at Tyeleda.

Grain yields in Tyeleda were adversely affected by bird damage both in 1988 and 1989. Hence, biomass was used as a yield parameter at all three sites (Table 4). Adequate rainfall coupled with generally better fertility status of soils at Tyeleda promoted considerable millet yields. The highest yields were obtained at this site, although Malgorou had the highest rainfall. It is interesting to note that yields at Ounditan and Malgorou were practically similar in 1988, although the latter received 58% more rainfall than the former. This finding reinforces the importance of the fertility-water interaction: in a year with adequate rainfall, the northern, more-fertile soils benefit from increased rains and become as productive as the soils in the high-rainfall southern zone.

Considerable influence of rainfall distribution on millet yields was observed at all sites. Increased rainfall (absolute amounts) in 1989 compared to 1988 did not translate into increased millet yields due to erratic distribution (Figure 6). Three drought episodes that occurred at very critical stages during the [illegible]h of millet had an adverse effect on millet productio...

Conclusions

1) Soils of the three TropSoils sites of western Niger are generally sandy and have inherently low nutrient status. Tyeleda soils have high levels of available P in both the topsoil and subsoils.

2) Rainfall was not a limiting factor at any of the three sites in 1988.

3) Although higher amounts of rainfall fell in 1989 than in 1988 at all three sites, of poor rainfall distribution in 1989 resulted in consistently lower yields. This suggests that distribution of rainfall during the season is as important as the absolute amounts in influencing millet production.

4) Strong soil-rainfall interaction was obtained in both years. Millet yields were higher on lower rainfall areas with high soil fertility, provided that the minimum moisture requirement was met.

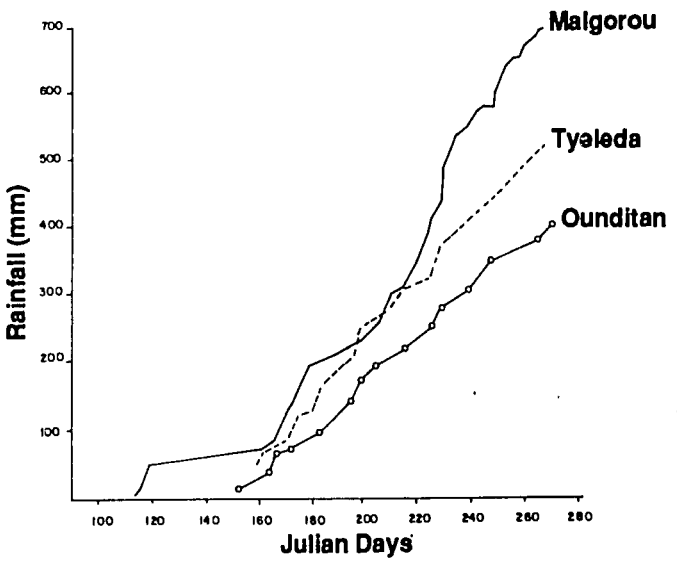

Figure 5. Cumulative rainfall for 1988.

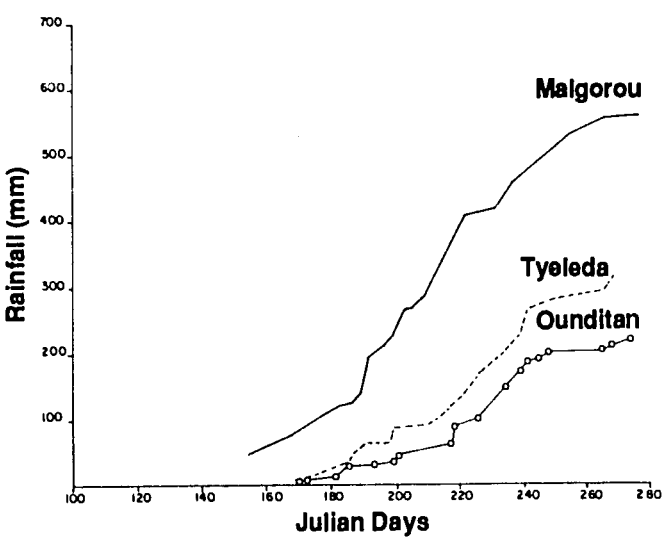

Figure 4. Cumulative rainfall for 1987.

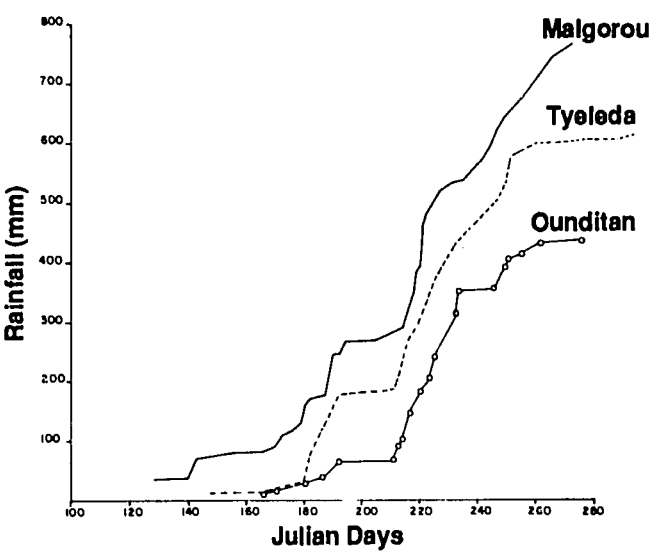

Figure 6. Cumulative rainfall for 1989.

Classification and Characterization of Research Sites in Mali

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The soil variability problem at Cinzana Station has developed into a special sorghum (*Sorghum bicolor* [L.] Moench) problem in sandy soils. However, no study has been conducted to describe and classify problem soils at the Cinzana Station according to the U.S. soil taxonomy system. This project focused only on a study site used for a research in defining the causes of poor early sorghum growth (TAMU-407).

Objective

The objective of this study was to classify one of the sandy soils displaying poor early sorghum growth at the Cinzana Station.

Procedures

Two pits (B and C) were dug at the site. A profile description was made in each pit. Soil samples were taken from each horizon for analysis (duplicate determination).

Laboratory determinations on soil samples included particle-size distribution, pH, exchangeable basic cations, organic matter content and clay mineralogy. In addition, the sand fraction was separated into very coarse (2.0 to 1.0 mm), coarse (1.0 mm to 0.5 mm), medium (0.50 to 0.25 mm), fine (0.25 to 0.10 mm), and very fine (0.10 to 0.005 mm) components. Calcium-feldspar and K-feldspar were also determined in the silt and sand fractions. Then soils were classified according to the U.S. soil taxonomy system.

Results

The soil parent material is an eolian sand over loamy fluvial sediments. The geology of this soil is as follows: Surface deposits are a sequence of sandy materials that cover ironstone caps, which, in turn, cover loamy Miocene (possibly as young as Eocene) deposits called the Continental Terminal.

Profile B represented the major soil of the research plot. Its plinthite horizon had a very high penetration resistance. This plinthite horizon restricted water movement and root growth. Profile C was shallow to plinthite, which was maximum in 50 to 77 cm. This profile had live termites in pit faces and termite chambers (1 to 4 cm in diameter). Both profile B and C had an argillic horizon.

The mineralogy of profiles B and C is generally similar. Quartz was the major mineral of both sand and silt fractions, while kaolinite was the dominant clay mineral. A small amount of K-feldspars was found in the sand fraction. K-feldspars, kaolinite, and muscovite were contained in minor quantities in the silt fraction. The clay fraction contained muscovite, albite, and quartz as secondary minerals. The mineralogy of each profile did not change with depth, but there were small variations in the proportion of these minerals.

The Fertility Capability Classification (FCC) for both profiles was defined as SLdch. Classification for profile B was sandy, mixed, isohyperthermic Grossarenic Paleustalfs. Profile C was classified as sandy, mixed, isohyperthermic Plinthic Paleustalfs.

Table 5. Soil classification and characterization, Profile B: particle size distribution.

			Particle size distribution							
			Sand							
Depth	Horizon	Textural class	v.coarse (2.0–1.0)	coarse (1.0–.5)	medium (.5–.25)	fine (.25–.1)	v.fine (.1–.05)	total (2.0–.05)	Silt (.5–.002)	Clay (<.002)
cm			%							
0–14	Ap1	L.sand§	1.2	10.7	25.6	25.8	19.1	82.4	13.7	3.9
14–43	Ap2	L.sand	1.0	12.5	25.5	25.5	20.5	85.0	10.9	4.1
43–57	Bt1	L.sand	1.8	8.7	27.8	22.4	24.5	85.2	9.9	4.9
57–73	Bt2	L.sand	1.3	10.6	28.1	22.8	22.2	85.0	9.3	5.7
73–85	Bt3	L.sand	1.3	10.8	26.0	26.8	19.6	84.5	9.5	6.0
85-102	Bv1	L.sand	1.0	10.9	28.1	18.9	16.0	84.9	8.1	7.0
102–125	Bv2	L.sand	0.9	16.1	28.1	29.8	10.1	85.0	7.1	7.9
125–160	Bv3	L.sand	1.0	16.7	27.3	25.9	12.5	83.4	5.1	11.5

§ L = loamy.

Data on particle size distribution and selected chemical properties of profile B (major soil of the research plot) are given in Tables 5 and 6.

Conclusions

The major soil of the research plot (profile B) was a sandy, mixed, isohyperthermic Grossarenic Paleustalf while the profile C was a sandy, mixed, isohyperthermic Plinthic Paleustalf.

Table 6. Soil classification and characterization, Profile B: selected soil chemical properties.

Depth	Horizon	Diagnostic Horizon	Organic C	pH (H_2O,1:2)	— NH_4OAc-extractable bases — Ca	Mg	K	Na	Al + H	ECEC
cm			%		cmol$_c$/kg					
0–14	Ap1	Ochric	0.14	5.85	0.56	0.13	0.10	0.01	0.08	0.88
14–43	Ap2	Ochric	0.17	5.56	0.53	0.13	0.09	0.01	0.08	0.84
43–57	Bt1	Argillic	0.16	5.40	0.58	0.11	0.08	0.01	0.05	0.83
57–73	Bt2	Argillic	0.19	5.44	0.63	0.16	0.12	0.01	0.10	1.02
73–85	Bt3	Argillic	0.10	5.64	0.56	0.16	0.09	0.01	0.10	0.92
85–102	Bv1	Argillic	0.10	4.93	0.52	0.18	1.09	1.01	0.20	1.00
102–125	Bv2	Argillic	0.11	5.23	0.50	0.18	0.09	0.02	0.15	0.94
125–160	Bv3	Argillic	0.13	4.87	0.16	0.16	0.09	0.01	0.35	1.07
167–169	Bv	C.D.[§]	0.08	4.84	0.63	0.44	0.09	0.01	0.35	1.52

[§] Critical depth (125 cm below the upper boundary of the argillic horizon) for base saturation.

Dynamics of Soil-Moisture Movement and Chemical Characteristics of Sandy Toposequences of Niger

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In the western part of Niger (Tillabery, Dosso, and Tahoua departments), most dryland agriculture occurs on the slopes of dry valley systems separated by flat ironstone-capped plateaus. The substratum of the soils is fairly uniform and consists of highly weathered geologic sediments of sandy and loamy Continental Terminal deposits overlain by eolian sand presumably derived from these sediments. Mineral reserves in these soils are low. The soils are acidic, they crust on the surface, and they often have a low water-holding capacity.

It has been long recognized that soils developed on slopes are systematically variable bodies, both vertically and horizontally, and that they are linked by transfer mechanisms, sometimes over long distances. It is only recently that these implications have begun to receive due attention in terms of their consequences for soil management.

In western Niger, soil characteristics important to crop production, such as moisture content, plant-available nutrients, and base status, may also be linked to position in the landscape. Technologies offered to farmers in Niger are rather general and do not accomodate variations in soil characteristics. The present study proposes that land-characterization methods based on such factors as available soil moisture, plant mineral reserves, base status, and erosion hazards. Land units may exhibit edaphic characteristics requiring specific management, such as fertilization, varying plant densities, and type or variety of crops, and should, therefore, be dealt with separately by research and extension.

The hypothesis of this study was that soil characteristics important to plant growth such as acidity, phosphorus fixation, and moisture regime are a function of landscape position on the sandy valley toposequences of West Niger.

Objectives

The objectives of this study were 1) to determine physical, chemical, and mineralogical characteristics of the soil and to classify soils along the toposequences; 2) to determine soil moisture regimes as a function of position on the toposequence; and to assess the variability of selected physical and chemical characteristics of soils as a function of position on the toposequence.

Procedures

Relationship between landscape position and soil characteristics (moisture regime, phosphorus-fixing capacity, and acidity) were investigated on two toposequences of western Niger (Figure 7). The toposequences studied overlie the Continental Terminal geologic deposits and

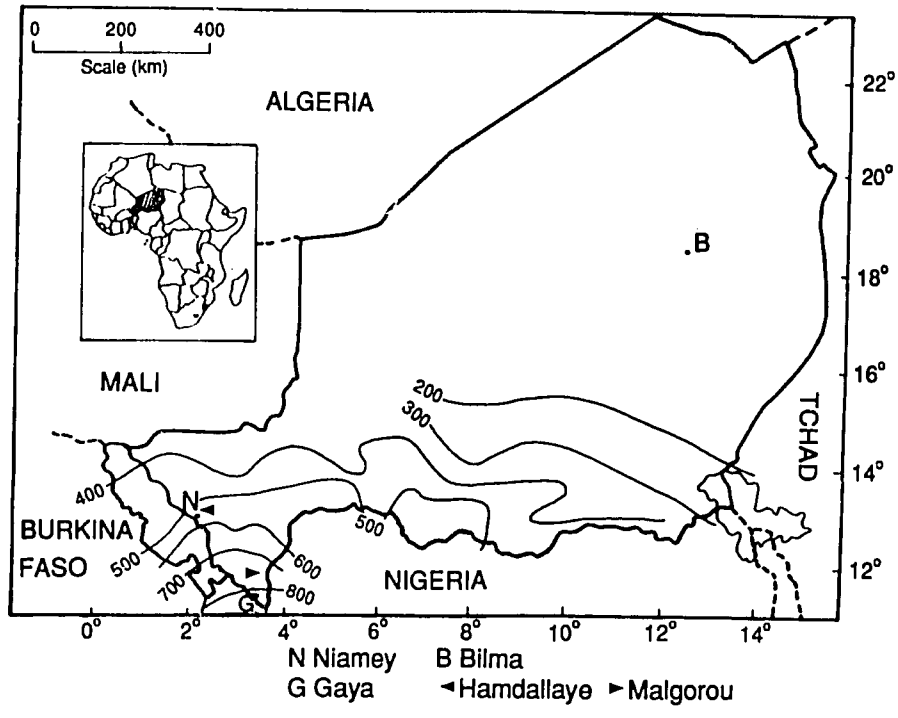

Figure 7. Map of Niger showing isohylets for mean and annual rainfall (mm) (adapted from Sivakumar et al n.d.) and location of the experimental sites.

have different mean annual rainfall (Hamdallaye, 550 mm; Malgorou, 750 mm).

One toposequence was selected in each of the sites by using aerial photographs at a scale of 1/60,000, topographic maps, and a rapid field survey. The criteria used for selecting the toposequences were geology (clayey sandstone of "Moyen Niger" or "ancient erg"), slope aspect and slope length (representative of valley systems in the landscape), land use (toposequences mostly under cultivation by farmers), and absence of incised drainage ways that traverse the toposequence and drastically modify the moisture regime.

The toposequence at Hamdallaye was selected first (Figure 8); the toposequence at Malgorou (Figure 9) was selected to approximate the length (2 km) and the aspect (SW-facing, azimuth 230°) of the Hamdallaye site.

The initial survey was conducted along a transect extending from the top of the plateau to the valley floor,

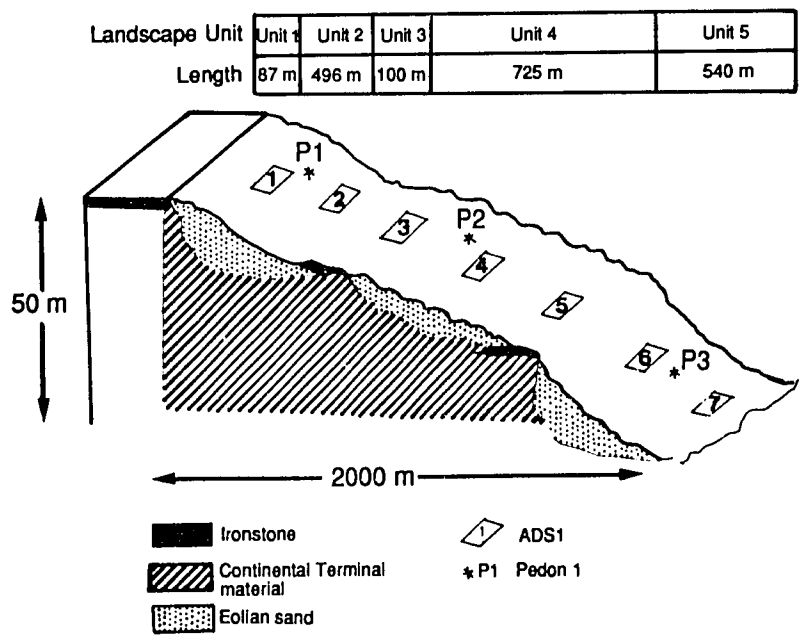

Figure 8. Schematic diagram of the Hamadallaye toposequence.

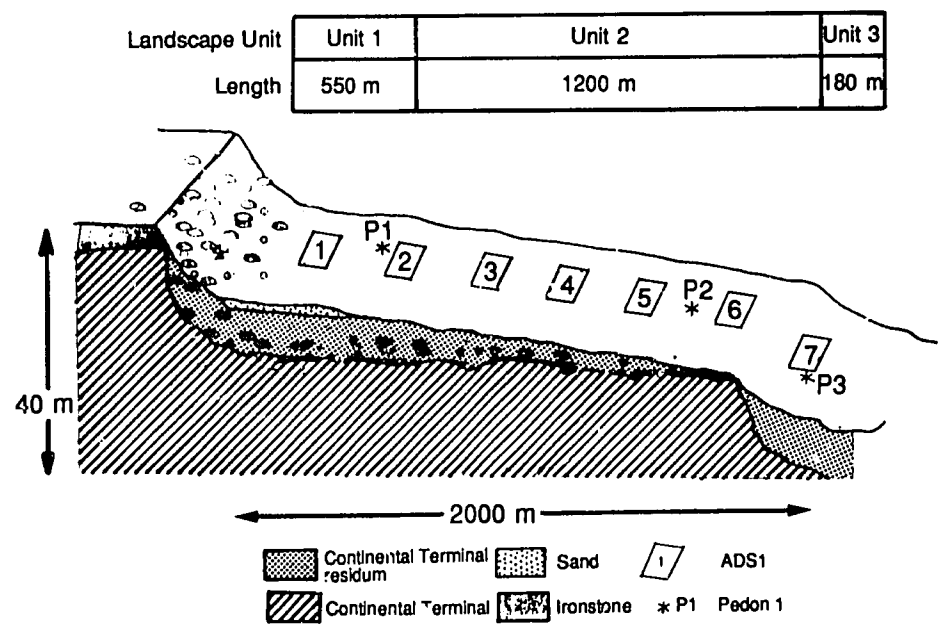

Figure 9. Schematic diagram of the Malgorou toposequence.

with observations every 100 to 200 meters. On each toposequence, seven Areas of Detailed Study (ADS) were initiated at 300-m intervals from the edge of the plateau to the valley floor (Figure 8 and 9). Each ADS consisted of a square 70 m by 70 m. A nonrecording rain gauge was placed one meter above the ground in the center of each ADS.

In addition to routine characterization data, soil measurements included soil moisture retention, soil moisture content throughout the year, phosphorus availability and retention, and clay mineralogy.

Results

At the Hamdallaye toposequence, soils are formed on a deep-eolian sand mantle (2- to 5-m thick) covering the valley slope; they were classified as Aridic Alfic Quartzipsamments, Aridic (Rhodic) Kandiustalfs (Table 7), and Psammentic Kandiustalfs. Characteristics common to all the toposequence members are low clay content (3 to 6% in the epipedon, 6 to 12% in the subsoils), low organic matter content (organic carbon is less than 0.2% for all soils), and low effective cation exchange capacity (ECEC)—generally less than 1 cmol(+)/kg. The soils of the Hamdallaye toposequence are moderately to strongly acid.

At the Malgorou toposequence, soils, except those of the footslope position, are formed dominantly on Continental Terminal residuum and have limited contributions of eolian sand to the surface; these soils are generally shallow (less than 0.5 m to 2 m deep) and increase in gravel content with depth, toward the lower end of the backslope position, they are often associated with an ironstone outcrop. Soils of the footslope position, on the other hand, are formed on a wind-reworked, fluvial riverine levee. They are deep (> 2 m) and do not contain gravels.

The Malgorou toposequence members have clay contents that vary from 7 to 18% on the surface and from 13 to 34% in the subsoil; in both surface and subsurface horizons, their clay contents are 2 to 5 times higher than those of the Hamdallaye toposequence. All soils of the Malgorou toposequence have low organic-matter contents and low ECEC. Their base saturation is generally 50 to 85 percent in the epipedon, and 34 to 75 percent in the Bt horizons; the Al saturation varies from 10 to 36% in surface horizons and 19 to 57% in subsoils. The soils are classified as Rhodic Kanhaplustalfs, Rhodic and Typic Kandiustalfs (Table 7).

The standard P requirements (SPR), defined as the amount of phosphorus retained by soil at 0.2 g P/cm^3 equilibrium solution concentration, was low for both toposequences, although P retention was much higher for the Malgorou toposequence than the Hamdallaye toposequence (Table 8). No trend in P sorption was observed with landscape position at Hamdallaye. At Malgorou, an increase in P sorption was observed for the upper segment of the toposequence corresponding to a major portion of the backslope position. At both sites, P sorption as estimated by SPR increased over 2.5-fold from surface horizons to the upper Bt horizons. At Hamdallaye, the SPR values appear to be highly correlated with clay content, exchangeable acidity, exchangeable Al, Bray P, and organic carbon; at Malgorou, values were correlated with clay content, exchangeable acidity, exchangeable Al, Al saturation, and free iron. Erosion and soil management

Table 7. Classification of the soils of the Hamdallaye and Malgorou toposequences by the U.S. (Soil Taxonomy) and French (CPCS) classifications.

Pedon	LP§	Classification: Soil Taxonomy	Classification: CPCS
		Hamdallaye	
1	Upper backslope	Aridic Alfic Quartzipsamment, sandy, siliceous, isohyperthermic	Sol ferrugineux Tropical, peu lessivé
2	Mid-backslope	Aridic (Rhodic) Kandiustalf, sandy, siliceous, isohyperthermic	Sol ferrugineux Tropical, peu lessivé
3	Footslope	Psammentic Kandiustalf, sandy, siliceous, isohyperthermic	Sol ferrugineux Tropical, peu lessivé
		Malgorou	
1	Upper backslope	Aridic (Rhodic) Kandiustalf, fine loamy, siliceous, isohyperthermic	Sol ferrugineux Tropical, lessivé
2	Lower backslope	Aridic (Rhodic) Kanhaplustalf, fine loamy, siliceous, isohyperthermic	Sol ferrugineux Tropical, lessivé, induré
3	Footslope	Typic Kandiustalf, coarse loamy, siliceous, isohyperthermic	Sol ferrugineux Tropical, peu lessivé, à hydromorphie de profondeur

§ Landscape position.

also control P behavior in these soils by influencing the determinant properties identified above.

Soil moisture, monitored from June 1988 to May 1989, was strongly dependent on rainfall at both Hamdallaye and Malgorou. Due to their higher clay content, soils on the Malgorou toposequence have cumulative water retention difference values more than twice as high as those of the Hamdallaye toposequence. There was no simple relationship between soil moisture availability and topographic position at either toposequence; main factors controlling moisture availability of soils were surface texture, surface degradation (sealing and crusting), and evapotranspiration.

Soils on ADS4 and ADS5 positions of the Malgorou toposequence were particularly crusted and sealed, and they had moisture deficits even during the rainy season. At Hamdallaye, Soil Taxonomy placements of soil moisture regimes are Ustic; even though soils at Malgorou are in a zone of higher mean annual rainfall, they are marginally Ustic to Aridic because of impeded surface infiltration and high water demand by plants.

At Hamdallaye, soil characteristics important to plant growth are controlled by factors such as surface degradation, management, and vegetative cover, rather than position on the toposequence. At Malgorou, surface degradation, management, and vegetative cover are also important factors controlling soil characteristics important to plant growth; however, characteristics that influence production, such as phosphorus retention, varied along segments of the toposequence. Soil texture and soil depth are also closely related to landscape position at Malgorou. Characteristics important to plant growth are thus related to landscape position at Malgorou.

Soils at the Hamdallaye toposequence have been highly degraded through cultivation and by wind and water erosion. Conservation practices, including wind breaks, agroforestry, and the incorporation of manure and crop residue, are highly desirable for reversing the trend in degradation of the soil resources of the area and for restoring soil fertility. Low application rates of P fertilizer will be necessary on these soils. Split applications of other fertilizers should be used because the soils are very sandy. Water conservation practices and water erosion control are particularly needed in the upper portion of the toposequence.

At the Malgorou toposequence, soils are very sensitive to clearing of the vegetative cover and to cultivation because of their loamy texture and their high susceptibility to crusting. Once degraded, these soils develop characteristics unfavorable to plant growth, such as low moisture reserve due to impeded surface water infiltration, relatively important P-fixation capacity, and crusting, which is detrimental to seedling emergence. Management of these soils should include soil- and water-conservation practices to protect the topsoil from water erosion, increase infiltration rates, and control soil crusting. The phosphorus requirement of the soils will depend on surface texture and the extent of surface degradation; topographic position may be used to predict the P-fixing capacity of these soils. Effects of soil acidity on both natural and cultivated systems and the effect of burning as a regenerative or degradational practice should be further investigated at Malgorou.

Although trends in soil characteristics along the toposequences have not always been observed, the soil landscape approach is still a useful approach to land evaluation. This is particularly true in the Malgorou area, where soil texture, depth of soil, P-fixing capacity, and moisture are related to landscape position on specific segments of the toposequence; at Malgorou, landscape variation is also taken into account by local farmers when managing their land.

Table 8. Standard P requirement (SPR) values (in •g P/g soil) at ADS's positions for Hamdallaye and Malgorou.

Position	0–20 cm (Ap)	40–60 cm (Bt)	R[§]
		Hamdallaye	
ADS1	22.6	61.4	2.7
ADS2	13.5	34.6	2.6
ADS3	45.6	84.2	1.8
ADS4	16.4	56.7	3.5
ADS5	24.4	61.7	2.5
ADS6	22.7	55.0	2.4
ADS7	15.1	52.0	3.4
mean	22.9	57.9	2.5
		Malgorou	
ADS1	45.0	87.9	2.0
ADS2	44.2	198.0	4.5
ADS3	62.4	224.2	3.6
ADS4	75.5	248.5	3.3
ADS5	141.7	344.4	2.4
ADS6	34.3	104.5	3.0
ADS7	59.3	57.2	1.0
mean	66.1	180.7	2.7

[§] R is the ratio of the 0- to 20-cm to 40- to 60-cm SPR values.

Phosphorus Status of Selected Millet-Producing West African Soils

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The West African subregion produces 74% of the total millet (*Pennisetum glaucum* (L.) R. Br.) grown in Africa and 28% worldwide, making it an important millet-producing area. The majority of this production occurs in the Sahelian and Sudanian ecological zones, where annual rainfall averages between 200 to 1200 mm/yr and potential evapotranspiration (PET) can range from 220 to 1200 mm/yr.

The sandy texture and the consequent low inherent fertility of the majority of soils in this region result in a strong yield response of crops with the use of fertilizers or organic amendments. Phosphorus has been shown to be one of the most limiting nutrients to millet growth in the Sahel. However, further work to improve the fertility status of these soils should be preceded by an understanding of the chemical interactions influencing nutrient availability.

Objectives

The objectives of this study were 1) to survey the nutrient status of selected millet-producing soils of the West African subregion and 2) to examine the factors influencing phosphorus sorption and availability.

Table 9. Chemical and physical soil properties.

	Location	pH H_2O	pH KCl	Total OC	N	Clay	Exchangeable Ca	Exchangeable Mg	Exchangeable K	Exchangeable Na	Acidity	ECEC
Physical Properties				%	ppm	%	cmol/kg					
1	Makalondi	6.8	5.5	0.36	177	1.2	0.60	0.33	0.25	0.02	0.07	1.26
2	Fada	7.1	6.3	2.94	1160	7.3	9.14	2.16	0.13	0.04	0.11	12.57
3	Bittou	6.8	6.1	0.72	181	2.7	2.25	0.88	0.60	0.03	0.09	6.82
4	Tenkodogo	6.0	4.8	0.72	192	3.0	1.55	0.73	0.15	0.06	0.08	2.57
5	Pya	6.5	5.0	0.72	226	5.1	1.53	0.83	0.07	0.04	0.07	2.54
6	Dapaong	6.4	5.8	0.51	219	1.7	0.90	0.43	0.12	0.04	0.20	1.68
7 a	Bambey	6.4	4.5	0.23	87	1.3	0.59	0.36	0.03	0.03	0.13	1.14
7 b	Bambey	6.6	5.2	0.26	93	1.0	0.89	0.57	0.04	0.03	0.05	1.58
8 a	Sinkou c	6.0	4.7	0.75	333	9.0	1.58	0.72	0.29	0.06	0.10	2.75
8 b	Sinkou f	6.5	5.5	0.95	336	5.5	2.42	0.87	0.22	0.04	0.06	3.60
9 a	Gaya c	5.8	4.3	0.52	226	3.9	1.15	0.42	0.06	0.04	0.20	1.87
9 b	Gaya c	5.7	4.2	0.56	235	4.0	1.03	0.38	0.06	0.05	0.22	1.73
9 c	Gaya f	5.9	4.7	0.84	298	4.7	1.98	0.63	0.12	0.04	0.08	2.85
9 d	Gaya f	6.3	5.4	0.69	189	2.9	1.14	0.30	0.16	0.02	0.07	1.69
10	Gobery	5.7	4.2	0.32	103	1.5	0.23	0.12	0.05	0.03	0.21	0.64
11	Tara	5.6	4.1	0.45	197	3.1	0.47	0.27	0.10	0.02	0.39	1.20
12	Navrongo	6.2	5.1	0.94	225	1.3	1.84	0.63	0.09	0.03	0.07	2.66
13 a	Sadore f	5.7	4.3	0.42	123	1.3	0.37	0.23	0.08	0.02	0.22	0.91
13 b	Sadore c	6.0	4.8	0.34	163	1.8	0.44	0.33	0.16	0.02	0.07	1.01
13 c	Sadore c	5.2	4.1	0.22	74	1.0	0.15	0.08	0.06	0.02	0.23	0.54
14	Daoura	6.1	5.4	0.39	128	1.1	0.83	0.50	0.06	0.02	0.07	1.48
15	Samaru	6.0	4.9	0.96	299	5.3	1.77	0.94	0.33	0.02	0.10	3.14
16	Bakura	5.6	4.3	0.80	243	11.7	3.32	1.41	0.15	0.04	0.23	5.15
17	Funtua	7.6	6.8	2.76	1180	4.4	16.45	2.07	0.41	0.05	0.23	9.20
18	Bembereke	7.0	6.4	2.17	701	4.4	4.13	0.32	0.05	0.06	0.14	4.70
19	Kandi	6.6	5.8	1.10	251	3.7	2.67	0.13	0.16	0.04	0.08	3.08
20	Sotuba	6.2	4.9	0.48	142	3.0	1.49	0.13	0.16	0.05	0.06	1.89
21	Bamako	5.6	4.3	0.64	194	6.0	1.86	0.09	0.15	0.09	0.19	2.36
22	Cinzana	5.3	4.0	0.41	178	3.2	0.93	0.07	0.09	0.06	0.45	1.59
23	Zinder	6.7	5.3	0.08	31	0.7	0.53	0.02	0.06	0.05	0.06	0.71
24	Yeda	6.7	5.5	0.15	69	1.0	0.98	0.08	0.07	0.06	0.05	1.23
mean		6.2	5.0	0.75	266	3.	.10	0.55	0.18	0.04	0.14	3.10

Procedures

Thirty-one surface (0 to 20 cm) soil samples were randomly selected from six West African countries for this study. Air-dried soils were analyzed for texture, pH, exchangeable Al and total acidity, exchangeable bases, and organic carbon. Total and available P, as well as P-sorption characteristics, were also determined.

Results

Fertility Parameters

Data on soil chemical and physical properties are presented in Table 9. All soils were sandy to sandy loam in texture. Clay contents ranged from 0.7 to 11.7%, with an average of 3.5%.

Table 9. (continued)

	Location	BS	Alsat	Dithionite Al	Dithionite Fe	Oxalate Fe	Oxalate Al	Bray P	Total P	b	P_{ext}
		%	%	mg/kg							
Chemical soil properties											
1	Makalondi	94.84	0.00	312	4500	247	171	3.7	51	46.08	12.3
2	Fada	99.16	0.00	1455	14400	1025	663	15.8	237	141.32	22.8
3	Bittou	98.68	0.00	312	3400	539	202	6.9	71	77.32	19.9
4	Tenkodogo	96.88	0.00	581	5900	69	184	5.6	64	82.34	23.1
5	Pya	97.23	0.00	2509	25100	150	337	1.0	87	94.91	28.2
6	Dapaong	87.88	1.12	738	9300	42	229	4.1	82	52.04	14.4
7 a	Bambey	88.59	0.00	289	2100	256	192	3.1	89	52.78	17.2
7 b	Bambey	96.82	0.00	289	2100	236	233	4.1	77	48.10	28.2
8 a	Sinkou c	96.36	0.00	1971	18600			9.1	180	130.68	33.8
8 b	Sinkou f	98.33	0.00	1657	18900	669	430	6.7	135	123.72	15.6
9 a	Gaya c	89.11	1.00	670	8400	445	257	3.2	96	101.00	20.8
9 b	Gaya c	87.53	0.00	626	6800			4.3	109	91.12	23.3
9 c	Gaya f	97.19	0.00	693	8200	616	450	1.7	114	104.88	25.9
9 d	Gaya f	95.84	0.00	1141	19200	694	247	5.9	191	101.00	30.7
10	Gobery	61.71	10.99	513	7500	214	157	2.0	73	61.37	25.0
11	Tara	58.06	10.04	850	14100	550	481	3.3	129	129.20	27.7
12	Navrongo	97.55	0.00	648	7300	500	184	4.5	73	66.69	14.9
13 a	Sadore f	76.24	2.20	469	6000	225	148	2.8	68	55.31	15.8
13 b	Sadore c	93.06	0.00	312	5600	297	275	8.5	85	51.51	12.4
13 c	Sadore c	57.00	9.34	357	6300	198	112	6.9	68	51.67	15.9
14	Daoura	95.25	0.00	132	1500	323	130	4.6	41	28.76	10.5
15	Samaru	96.94	0.00	1007	7500	878	502	9.6	132	130.43	26.1
16	Bakura	95.52	0.00	1253	10200	2225	761	1.4	112	192.61	56.8
17	Funtua	98.80	0.00	1007	8600	1116	654	30.3	349	253.08	11.6
18	Bembereke	97.10	0.00	1388	14600	1138	595	7.9	160	155.35	38.6
19	Kandi	97.39	0.00	693	7000	385	295	3.2	101	78.11	20.5
20	Sotuba	36.82	0.00	670	7800	321	336	1.7	87	93.06	23.2
21	Bamako	92.14	0.42	895	8800	822	502	12.3	149	137.39	33.6
22	Cinzana	71.92	14.51	895	8800	507	502	11.1	124	133.77	39.2
23	Zinder	92.25	0.00	155	2900	111	49	1.9	43	27.80	11.0
24	Yeda	95.93	0.00	110	1700	214	147	2.4	25	30.15	11.8
	mean	88.33	1.60	79	8810	599	325	6.1	109	94.30	22.9

f = fallow in year preceding sampling.
c = cultivated in year preceding sampling.
OC = organic carbon.
Al_{sat} = Al saturation.
BS = base saturation.
b = P sorption maximum.
P_{ext} = P external requirement (mg P/kg).

These soils exhibited a wide range of pH, from a slightly acid (pH 5.2) to a high value of pH 7.6. However, only one soil had a pH higher than 7.2. While percent Al saturation ranged to 14.51 cmol/kg, four out of the 31 soils (31%) had any measurable amount of exchangeable Al.

General nutrient status of these soils was low, as expressed through low levels of organic matter, total nitrogen, and effective CEC. The interrelationships between these fertility-related variables are listed in Table 10. Native levels of organic carbon (although very slight) were highly correlated with total nitrogen (r = 0.97***), which indicated that crop production within these systems, where N fertilizers are not used to any great extent, is most likely dependent on the maintenance of soil organic matter. Organic carbon was also highly correlated with ECEC (r = 0.87***), which indicated that soil organic matter might be a more dominant influence on soil CEC than the soil clay fraction.

Native Phosphorus Status

The amount of total P in these soils ranged from 25 to 349 mg/kg. Available P ranged to 30 mg/kg in some of these soils, indicating that P is most likely not a limiting factor for millet growth in some soils in this region (Table 9). However, 87% of these soils had available P values of less than 10 mg/kg, and 58% had available P values of less than 5 mg/kg. With none of these soils having a history of phosphorus fertilization, the available P parameter could represent a background level for agricultural soils of this region. The low contents of the P parameters may be related to several factors, including the following:

1) Parent materials, which are mainly composed of eolian sands deposited on the continental terminal; and

2) Low levels of organic phosphorus, which are a consequence of both low levels of organic matter accumulation under the environmental conditions found in the semiarid tropics and a lack of nutrient recycling, where biomass, as well as grain, is generally removed from the field to be used for animal feed or traditional village industries.

Phosphorus-sorption Characteristics

Uptake of phosphorus by growing crops is affected by total P levels in the soil and the interaction of total P with constituents of the soil matrix.

To gain a greater appreciation of the dynamics of P within these soil systems, P-sorption characteristics were determined. The P external requirement, which is the critical level of P in the soil solution needed to obtain 95% of maximum yield, was also determined using the P-sorption data. A value of 0.2 g P/ml has been observed as the P external requirement for millet when grown in pots in an Ultisol. This value was used as a reference level within this document for the calculation of the P external requirement.

A large range of P-sorption maxima was obtained on these soils (Table 9). Soils of this region can be considered as having relatively low P-sorption capacities compared to the Ultisols and Oxisols found in more humid tropical regions. The low P-sorption capacity is also reflected in the low range of the P external requirement.

Total P was highly correlated with organic matter and the poorly crystalline Al phase (as measured by oxalate extraction), and to a lesser extent with clay, poorly crystalline Fe, and the free Al- and Fe- oxide phases (citrate-dithionite extraction) (Table 11).

Phosphorus-adsorption maxima were most highly correlated with organic matter, clay, and poorly crystalline Al and Fe phases. The interrelationships between clay and poorly crystalline Al and Fe phases appear to control not only P availability, but also the potential reactivity of P (as measured by the adsorption maxima).

The relationships between organic matter, clay, and poorly crystalline Al and Fe are presented in Table 12. These models indicated that poorly crystalline Al and Fe are highly associated with the clay fraction occurring in these soils.

Bray-1 P was most highly correlated with organic matter and poorly crystalline Al, but no significant correlation was obtained with the free Al and Fe phases.

Table 10. Simple correlations (r) between selected soil fertility parameters and average annual rainfall (n = 31).

	Ca	ECEC	Organic matter	Total N	Clay	Rainfall
pH KCl	.62***	.64***	.65***	.62***	-.02	.25*
Ca		.98***	.88***	.92***	.36***	.31***
ECEC			.86***	.91***	.40***	.36***
Organic matter			.97***	.46***	.42***	
Total N					.44***	.34***
Clay						.40***

* and *** indicate significance at the .05 and .0005 levels, respectively.

Table 11. Simple correlations (r) relating selected soil properties, P sorption, and availability indices (n = 31).

	Total P	Bray-1 P	b	P_{ext}
Organic matter	.81***	.71***	.71***	.12
Clay	.52***	.24*	.75***	.71***
Oxalate:				
Al	.73***	.51***	.91***	.64***
Fe	.48***	.24	.75***	.69**
Dithionite:				
Al	.52***	.21	.60***	.50***
Fe	.48***	.11	.49***	.42***
P parameters:				
total P		.83***	.85***	.24
Bray 1 P			.66***	-.06
b				.55***

* and *** indicate significance at the .05 and .0005 levels, respectively.
b = P adsorption maximum.
P_{ext} = P external requirement.

Table 12. Stepwise multiple regression models describing relationships between organic matter, clay, and poorly crystalline Al and Fe (n = 29).

	r^2
Poorly crystalline Al:	
Al = 184 + 185 organic matter	.45***
Al = 105 + 67 clay	.72***
Al = 79 + 92 organic matter + 54 clay	.80***
Poorly crystalline Fe:	
Fe = 340 + 340 organic matter	.24***
Fe = 45 + 168 clay	.78***
Fe = 27 + 63 organic matter + 160 clay	.80***
Poorly crystalline Al + Fe:	
Al + Fe = 534 + 520 organic matter	.33***
Al + Fe = 166 + 234 clay	.84***
Al + Fe = 123 + 154 organic matter + 211 clay	.86***

*** indicates significance at the .0005 level.

Conclusions

The results of this study indicate that millet-growing soils of the semiarid tropical region of West Africa can be described by the following characteristics:1) sandy to sandy loam textures in the surface horizon; 2) low levels of clay and organic matter resulting in low effective CEC, where organic matter contributes to CEC to a greater extent than clay; 3) a small percentage of soils containing any appreciable amount of exchangeable Al; 4) low levels of native soil P; 5) relatively low P-sorption capacity; 6) P-sorption and availability parameters controlled by Al and Fe oxides, organic matter, and clay soil fractions.

The management of these soils for increased millet production will generally require the addition of low to moderate amounts of phosphorus. The application of organic materials (i.e., crop residues, manures) will have a beneficial effect on the retention and availability of nutrients. Sustainable agricultural production will most likely necessitate the use of low-level application of residues, manures, or fertilizers with lime, as these poorly buffered soil systems become depleted.

Structural Restoration in Vertisols under Pastures

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Productivity of Vertisols is closely correlated with the evolution of their structure. Porosity is the best guide to structural status. Structural degradation under cultivation is mainly due to 1) tillage and traffic, 2) changes in soil moisture regime, and 3) altered biotic activity. The dynamic nature of soil structure in Vertisols could enhance its ability for recovery once disturbance from cultivation ceases.

Objectives

The objectives of this study were 1) to develop and test procedures for evaluation and quantification of soil macroporosity in Vertisols (microfabric analysis coupled with image-processing techniques) and 2) to analyze changes in porosity and pedality that characterize a structural recovery process associated with a shift in land use from continuous cultivation to pastures.

Procedures

Three sites were selected at the USDA Research Station at Riesel, Texas. Soil at site HC-50 was a Udic Chromustert; at sites HB-25 and HB-15, soils were Udic Pellusterts. Each site consisted of homogeneous soils and topography, but with contrasting long-term, land-management systems: cultivated fields and regenerated pastures located a few meters apart. The cultivated treatments have been under continuous annual crops for at least 50 years. The pasture treatments consisted of permanent, regenerated pastures from 15 to 50 years old.

Image analysis (IA) of high-contrast negatives of polished blocks was advantageous in terms of time and labor requirements. Pore identification was facilitated with a UV dye included in the impregnating mixture. A high correlation (r = 0.8) was observed between porosity measurements by fully automated and manual IA systems. Fully automated systems are particularly appropriate for total macroporosity determinations. Some of their automatic features, however, cannot be used for object-specific measurements such as pore orientation.

Results

Regenerated pastures exhibited drastic changes in pedality and porosity. Topsoils with weakly expressed structures became self-mulched; porosity patterns, which are very simple under continuous cropping, became more diversified, with abundant tubular voids, vesicles, vughs, and chambers. The transition between topsoil and the compacted subsoil was abrupt under continuous cropping and much more gradual under pastures. Compacted layers and plow pans disappeared or became discontinuous due to vertical cracking.

Structural changes were not restricted to surface horizons. The Bw horizons evolved from a moderate, coarse, subangular, blocky structure under continuous cropping, to a compound, strong prismatic/subangular blocky structure under pastures. Indications of enhanced faunal activity, such as pedotubules and fecal pellets, were more common under pastures where roots were more abundant and deeper.

Image analysis confirmed observational evidence. Macroporosity (defined as pores > 0.02 mm^2) doubled under pastures; it shifted from 7% to 14% between 2 and 32 cm deep (Table 13, Figure 10). A strong shift in size distribution of equant pores toward larger sizes under pastures was also observed (Figure 11).

Changes in total macroporosity and pore-size distribution were combined with a radical modification in the orientation of elongated pores. Cultivated samples showed a preferred orientation, parallel to the soil surface. Samples from pastures, on the contrary, developed a random orientation. Quantification through IA is graphically expressed in polar coordinates plots (Figure 12). Cultivated samples showed elongated pores with a strong

Table 13. Means for percentage of macroporosity (averaged over sites).

Treatment	Depth§	Site HC–50	Site HB–25	Site HB–15	Means by: Depth	Means by: Treatment
Continuous cropping	D_1	5.9	4.0	9.0	6.3	7a
	D_2	7.8	5.6	11.0	8.1	
Pasture	D_1	18.2	12.9	17.1	16.1	14b
	D_2	12.4	9.4	17.0	12.9	
Average		11.1	8.0	13.5	10.9	

* Values with different letters are significantly different at P = 0.04.
§ Depths of sampling: D_1 = 2-16 cm and D_2 = 16–32 cm.

preferred orientation at low angles with the horizontal. Samples from pastures showed elongated pores randomly distributed at all angles.

These morphological changes are significant from the standpoint of soil hydrologic properties. Water movement under pastures is facilitated by the increase in macropore volume, the increase in size of macropores, and the disappearance of the horizontally oriented planar voids close to the soil surface. The gradual transition in pore geometry with depth under pastures favors interconnected

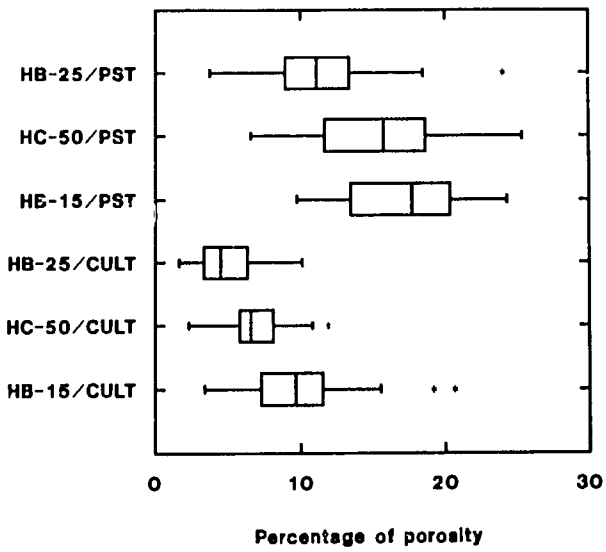

Figure 10. Multiple boxplots for percent of macroporosity for different site/treatment combinations. Sites: HC-50, HB-25, and HB-15. Treatments: pasture (PAST) and continuous cropping (CULT).

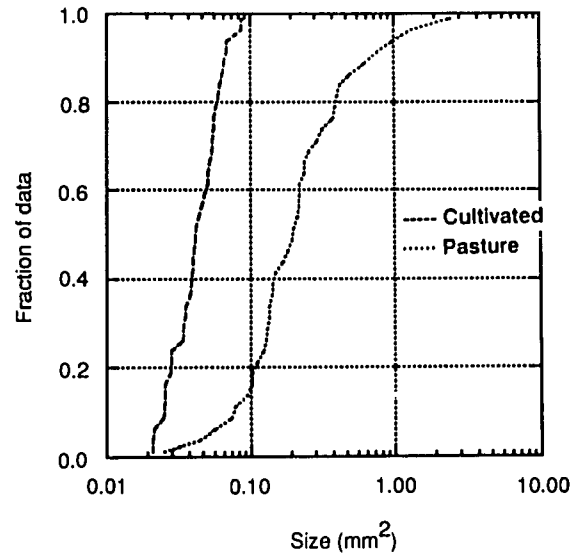

Figure 11. Cumulative sample distributions for size of equant pores. Cumulative distributions are plotted as a function of soil treatments: cultivated (- - - -) and pasture (. . . .). The x-axis (size of pores in mm²) is logarithmic.

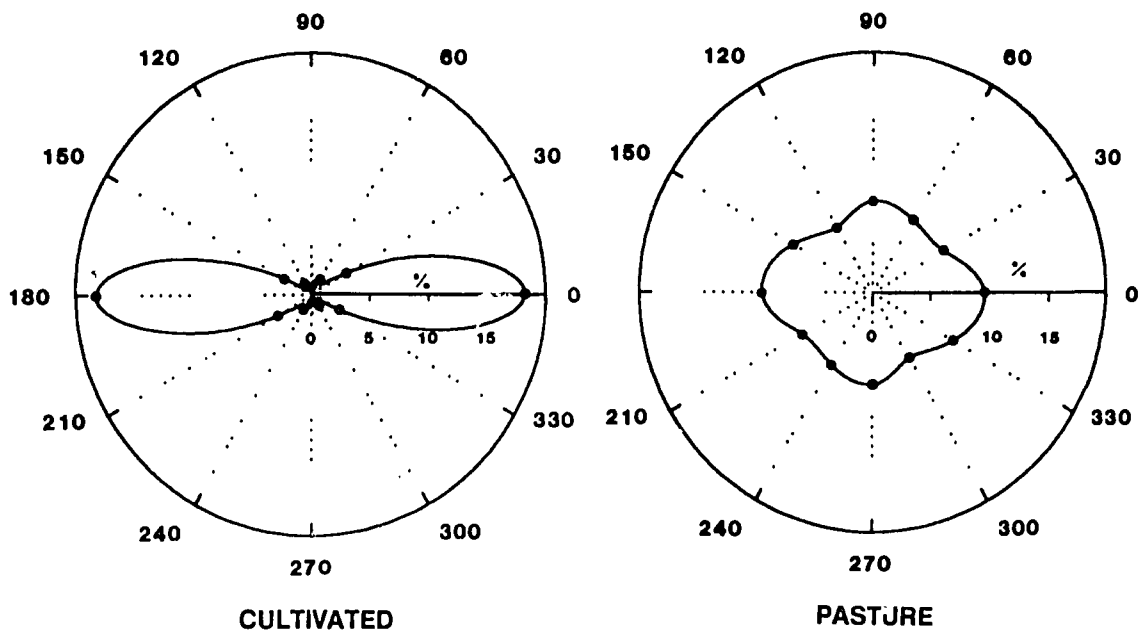

Figure 12. Star plots for cumulative length of pores and angular orientation (angle of longest diameter with the horizontal) for (a) continuous cropping and (b) pasture fields. The distance from the center of the circle (radius) indicates total length in mm/100 mm² of vertical section, at different angles with the horizontal.

pores with fewer pore-size discontinuities. The increase in biotic activity under pastures results in an abundance of vertically oriented channels.

Conclusions

These soils had been cultivated for decades before being converted to pastures. Nevertheless, the cessation of cultivation disturbance, the beneficial effects of the grasses, and a reactivated soil fauna have triggered a complex process of structural recovery. These changes confirmed the resilience of the structure of Vertisols and the potential of using pastures as key components in strategies for reversing structural degradation processes.

Characteristics of Eolian Dusts in Niger

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Some of the most important soils used for crop production in the Sahel region of Africa are often sandy, strongly leached, acid, weakly buffered, kaolinitic, and contain few weatherable mineral reserves. Despite the coarse texture of these soils and leaching up to 2 m under current rainfall, base saturation may increase from less than 35% in the upper 50 cm to 60–70% at 1.5 to 2 m. A possible base renewal vector in these soils is dust inputs. Thus, atmospheric dusts from Niger were evaluated for their potential role of nutrient cycling in the Sahel.

Procedures

Dust traps were installed in the major crop-production regions of western Niger (Figure 13). The Sadore site is located at the ICRISAT Sahelian Center, about 40 km southeast of Niamey. The Chikal site is near Filinque, about 200 km northeast of Niamey. Traps were installed at 2.5 and 5 m above the soil surface and sampled on or about January 15, April 15, July 15, and October 15. Water contained in the buckets was allowed to evaporate and the remaining contents were removed and sent to Texas A&M University for analysis.

Results

Total yearly infall averaged 2000 kg/ha, but was highly seasonal. Almost 60% of the infall occurred during the April to July pre-rainy season, averaging about 400 kg/ha/month (Figure 14). The period of Harmattan winds (January to March) contributed only about 11% of the total infall. Convectional storms associated with major rainstorms appear to be responsible for major dust inputs. There were no substantial differences between location or sampling height.

Particles in the dust ranged from clays to sands up to 1 mm in diameter, as determined by electrolyte dispersion. Total sand and fine silt were correlated with sampling dates. The greatest proportion of fine silt was measured during the period of maximum dust infall (April to July). The dust was coarsest during periods of lowest infall, when 50 to 65% of the dust was greater than 50 m (Figure 15).

The mineralogy of the dust is quite similar to reference soils adjacent to the sampling sites. The clay fraction is predominantly kaolinite. The occasional presence of smectite and mica does not appear to be correlated with site or sampling data. The coarser materials are primarily quartz with smaller amounts of feldspars and trace quantities of kaolinite and mica. Calcite was identified in

a few samples, but did not correlate with sampling data or location.

These dusts were also analyzed for exchangeable and water-soluble cations. Annually, dusts add about 5 kg/ha of Ca, about 2.7 kg/ha of K, and less than 1 kg/ha of Mg and Na (Figure 16). Most of the available Ca and Mg is in the exchangeable form, while Na and K exist mostly in the water-soluble form.

Although the yearly inputs of available cations by dusts may appear low, dusts are enriched in nutrient bases relative to adjacent crop-producing soils, contain low Al compared to high levels in soils and have high base status (Table 14). These soils seldom show a crop response to K fertilization; thus, dusts may serve as a readily available source of available K, providing a nutrient renewal to these soils.

Conclusions

Dust inputs in the Sahel region of West Africa are highly variable with season, with greater than 50% of the dust

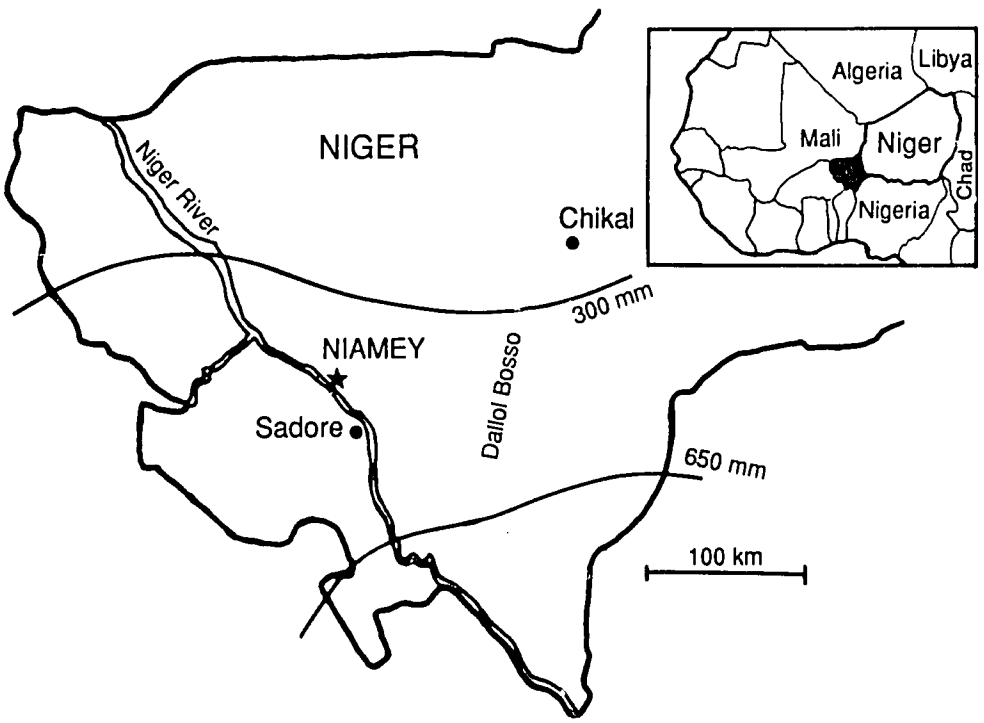

Figure 13. Location of dust traps in Niger.

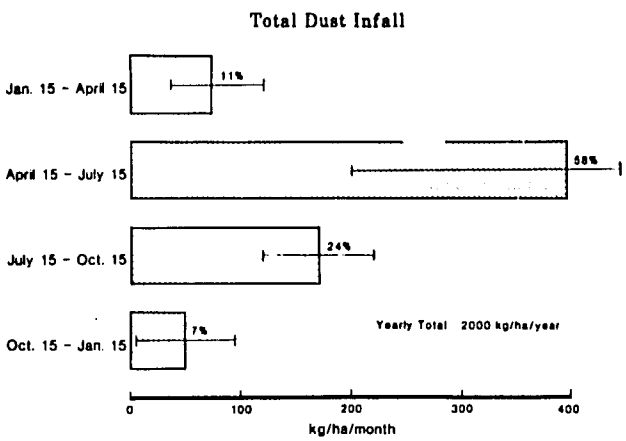

Figure 14. Dust infall by season averaged for both sites and heights. Bars represent plus or minus 1 standard deviation about the mean.

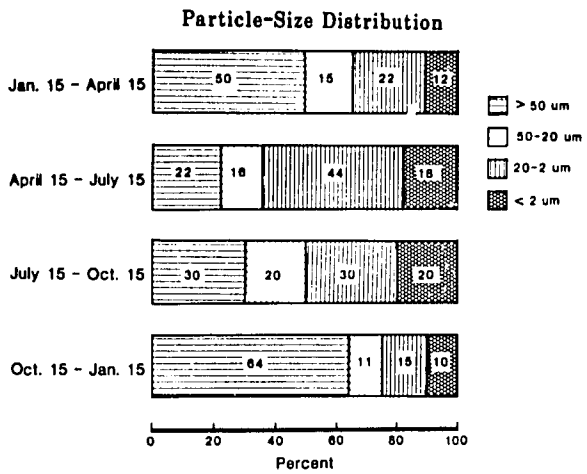

Figure 15. Particle-size distribution by season averaged for both sites and heights.

infall occurring during the April 15 to July 15 pre-rainy season. If all measured inputs were not redistributed, the study area would receive about 2000 kg/ha/year. This would amount to about 10 to 15 mm deposition over 100 years.

Available cations from dust inputs are a continual input vector that, over time, may supply needed bases and maintain the nutrient balance of these crop-producing soils. Soil-management practices should be designed to entrap these dusts by using residue management, wind- and water-control practices, alley-cropping, and agroforestry.

Table 14. Chemical analysis of dust and adjacent reference soils.

	Dust	Soil Surface (cmol (+)/kg)
Ca	5–24	0.1–0.3
Mg	1–4	0.1–0.2
Na	0.1–1.5	0
K	0.3–4	0.1
Al	0	0.25–0.65
CEC	6–22	1–1.8
Base Sat.	100%	18–42%

Values = plus or minus 1 standard deviation.

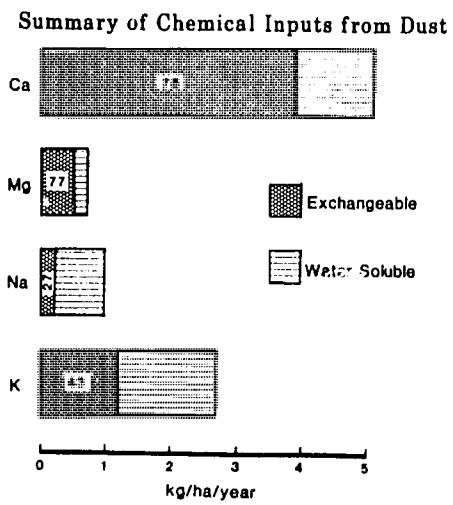

Figure 16. Summary of exchangeable and water-soluble cations averaged for season, site, and height.

Evaluation of Indigenous Soil- and Crop-Management Technologies: TAMU-405

Attempts to modernize agricultural production systems in Africa often overlook the role of indigenous knowledge evolved through centuries of continuing interaction between the sub-Saharan farmer and the environment. Many successful innovations in soil and crop management for the semiarid tropics are indigenous. Local agricultural skills and ecological knowledge should be part of the essential knowledge base for future research and development. Most published work on indigenous knowledge has been conducted by social scientists. Quantitative studies by soil scientists and agronomists are extremely scarce.

Farmers in West Africa possess a thorough knowledge of soil diversity. They recognize different types of soils by using criteria such as soil texture, colors, drainage, and workability. Natural vegetation is often considered an indicator of soil fertility.

Sub-Saharan farmers are also acutely sensitive to the problem of drought and particularly to the problem of forecasting the onset of the rainy season. Ways of coping with these uncertainties vary from area to area; however, most communities have developed a range of forecasting techniques. At the same time, they have developed different strategies aimed at adapting their farming systems to the inherent unreliability of rainfall at the beginning of the rainy season. These systems do not serve to maximize yields, but, under such circumstances, the farmers choose to minimize risk rather than maximize yield.

Sahelian farmers are also usually aware of deteriorating trends in soil productivity. This perception is not only based on direct recall from past harvests, but also on knowledge passed from generation to generation. *Kasar mu, ta gaji* ("the land is tired"), and *Laabu, y bu* ("the land is dead") are Hausa and Zarma farmers' common expressions that suggest an unambiguous awareness of soil degradation. The most frequently mentioned indicator of the problem is the decline in grain production; whenever harvest is discussed, the comment is that fields do not produce as many bundles of millet as they used to. While some farmers do not see any remedy to this problem, others have been testing soil conservation and traditional land-regeneration practices. These indigenous skills can provide valuable information to TropSoils scientists in planning and designing research, training programs, and technology transfer.

Evaluation of Indigenous Soil- and Crop-Management Technologies in the Hamdallaye Watershed

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Indigenous or local knowledge is unique to a given culture or society. It is dynamic knowledge that changes through local creativity and innovativeness or in response to contact with other cultures. An important type of indigenous knowledge is the appreciation and comprehension of the natural and physical environment.

The goal of the TropSoils program in Niger is to develop sustainable agricultural watershed-management technologies for semiarid regions. The program was planned with the recognition that local agricultural skills and ecological knowledge should be integrated with appropriate modern technologies, enabling farmers to adopt sustainable agricultural practices.

Objectives

Work at the Hamdallaye watershed was carried out 1) to identify all farmers within the watershed and document land history of cultivated and fallow areas and 2) to obtain, through interviews with farmers, their general assessment of land tenure, a sense of their indigenous knowledge of soil and crop management, and their perceptions of problems and solutions.

Procedures

The pilot watershed selected for the project is near the village of Hamdallaye, 30 kilometers east of Niamey. Fifty-six farmers were identified within the watershed; 42 of them were interviewed. During the interview processs, the researcher walked with the farmer on his or her field soliciting comments and probing for explanations related to soil management. Several group interviews were held with village elders and three village chiefs who have administrative responsibility over territory in the watershed.

Results

Description of the Project Watershed

The 589-hectare pilot watershed is located two kilometers east of the village of Hamdallaye. The region was originally settled and claimed by Zarma cultivators. Of the 42 interviewed farmers, 32 are Zarma (76%), 6 are Hausa (14%), and 4 are Peul (10%).

Four villages have administrative territory within the watershed (TAMU-402, Figure 1). Approximately 13% of the land in the project watershed falls within the territory of Hamdallaye, the *chef-lieu du canton*. The village of Bokotchili Kaina, four kilometers east of Hamdallaye, falls outside the project boundaries, but 56% of the watershed land area falls under its administration. Falanke Kaina, a hamlet entirely located within the project boundaries, lies about six kilometers east of Hamdallaye; 25% of land within the watershed boundaries comes under the administration of the *Chef de Famille* of Falanke Kaina. Outside the watershed boundaries on the easternmost corner lies Falanke Beri, whose administrative district covers about 6% of the watershed land. Land area falling within each village territory is reported in Table 1.

Table 1. Land area in each village district.

Village territory	Land area
	(ha)
Hamdallaye	71.6
Bokotchili Kaina	308.7
Falanke Kaina	137.8
Falanke Beri	30.6
Total	548.7

Land tenure

The land tenure system in the watershed is based on the settlement history of the region. Zarma pioneers, usually single families, moved into areas of virgin land, gaining rights to what they cleared. Villages gradually grew, and holdings were accumulated until they reached the borders of neighboring village land.

Today, all land in the watershed is claimed by families of the original settlers. Forty-one families claim rights over land distributed among four villages and used by 56 cultivators. Thirty-two (57%) of these cultivators are farming on family land. Six (15%) are nonresident landowners.

Under Zarma land tenure, land rights in the watershed rest in the lineage (group of people claiming descent from a common ancestor) of the original Zarma settlers. Land passes from father to sons through a patrilineal inheritance system. When a son marries, he is allocated land for his household needs. Through this process, land has come under the management of individual household heads (*windi koy*) fragmenting the original family land.

Land agreements

Besides inheritance, cultivators acquire land through loan. Forty-three percent of the cultivators in the watershed are farming on borrowed land. Verbal agreements are reached between the household head and the borrower, providing access to the land as long as he/she uses it. No formal time

periods are set. The general understanding is that the land will be cultivated until the field becomes too old and too difficult to cultivate, at which point the land is fallowed and ownership reverts to the lending family. The borrower may acquire another field from the same family, negotiate land use with another family, or subdivide the field so that portions can be fallowed. Few instances were reported where land was actually reclaimed. Tenure security appears to exist through established lender-borrower relationships. Several cultivators were subleasing parcels of their borrowed land.

For use of the land, the cultivator typically gives the lending household head a proportion of the harvest—reportedly 10% of the yield, though amounts vary according to relationship and yield. No money transactions for use of land are reported in the region, nor is land sold.

Perceived Agricultural Problems

Principal farming problems as expressed by farmers are related to the same agroecological changes affecting the region:

1) inadequate and irregular rainfall,
2) low soil fertility,
3) unavailability of animal manure and limited access and capital to purchase chemical fertilizer,
4) labor shortages due to out-migration of young men in the household and expense of hired labor, and
5) wind erosion, which carries away topsoil and buries millet seedlings.

Insects and pests were not often mentioned in discussions of agricultural problems, perhaps because pest incidence varies with respect to annual rainfall. However, when in the field, farmers quickly point to insect damage in process. In this context, farmers attribute yield losses in 1989 to mice attacks on cowpea seed, a nocturnal millet beetle, grasshoppers, and various millet-grain-eating worms.

Perceptions of Land Degradation

Most commonly, farmers attribute land degradation first to loss of vegetation and second to increase in wind. Farmers attribute loss of vegetation to general climatic changes, the severe drought which ended in 1974, and increased cultivation. They speak not only of reduced flora but also of changes in species composition.

At the same time that the vegetative cover has been decreasing, farmers note an increase in the frequency and velocity of the dry-season wind. These winds carry away valuable topsoil, leaving unproductive *gangani*, (literally, "bare earth"). Farmers also complain of wind damage when transported soil buries millet seedlings.

Water erosion was seldom mentioned as an agricultural problem. This may be because all farmers are faced with the potential deleterious effects of wind erosion. Water erosion, in contrast, is more site-specific, depending upon location and slope of fields.

Indigenous Classification Systems

Land types

Farmers in the watershed classify land by elevation. Typically, farmers classify lands at higher elevations as less fertile, given the water and nutrient runoff. Land closest to the plateau is considered the poorest in structure. Farmers recognize, however, that management practices affect land productivity, and they distinguish attributes of particular soils within a topographical sequence. Consequently, farmers now tend to associate land quality more with cultivation/fallow practice than with topography. Recently marginal cultivated land near the plateau is considered more productive than older fields downslope.

Soil classification

Farmers principally use sight and touch to determine the physical properties of the soil. Attention is focused on the topsoil. Properties that farmers distinguish are color, organic matter, texture, drainage condition, and depth. Chemical properties do not seem to figure in their soil classification system.

Soil color is related to the presence or absence of organic matter, the process of soil erosion, and exposure of subsoil. Black soil contains more organic materials and is considered more fertile. Through cultivation and erosion, valuable nutrients are depleted, leaving the less productive white soil. Further degradation results in red soil. Within each soil-color class, farmers distinguish gradations in fertility.

The second major soil classification system distinguishes three basic textures:

1) *tatssi:* sandy soils,
2) *botogo*: soils with some clay content,
3) *gangani*: concreted, lateritic soils.

Classification of Vegetation in the Watershed

Various indigenous species are valued in the production system. Table 2 lists, in order of priority, the principal plants and trees and their uses as identified by local farmers.

Soil-management Practices

Fallowing

Fallowing continues to be the principal management practice to restore soil productivity. Almost 49% of the land in the watershed was in fallow during the 1989 cultivation season. The traditional practice of long-term bush fallow, however, is breaking down. Farmers report that former fallow periods were generally ten years or

Table 2. Farmer use of beneficial plants and trees in the watershed.

Zarma name	Scientific name	Use
Plants		
Subu nya	*Andropogon gayanus*	mats; roofing; leaf sheath fed to animals
Bata	*Aristida longiflora*	mats; roofing as underneath layer to *Andropogon*
Borboto	*Pennisetum pedicellatum*	animal feed; can replace *Aristida* in roofing
Ganda bani	*Cassia mimosoides*	soil fertility; mats; can replace *Aristida* in roofing
Haramdam	*Diheteropogon hagerupii*	animal feed; roofing as underneath layer to *Aristida*
Tutu	*Setaria pallide fusca*	animal feed
Trees		
Kosey	*Piliostigma reticulatum*	bark used for cord; soil fertility; consume fruit; dried fruit and new leaf growth as animal feed
Korko: ɔy	*Combretum glutinosum*	medicine; soil fertility
Darey	*Ziziphus mauritiana*	consume fruit; leaves as animal feed; thorny branches used to protect mats and granaries from animals
Zamturi	*Prosopis africana*	construction; soil fertility; cut branches for animal feed in late dry season; wood for mortar, daba, etc.
Sabara	*Guiera senegalensis*	medicine; leaves as sheep feed; firewood
Deli-nya	*Combretum nigricans*	firewood; consume/sell fruit

more, but now seldom exceed three to five years on land that is owned. On borrowed land, the fallow period can only be two to three years. Organization of fallowing among farmers in the watershed varies. The main types include the following:

1. Half-year fallow. Land is not used during the period between harvest and the following growing season. Crop residues are grazed by livestock. Residues may be mulched, but no field crops are grown. Half-year fallowing is practiced by all farmers.

2. Full-field fallow. Land productivity declines to such an extent that further cultivation is not economical. Thus, the entire field is left fallow. The usual fallow interval is two to five years.

3. Within-field fallow. The least productive areas within a field are fallowed, and the remaining land is cultivated. In this manner, a field can be composed of several parcels of varying fallow lengths. Usually the fallow interval is two to three years.

4. Emergency fallow. A field or portion of a field is fallowed due to illness, lack of labor or some other circumstance that impedes planting.

Use of manure

Farmers prefer animal manure to chemical fertilizer since its benefit to crop production is said to last from five to ten years depending upon amount and type applied (goat, sheep, cattle, or donkey), soil, method of application (kraaling vs. transporting manure from compound to field), and season of application (rainy vs. dry season). Eleven of 39 (28%) cultivators with cropped fields reported applying animal manure during 1989, principally by kraaling animals on crop land.

Use of fertilizer

Nearly 60% of the those interviewed have used fertilizer at some time. Half discontinued use in 1989. Reported usage ranged from one 50-kilo bag of either triple superphosphate (TSP) or urea, to 20 bags of phosphate and 14 bags of urea. Overall, application rates were minimal in relation to total cultivated area per household. Timing of application also varied depending upon when farmers obtained their supplies.

Compound sites and refuse-accumulation sites

The Peul herders living in the watershed move their compounds up to three times per year so that the accumulated household and animal refuse can improve land productivity. Sites for locating compounds are purposefully chosen where fertility amendments are most needed. Three Zarma cultivators who reside on their fields also move their compound sites at least annually to capitalize on the fertility from accumulated refuse.

Another practice to enhance productivity is to cultivate sites formerly used for pounding grain. Some farmers burn the accumulated grain refuse, which is thought to produce a particularly fertile area. Typically, these sites are in the shade of a tree or on *gangani* where millet is laid to dry.

Reportedly, men may request that their wives pound grain at a degraded site in order to restore the soil there.

Crop-residue management
Cultivators report that they have changed crop-residue management over the past ten years in response to increasing wind erosion. Previously, unused crop residue and debris were gathered and burned on the field. Now, crop residues and small bushes are left on the field to combat wind erosion.

Mulching
Mulching is practiced principally to build up eroded soils or combat potential wind erosion. Among the various crop, plant, and household residues used as mulch are the following: 1) branches of native shrubs, *kosey* (*Piliostigma reticulatum*), *korkobey* (*Combretum glutinosum*), and *sabara* (*Guiera senegalensis*); 2) millet stalk residue; 3) refuse from old granaries; 4) old roof thatching from dismantled homes; 5) fallen tree limbs; 6) cut grasses.

Mulching materials may be generally distributed over a field or placed strategically on severely eroded areas. The purpose is to entrap windblown soil and to provide an adequate soil depth for plant growth without having to break up the lateritic crust. Mulch may also be placed on the windward side of a field to inhibit wind erosion.

Indigenous Perception of Soil Erosion within the Hamdallaye Watershed (Niger)

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Farmers on the Hamdallaye watershed see land degradation as a result of a general loss of vegetation and an increase in wind erosion due to climatic changes within the past 20 years.

Water erosion within the watershed is associated with runoff from the laterite plateau and lateritic outcrops and from large areas of exposed Bt horizons with surface crusts. Gullies are also common, but do not appear to take up a large part of the land surface. Farmers state that they are relatively powerless to control water erosion, as runoff from the plateau and adjacent talus slopes involves erosion-control works that are not on farmers' fields and, therefore, are of little interest.

Wind has gradually eroded the A1 horizon, in extreme cases leaving an exposed Bt horizon that is prone to surface crusting. Such crusting increases surface runoff and water erosion hazard.

Objectives
The objectives of this study were 1) to investigate the indigenous perception of soil erosion, 2) to estimate the aerial extent of wind and water erosion within selected landscape units at the Hamdallaye watershed, and 3) to survey farmers' methods for controlling erosion.

Procedure
Site Description
The study site is a 600-ha watershed located 4 km NE of the village of Hamdallaye, Niger (approximately 30 km NE of Niamey). Geomorphology is representative of the plateau-sand valley systems. Soils extending through the toposequence from the edge of the laterite plateau to the valley bottom are sandy to loamy sand in texture. A secondary and tertiary lateritic outcrop bisect the toposequence, so that soil depth to laterite is a function of toposequence position.

Water-eroded gullies arise from the plateau surface and adjacent talus slopes and also from the exposed areas of the secondary and tertiary lateritic outcrops. Only one gully traverses the entire length of the toposequence. All other gullies disappear into alluvial sand fans as a result of a decrease in slope closer to the secondary and tertiary laterite outcrops.

Types of Erosional Surfaces

Erosional surfaces are referred to by farmers by their names in *Zarma*, which is the language spoken in the region of the watershed.

Tassi gande: Depositional surface of alluvial sand fans resulting from a decrease in slope at the end of a gully, rill, or ravine. Generally devoid of plant growth due to high-energy water flow during intense rainstorms. Good water balance for crop growth, but the soil is generally depleted of nutrients and organic matter. Farmers state that once millet is established, it grows well in these areas.

Gorou gande. Sheet erosional surface, as evidenced by stratification of the upper A1 horizon.

Gorou. Gully erosion as a result of water concentration from impermeable surfaces, such as those found on laterite plateau and outcrop surfaces and *Gangani kirey* soils.

Gangani kware: White *gangani* (a denuded soil resulting from the effects of wind erosion) in which part of the surface soil is removed exposing the lower A horizon and sometimes upper Bt horizon.

Gangani kirey: Red *gangani* (a denuded soil resulting from water erosion) in which the surface horizons are completely removed and the Bt horizon is exposed. These are generally crusted and are more difficult to regenerate than the *gangani kware*. These areas may represent sites of old termite mounds.

Estimation of Aerial Extent of Erosion

Three hundred of the approximately 600 ha of the watershed were surveyed to estimate the extent of erosion and to investigate indigenous perception of the problem. This area included those landscape units where farming was most concentrated. Twenty-five farmers were interviewed in their fields regarding soil type and erosion-control methods. Each field was toured, erosional surfaces were classified, and their extent was measured with a tape.

Results

Distribution of Erosional Surfaces

Gangani kirey comprises the largest erosional surface within the surveyed area, followed by *tassi gande*. However, less than 2% of farmers' fields are affected by *gangani kirey*. Almost 4% of farmers' fields within the surveyed area were affected by one of the five types of erosional surfaces. However, distribution of erosional surfaces was not uniform, as evidenced by the large standard deviations for each type of surface (Figure 1).

The aerial extent of erosion was broken down by position on the landscape, from the valley bottom to the laterite plateau (Figure 2). *Gangani kirey* is the largest erosion surface at all five positions. *Tassi gande* and *gorou gande* occur between 0 to 1% slopes in the valley bottom, decrease with elevation within the toposequence, and then increase rapidly closer to the laterite plateau. *Gorou* and *gangani kware* show no evident trends.

Farmers associate *Gangani kware* with wind erosion. The results of this survey indicate that, as a percentage of total fields surveyed, this effect is not very pronounced. However, *gangani kirey* may also result, in part, from wind erosion, therefore, the two *gangani* surfaces might indicate a substantial contribution of both wind and water to the erosion process.

Farmer Practices to Control Erosion

Several native plant species are used by local farmers to control wind erosion, primarily on areas with *gangani kware* surfaces (Table 3). Forty-eight percent of farmers interviewed use *Guiera senegalensis* to control *gangani kware*, 40% use *Piliostigma reticulatum*. Branches from these plants are generally cut twice a year and laid out on the erosional surfaces to trap wind-borne soil and therefore building up the surface horizon. To a lesser extent, farmers use *Combretum glutinosum*, *Cassia mimosoides* and *Combretum micranthum* for the same purposes.

A few other methods are used to control erosion (Table 4). Sixteen percent of the farmers use the millet stalks that remain on the soil during the dry season. The stalks are cut and laid on the surface to trap wind-borne soil. One farmer used millet chaff for this purpose. Two farmers used animal manure exclusively to combat erosion, laying it on the surface to build soil fertility, trap wind-borne soil, and therefore provide a seedbed for crop establishment. The manures were generally applied to the *gangani kirey* soils. One farmer used animal traction to break up

Table 3. Native plants used for erosion control (n = 25 farmers).

Scientific name	Zarma name	# fields used	% fields used
Guiera senegalensis	Sabara	12	48
Piliostigma reticulatum	Kosey	10	40
Combretum glutinosum	Kokorbey	6	24
Cassia mimosoides	Ganda bani	1	4
Combretum micranthum	Kubu	1	4

Table 4. Different methods of erosion control practiced by local farmers (n = 25) farmers.

Method	# fields used	% fields used
Millet surface mulch: stalk	4	16
Chaff	1	4
Animal manure	2	8
Animal traction	1	4

the surface crust and loosen the soil surface in a *gangani kirey* soil; afterward he applied manure to prevent the crust from reforming.

Conclusions

A survey was taken to estimate the indigenous perception of farmers and the aerial extent and topographic distribution of soil erosion within selected landscape units at the Hamdallaye watershed. Mean erosional surface areas were 3.7% for all farmers' fields; however, there was considerable variation. *Gangani kirey* was the most prevalent erosional surface. Erosion was most prevalent close to the plateau (upper part of the toposequence) and in the valley bottom. However, *gangani kirey* was also associated with shallow soils at the secondary and tertiary laterite outcrops.

Farmers used several species of native plants to control wind erosion (primarily on *gangani kware* surfaces). These include *Guiera senegalensis*, which is the predominant ligneous species for this ecological zone, and*Piliostigma reticulatum*. A few farmers lay millet stalks on their fields to control wind erosion. *Gangani kirey* surfaces have been regenerated by plowing and in one case, by applying manure. The results of this survey also indicate that farmers are more prone to try to control wind erosion than water erosion.

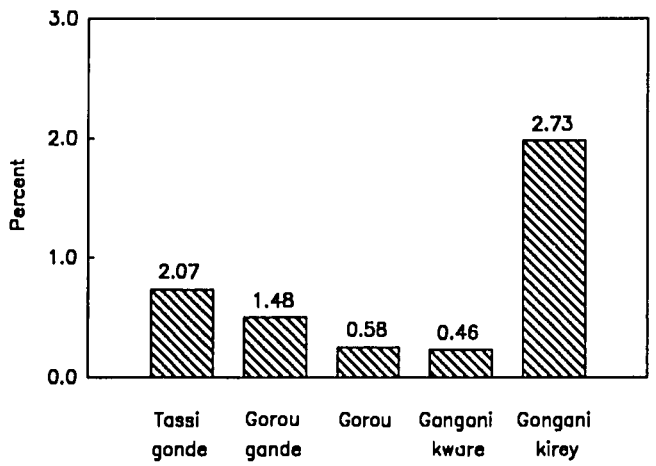

Figure 1. Aerial extent of erosional surfaces. Values above each bar are standard deviations, in percent (n=25).

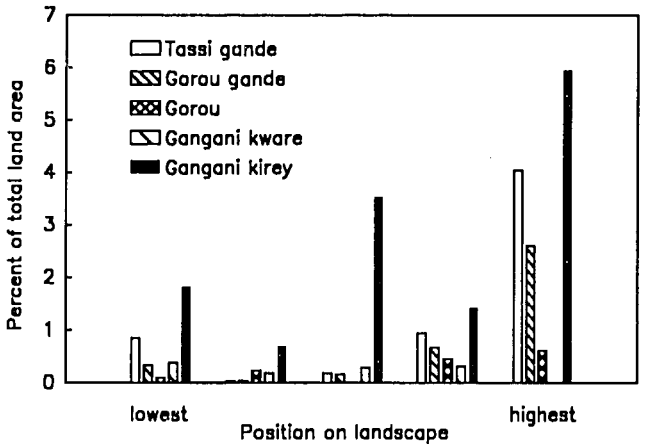

Figure 2. Distribution of erosional surfaces within the watershed toposequence.

Development and Evaluation of Agroforestry Systems for Control of Wind and Water Erosion and Modification of Microclimate: TAMU-404

Increased population pressure coupled with climatic changes in recent decades has resulted in severe land degradation, water and wind erosion, and loss of abundance and diversity of natural vegetation in the semiarid tropics of Africa (SAT). Systematic long-term research therefore is needed to develop effective agroforestry-related systems of land rejuvenation.

Past TropSoils-SAT research has addressed the topic of microclimate modification with Neem windbreaks. The Neem tree (*Azadirachta indica*), introduced from India, is now ubiquitous in the zone south of the 250 to 300 isoyet in Niger. Windbreaks established by CARE in the Maggia Valley provided an opportunity for studying the role of shelterbelts and windbreaks for improving crop growth and yield in millet. The hypothesis for these windbreak studies was that by modifying the influence of hot, dry, desiccating winds in Niger, tree windbreaks serve as a semi permanent method for soil-water conservation and as a practical preventative against wind erosion. The trees, if rationally harvested, can provide much-needed fuel wood without seriously impairing their wind-protective efficiency. In addition to its effects on grain yield, this technology has an implicit and strong resource-conservation component, although Sahelian farmers' adoption may be triggered by perceived increases in comfort and protection. These studies have been summarized in *TropSoils Technical Report, 1986-1987.*

The beneficial effects of trees and perennials on soil and water conservation in the semiarid tropics are widely recognized. Leguminous trees such as *Acacia albida* and *Prosopis* spp. have for centuries constituted an integral part of traditional farming systems. In recent years, however, agroforestry research and development has dealt primarily dealt with soil fertility maintenance (i.e., alley-cropping) and fuel-wood production. Little attention has been given to the use of different tree species for soil and water conservation.

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A Survey of the Distribution of Vegetation Within the Hamdallaye Watershed

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The integration of natural-resource management with agriculture is widely practiced by both farmers and herders within the Sahel. This management requires that farmland be used for wet season crop production and for dry season grazing. As is typical in subsistence economies, farmers exploit many native plant species for food, fodder, fuel, construction materials, and other uses.

Two types of vegetation occur in the watershed as functions of topography: vegetation of the laterite plateaus and vegetation of the toposequence soils. The vegetation of the laterite plateaus of the Continental Terminal is typically a thicket of *Combretum micranthum* which occurs in a "tiger bush" pattern.

The forest is exploited daily by local people, and the plateau itself is a passageway for livestock, especially in the rainy season when entering cultivated areas is forbidden. The vegetation on the plateau is a source of wood and medicine for the local populace.

The vegetation of the toposequence soils consists of a shrub savanna of *Guiera senegalensis*, which is defined as a dominant strata of shrubs at least 80 cm in height and inferior strata of annual grasses and woody plants.

Objectives

In order to gain a complete understanding of the natural-resource base within the 600-ha Hamdallaye watershed (30 km NE of Niamey, Niger), we conducted a survey to estimate species diversity and distribution. These species were also defined according to their local use.

Procedure

The vegetation survey was conducted between October and December 1989 along a transect running from the surface of the primary plateau to the valley bottom. Study areas within the transect were located on the primary plateau, the secondary plateau, and in seven positions within the toposequence. All sample areas within the toposequence were in fallow, enabling a description of native species.

Two methods were used to determine the distribution of vegetation: 1) the linear or segment method, which is best adapted to the study of herbaceous vegetation, and 2) the surface-area method, which is best adapted to the distribution of woody species.

The linear method consisted of measuring the distribution of all species occurring along a fixed line. For the toposequence, lines were 50 m long with 0.5 m-intervals. For the plateaus, lines were 100 m long with 0.1-m intervals. In each case, 100 segments were studied. Each individual species was counted only once within a segment; thus, the final frequency represents linear distribution, not total numbers along the line of study.

The surface area used in the measurement of the distribution of lignaceous vegetation was determined to be 100 x 50 m (5000 m^2) on the toposequence. On the laterite plateaus, the homogeneity of vegetation did not permit an accurate determination of the minimal surface area for counting plants.

Species were categorized by the relative frequency of distribution within each linear segment. This report will describe vegetation that is primarily of importance to the local populace. (For a complete listing of vegetation occurring along the transect, see the report entitled *Integrated Management of Agricultural Watershed (IMAW) Feasibility Study*, TropSoils, Dept. of Soil and Crop Sciences, Texas A&M University.)

Table 1. Dominant species of the laterite plateau.

Dominant	Less dominant
Firewood:	
Combretum micranthum	*Combretum nigricans*
Guiera senegalensis	
Pasture:	
Zornia glochidiata	*Alysicarpus ovalifolius*
Schoenefeldia gracilis	
Aristida adscencionis	
Brachiaria disticophylla	
Dactyloctenium aegyptium	
Others:	
Microchloa indica	*Tripogon minimus*
Aristida adscencionis	*Polycarpaea eriantha*
Pandiaka heudelotii	*Evolvulus alsinoides*
Borreria scabra	*Ipomoea vagans*
Eragrostis pilosa	*Sporobolus festivus*
Achyranthes aspera	*Sporobolus panicoides*
Desmodium setigerum	*Minacarpus scaber*
Setaria pallide-Fusca	
Digitaria horizontalis	
Mollugo nudicaulis	
Panicum laetum	
Pycreus macrostachyos	
Acacia erythrocalyx	
Persitrophe bicalyculata	

Dominant species: relative frequency > 4%.
Less dominant species: relative frequency 1–4%.
Relevant frequency = individual species frequency x 100 / total species frequency.

Results

Description of Plateau Vegetation

The plateau vegetation occurs in a network of thickets, which vary in size and floral composition. These thickets are separated by spaces containing pieces of disseminated wood, and herbs growing in small mounds of sand. These mounds often form around dead tree or shrub stumps and restrict surface flow after a heavy rainfall. The slowing of the water permits greater percolation into the soil and also creates small pools in which certain semiaquatic species grow (such as *Microchloa indica*, *Tripogon minimus*, and *Pycreus macrostachyos*).

Vegetation on the plateau is in three strata: 1) herbaceous strata within bare areas that are sufficiently open and are more dense under the thickets (up to 40 cm in height); 2) strata of shrubs with an open nature in the bare areas and a more dense growth within the thickets (height varies from 0.5 to 2.5 m); and 3) strata of trees at the center of the thicket (up to 10 m in height).

Within the thickets the principal species are *Combretum micranthum* and *Guiera senegalensis*. Because the thickets are low (0.5 to 2.5 m) and dense, they create a vault that diverts air currents and reflects solar radiation. At the same time, they trap eolian sands that slowly create a thin layer of soil on the thicket floor.

Lignaceous species that demand the most water (*Combretum nigricans*, *Acacia macrostachya*, *Grewia flavescens*, *Acacia erythroculyx*, and *Acacia ataxacantha*, etc.) grow at the center of the thickets. These species often have creeping roots, which exploit rainwater efficiently.

Underneath the thickets grow *Microchloa indica*, *Tripon minimus*, *Triumphetta pendandra*, *Cardiospermum halicacabrum*, *Aspilia kotschyii*, *Commelina forskalaei*, *Ipomoea heterotricha*, *Sporobolus panicoides*, *Borreria scabra*, *Hybanthus enneaspermus*, *Cyanotis lanata*, *Archidium tenellum*, and *Riccia trichocarpa*. The last two species are Muscinees, which indicate a favorable water balance within the soil in the thickets.

In the bare areas between thickets grow *Combretum glutinosum*, *Commiphora africana*, *Boscia senegalensis*, *Boscia augustifolia*, *Schyzachirium exile*, *Aristia adscencionis*, *Evolvulus alsinoides*, *Indigofera bracteolata*, *Jacquemontia tamnifolia*, *Brachiaria disticophylla*, *Merrimea pinnata*, *Polycarpaea* spp., *Dactyloctenium aegyptium*, *Schoenefeldia gracilis*, and *Alysicarpus ovalifolius*. Nothing generally grows within 1 m of termite mounds. Dominant species on the plateau are listed in Table 1.

Toposequence Vegetation

Vegetation on the toposequence is structured into three strata: 1) Herbaceous strata dominated by grasses; 2) strata of scattered shrubs; and 3) strata composed of a few trees higher than 10 meters.

The horizontal structure of this vegetation allows solar radiation to reach the soil. In areas where fallows have existed for some time, the vegetation is somewhat reconstituted, and some trees are permited to develop.

The spatial distribution of flora follows topography; the species with a greater need for water are found close to ravines that collect runoff water from the plateau.

Table 2 lists the dominant species found within each linear measurement for the toposequence sites. Table 3

Table 2. Dominant species of the toposequence.

Very dominant	Less dominant
Firewood:	
	Piliostigma reticulatum
	Guiera senegalensis
	Combretum micranthum
	Combretum glutinosum
Pasture:	
Eragrostis tremula	
Aristida adscencionis	
Zornia glochidiata	
Cenchrus biflorus	
Digitaria horizontalis	
Dactyloctenium aegyptium	
Alysicarpus ovalifolius	
Fabrication:	
	Aristida sleberiana
	Ctenium elegans
	Andropogon gayanus
Others:	
Mitracarpus scaber	*Waltheria indica*
Borreria radiata	*Ceratotheca sesamoides*
Merrimia pinnata	*Digitaria gayana*
Indigofera herhautiana	*Annona senegalensis*
Jacquemontia tamnifolia	*Monechma ciliatum*
Tephrosia linearis	*Schoenefeldia gracilis*
Cassia memosoides	*Ipomoea vagans*
Indigofera bracteolata	*Guiera senegalensis*
Kohautia senegalensis	*Pennisetum pedicellatum*
	Combretum micranthum
	Piliostigma reticulatum
	Polycarpaea linarifolia
	Chrozophora brocchiana
	Indigofera pilosa
	Aristida stipoides
	Fimbristylis hispidula
	Stereospermum kunthianum

Dominant species: relative frequency > 4%; less dominant species: relative frequency 1–4%; relevant frequency = individual species frequency x 100 total species frequency.

Table 3. Distribution of lignaceous species within a 5000 m² area at each toposequence position.

Species	Toposequence position*						
	1	2	3	4	5	6	7
	Number of species						
Guiera senegalensis	79	50	55	92	111	14	31
Piliostigma reticulatum	4	13		8	22	20	7
Combretum glutinosum	17	18	1	13	34		1
Combretum nigricans	2		3		1		
Combretum aculeatum						2	
Combretum micranthum			7				
Terminalia avicennioides	5	5		6	4	2	3
Acacia albida		2					
Acacia macrostachya		1					
Annona senegalensis		10		2	16	27	14
Stereospermum kunthianum		1				5	
Balanites aegyptiaca				3			
Prosopis africana				1			1
Calotropis procera				1			
Sclerocarya birrea					4		
Detarium microcarpum					1		
Ziziphus mauritiana						2	

*Toposequence position 1 corresponds to the site closest to the laterite plateau, with position 7 corresponding to the valley floor.

Table 4. Species important to the local populace.

Name	Use
1. Species utilized by man:	
Andropogon gayanus	Perennial grass used to make mats for the construction of roofs for houses and granaries. Serves to stabilize dunes and soils from wind erosion.
Aristida sieberiana	Perennial grass used to construct curtains, mats, and brooms. Sometimes used for house roofs.
Ctenium elegans	Annual species. Very sensitive to variations in rainfall. Used to make house roofs.
Cenchrus biflorus	Dominant grass, due to dispersal of thistle-like seeds that stick to animals (and pants).
Pennisetum pedicellatum	Annual grass that is not very dominant within the watershed. Used to make cord and as a fodder plant when fresh.
Dactyloctenium aegyptium	Annual pasture.
Digitaria horizontalis	Annual pasture.
Brachiaria disticophylla	Annual used as fodder for horses.
Brachiaria xantholenca	Annual pasture.
Corchorus tridens	Annual, fresh, or dried leaves used to thicken sauces.
Ceratotheca sesamoides	Annual found on dune fallows. Fresh or dried leaves used to make sauces.
Zornia glochidiata	Annual pasture (legume).

Table 4. (continued).

Name	Use
1. Species utilized by man:	
Alysicarpus ovalifolius	Annual used as fodder for horses.
Cassia italica	Perennial used as a medicine to cure constipation.
Merremia tridentata	Annual found on dune fallows. Fodder for small ruminants.
Pergularia tomentosa	Perennial containing tannins. Used to tan hides.
Calotropis procera	Perennial used for framing. Wood is resistant to insect attack.
Leptadenia hastata	Perennial. Boiled leaves eaten with peanut sauce.
Citrillus colocynthus	Perennial. Fruit eaten by man and animals; rich in water.
Prosopis africana	Wood used to make mortars, pestles, and other household utensils. Wood also makes good charcoal, which is used by blacksmiths, jewelers, and launderers.
Acacia albida	Protected by the state and farmers because of its beneficial effect on the environment. Wood used to make mortars, and fruit fed to small ruminants.
Terminalia avicennioides	Fodder for livestock during the rainy season.
Combretum aculeatum	Fruit eaten by man and small ruminants.
Balanites aegyptica	Fodder for small ruminants; rich in protein. Fruit used to prepare millet pate. The nut is eaten boiled. The flower is eaten boiled and mixed with peanut. The sap is used as a perfume.
Commiphora africana	Used as a living fence.
Boscia senegalensis	Animal fodder during the rainy season (on plateau). Grain boiled and eaten. Fruit eaten by children.
Piliostigma reticulatum	Flowers and young leaves eaten. Immature fruit is grilled. Fibers from the bark are used as cord material.
Combretum nigricans	Gum arabic. Preferred fuelwood, along with *Combretum micranthum*, *Combretum glutinosum*, and *Guiera senegalensis*.
2. Species parasitic on cultivated plants:	
Striga gesnerioides	Parasitic on *Vigna unguiculata* (cowpea).
Striga hermonthica	Parasitic on *Pennisetum glaucum* (millet).
3. Species indicating poor soil conditions:	
Borreria radiata	
Fimbristylis hispidulla	
Mitrocarpus scaber	
Indigofera berhautiana	
Ceratotheca sesamoides	
Aristida stipoides	

shows the distribution of lignaceous species within the 5,000 m^2 of each site within the toposequence. Table 4 lists species found within the watershed and used by the local populace.

Annual plants are predominant in the watershed (65% of all species), indicating their adaptation to the arid conditions of this ecological zone. This environment does not favor large trees, and tree and shrub species are dominated by the micro- and nano-phanerophytes and the chamephytes (15, 5, and 6% of all species, respectively). The hemicryptophytes (2% of all species) are well adapted to this environment, occupying a relatively large amount of space.

Species generally found within the Guineo-congolais and the Soudano-Zambesien ecological zones represent 46% and 51% of the plants, respectively.

A total of 119 species of plants were found along the chosen transect: 117 were angiosperms and 2 were bryophytes. Thirty-four families of angiosperms were represented: 4 were monocots (31 species) and 30 were dicots.

The families most represented along the transect were the Fabaceae (39 species), the Poaceae (23 species), the Convolvulaceae (8 species) and the Combrataceae (6 species). The most represented genera were *Acacia* (4 species), *Indigofera* (5 species), *Tephrosia* (4 species), *Combretum* (4 species), and *Ipomea* (4 species).

The generic coefficient (# genera/# species) is 0.73. This ratio indicates an impoverished flora that can be described as degradated to very degradated. The vegetation's evolution has been influenced by low rainfall and a long dry season (8 to 9 months), instability of the soil (especially on the toposequence), and human activities. The vegetation on the toposequence is very different from the original vegetation within this geomorphic unit and climatic regime.

Extent, Cause, and Control of Pronounced Growth Variability Over Short Distances: TAMU-407

Microvariability has been defined as the local and often recurrent variation at the scale of a single field or smaller, variation that is either permanent or persists through at least several cropping cycles. In addition to yield effects, such variability in crop growth exposes the soil surface to the erosive forces of wind and water. Past TropSoils research on short-distance, soil-related crop variability has been summarized in TropSoils Technical Reports for 1985-1986 and 1986-1987.

Areas of poor growth in millet fields are a significant problem in sandy soils of Niger. Millet growth diminishes from very productive spots to completely barren patches of 2 to 10 m. Plants germinate and grow uniformly across the field until two to three weeks after emergence, when plants in the poorly responsive areas begin to show signs of stress and mature very slowly, produce less grain, or die. Problems arising from this plant response result in a decrease in food production, and they confound agricultural research. The problem is linked to short-distance variability of soil properties. A similar problem has been observed in Mali. It has been seriously affecting sorghum research at the Cinzana Agronomic Research Station. Symptoms are described as root necrosis and leaf yellowing at the 3 to 4 leaf stage.

Application of Infrared Video Imagery to Evaluate Crop Spatial Variability in the Sahel

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Seedling establishment and growth of millet in sandy soils of western Niger is highly variable. Very productive regions often give way to nonproductive areas of 2 to 10 m. In this region, millet germinates uniformly across a field. Differences in plant growth occur one to two weeks after emergence. This short-rage variability in seedling establishment and plant growth results in decreased yields and poses a major constraint to field research.

Objectives

This research was conducted 1) to determine the proportion of farmed area that exhibits nonproductive millet growth and 2) to observe the differences in soil chemical and morphological parameters between productive and adjacent nonproductive areas over a wide range of sites in western Niger.

Procedures

Remote sensing was chosen as the most appropriate method for measuring the extent of nonproductive areas. Color infrared videography was used to obtain imagery with resolution sufficient to identify nonproductive regions within farmers' fields. The entire study area (Figure 1) was filmed along transects in three soil-geomorphic zones in western Niger. These zones were the Dallol Bosso (a "fossil" river valley), a river terrace west of the Dallol Bosso, and the plateau and valley system east of the Dallol Bosso. Transects totaled over 300 km in length and were flown at an altitude of 650 m, which gave a pixel resolution of 3.3 m^2. Each image at this altitude encompassed approximately 15.7 ha (Figure 2). Images were recorded after the head stage of the millet crop to obtain as much vegetative canopy cover on the ground as possible. Imagery was processed and classified by taking a ratio of data from three wavelength bands (Figures 3 and 4).

Ground verification was done in areas where imagery had been collected. Productive areas had millet that was at least 1 m tall and showed evidence of grain production. Nonproductive areas had plants that were shorter than 1 m and had produced no grain. Adjacent productive and nonproductive areas were sampled to a depth of 30 cm for morphological observations and laboratory analyses. Morphological observations included surface crusting, eolian deposition and horizonation. Samples were taken from the 0- to 10-cm and 10- to 30-cm depths and analyzed for total exchangeable acidity and Al, available phosphorus, and pH.

Results

Video image analysis shows that an average of 14% of farmers' fields were not producing millet. Values obtained ranged from 2 to 36% with over 50% of the fields having 22% of the field nonproductive. The percentage of nonproductive land was not significantly different between the three geomorphic regions. These values represent percent nonproductive land during a favorable rainfall season in terms of amount and distribution. During years with inadequate rainfall, the percentage of nonproductive land would probably be higher.

Morphological observations indicate that productive areas have thicker surface horizons and fewer surface crusts; they are also located in microtopographic "highs" relative to nonproductive areas (Table 1). Productive areas had an average of 19 cm of topsoil above the argillic horizon, whereas nonproductive areas had an average of 13 cm. Productive areas were, on average, 8 cm higher than adjacent nonproductive areas. Over 60% of all sites evaluated exhibited these microtopographic differences,

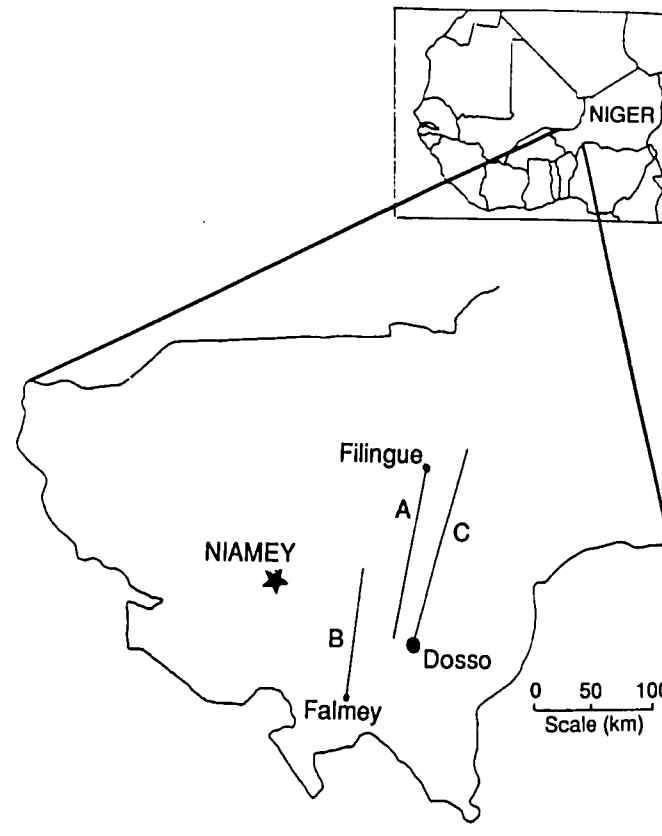

Figure 1. Map of western Niger with flight lines corresponding to transcets of video IR imagery and sampling areas: (a) the Dallol Bosso, (b) river terrace, and (c) plateau and sand valley system.

which are thought to reflect recent redistribution of eolian sands.

Chemical analyses showed significantly higher levels of exchangeable acidity and Al and lower soil pH in nonproductive areas than in associated areas (Table 2). This finding was observed at both the 0- to 10-cm and 10- to 30-cm sampling depth increments. Available P levels were not found to be significantly different between paired sites. Comparisons between sampling depths showed significantly higher exchangeable acidity and Al and lower pH and available P in the lower sampling depth as compared to the upper 10 cm.

Figure 2. A digitized scene from IR imagery of the plateau and valley sand transcet. Dark areas represent fallow fields (straight-edge outlines) or healthy millet growth in cropped fields. Gray tones are sparsely vegetated areas, and white tones are nonproductive soil areas.

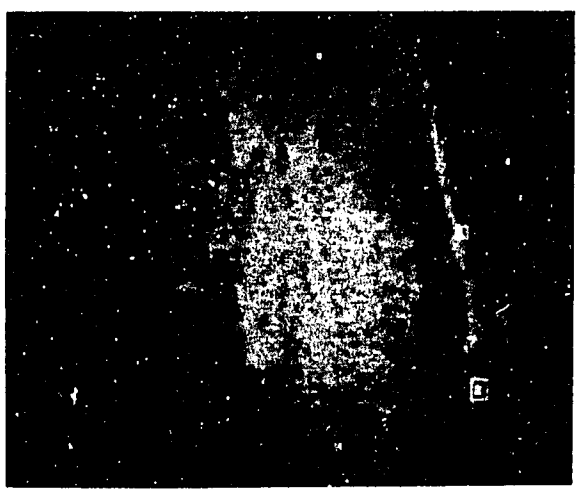

Figure 3. A computer enhancement of the image in Figure 2. Dark areas are vegetated, grayish areas and lighter areas are sparsely vegetated or nonproductive. Areas 1 and 2 are classification training sets for non-productive areas.

Conclusions

This research has shown that spatial variability negatively affects 14% of the sandy millet-production areas in western Niger. These nonproductive areas have thinner surface soils, lower pH levels, higher exchangeable Al and acidity, and are often associated with microtopographic low positions in the field.

Implications

Major implications of this work include the following:

1. Spatial variability negatively affects a significant proportion of the sandy millet-production areas in western Niger.
2. Color infrared videography is a potentially powerful means to document the loci and extent of poorly productive areas.

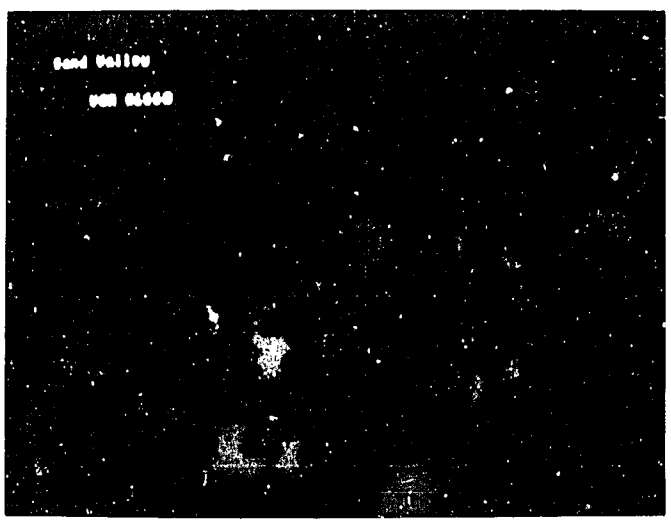

Figure 4. Classified image of Figure 3 illustrating non-productive and sparsely vegetated areas.

Table 1. Summary of morphological characteristics over all transects.

	Productive	Nonproductive
	cm	
Depth to subsoil	19	13
	%	
Sites located in microtopographic high positions	57	0
Sites classified as severely eroded	3	16

3. Thicker surface soils and greater depths to subsoils in productive areas reflect local eolian redistribution of sandy soil material from topographic microlow to microhigh positions.

4. Thicker topsoils in topographic microhighs provide a better growth medium for seedling establishment and root development.

Table 2. Summary of chemical data over all transects.

	Productive*				Nonproductive*			
	(0–10 cm)		(10–30 cm)		(0–10 cm)		(10–30 cm)	
Parameter	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Total acidity (cmol/kg)	0.1	0.1	0.2	0.2	0.3	0.2	0.5	0.3
Exchangeable AL (cmol/kg)	<0.1	<0.1	0.1	0.2	0.1	0.2	0.3	0.3
pH (2:5 H_2O)	6.0	0.4	5.6	0.6	5.6	0.4	5.3	0.4
pH (1*N* HCl)	4.9	0.5	4.4	0.6	4.3	0.5	4.0	0.3
Phosphorus (g P/g)	5.5	3.8	4.1	5.0	5.6	4.0	3.8	4.9

*Comparisons between sampling depths are significantly different for all parameters except available P at the 1% level for both productive and nonproductive sites.

Causes of Poor Sorghum Growth in Sandy Soils of the Cinzana Station, Mali

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In the acid, sandy soils of West Africa's Sahel region, a severe soil variability problem is reducing food production, inhibiting agricultural field research, contributing to environmental degradation, enhancing desertification, and disturbing the balance of pastoral and agrarian agriculture. This problem appears as a marked spatial variability in crop establishment, growth, and yield within a single field. At the Cinzana Agronomic Research Station, Mali (West Africa), it has developed into a special sorghum (*Sorghum bicolor* [L.] Moench) problem in sandy soils. Sorghum seedling emergence is, in general, uniform throughout the field, then, one to two weeks after emergence, the symptoms develop in irregularly distributed areas. The symptoms of poor early growth appear as purpling or yellowing of the leaves and death of the leaf tips. In extreme cases, seedlings become completely brown. The roots show necrotic spots and do not grow below the first 10 or 15 cm of topsoil. Plants in the most severely affected areas eventually die, leaving large areas of the soil surface completely devoid of vegetation.

Objective

The objective of this research was to define the nature of poor early sorghum growth in Grossarenic and Plinthic Paleustalfs of the Cinzana Station.

Procedures

A greenhouse experiment was designed to determine the causes of poor early sorghum growth. Researchers used a combination of soil amendments (lime and rock phosphate) and fertilizers (urea, triple superphosphate (TSP), diammonium phosphate (DAP) and potassium nitrate). Twenty-four treatments were applied to pots of unproductive soils. Three replications were used, and sorghum was grown for 37 days.

Laboratory analyses were performed to determine the effects of treatments on selected soil chemical properties and nutrient concentrations in plant tissue. Exchangeable Al and H, pH, exchangeable basic cations, and Bray-1 extractable P were determined on soil samples. Plant samples were analyzed for N, P, Ca, Mg, Al, Mn, and Fe.

Results

Application of urea (100 mg N/kg of soil) neither inhibited symptoms of poor growth nor resulted in significant dry-matter production (Figure 5). Liming followed by the above N rate had the same result. However, application of P alone or any treatment combination containing P resulted in good sorghum growth and yield (Figure 5).

Amending the soil with Tilemsi RP did not change the soil pH (Figure 6), but increased the concentration of exchangeable Ca. Tilemsi RP also reduced Al + H saturation of the soil (Figure 7) and shoot Al concentration. As expected, it significantly increased shoot P concentration (Figure 8). Liming increased soil pH (Figure 6), soil exchangeable Ca, shoot concentration of N, Ca, and Fe. Lime amendment significantly reduced Al + H saturation (Figure 7) and shoot Al and Mn concentration. Applying N and P (as TSP) had a greater impact on dry matter production (Figure 5), soil pH (Figure 6), soil concentration of exchangeable Ca, and Al + H saturation (Figure 7) than using DAP. Shoot P concentration (Figure 8) was significantly higher when DAP was used.

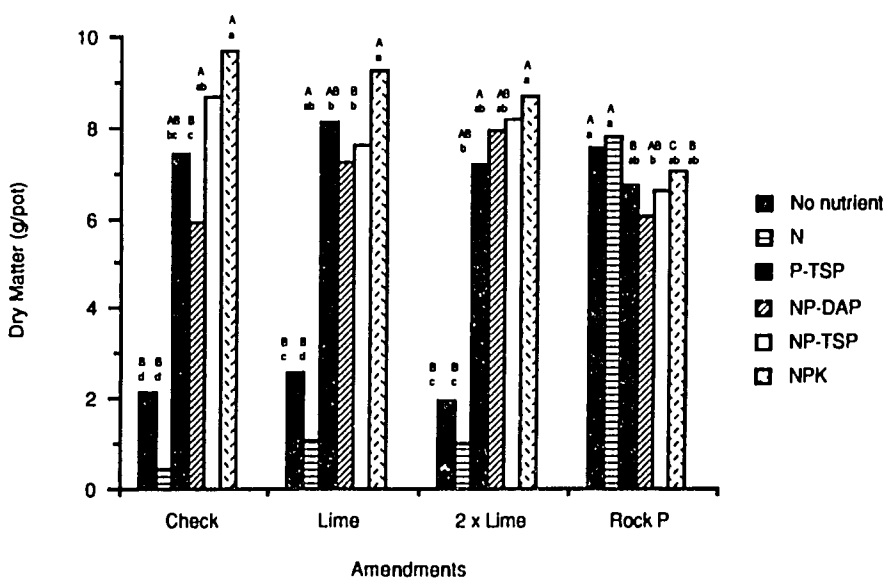

Figure 5. Sorghum dry-matter yield as influenced by lime, rock phosphate, and various nutrient combinations under greenhouse conditions. Interaction means are tested at the P = 0.05 level, using Duncan's new multiple range test as follows: lower-case letters indicate significance of nutrients within each amendment; capital letters indicate significance of amnendments within each nutrient.

Dry matter yield correlated well with Bray-1 P (r = 0.74**). Both exchangeable soil Al (34% Al saturation) and shoot Al concentration had a significant negative impact on dry-matter yield, but neither was strongly correlated with that yield (four values of -0.42** and -0.31**, respectively).

Conclusions

Phosphorus deficiency apears to be one of the major factors limiting sorghum growth and yield in acid, sandy soils of the Cinzana Station. Exchangeable Al, due to its negative and significant impact on dry-matter yield, seems to be a secondary cause of this soil problem.

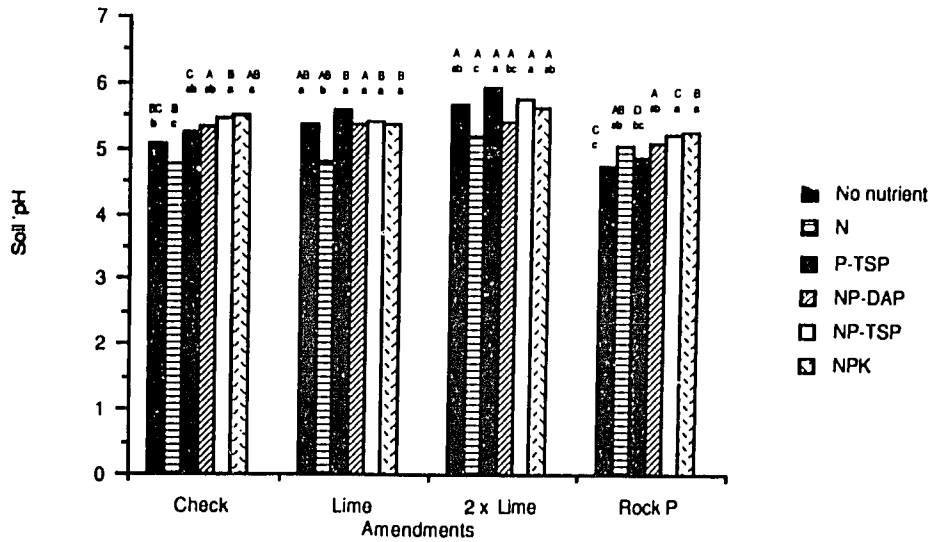

Figure 6. Soil pH as influenced by lime, rock phosphate, and various nutrient combinations under greenhouse conditions. Interaction means are tested at the P = 0.05 level, using Duncan's new multiple range test as follows: lower-case letters indicate significance of nutrients within each amendment; capital letters indicate significance of amnendments within each nutrient.

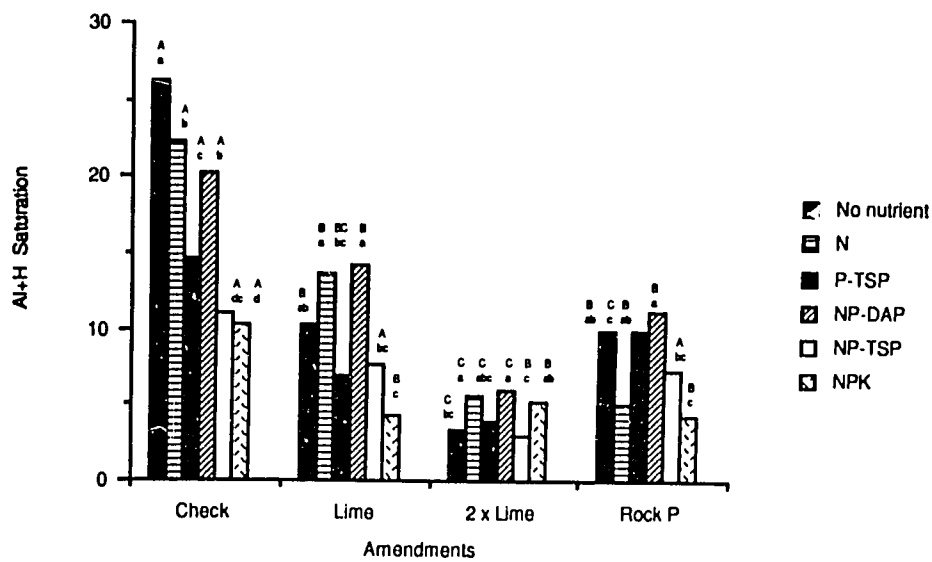

Figure 7. Aluminum + H saturation as influenced by lime, rock phosphate, and various nutrient combinations under greenhouse conditions. Interaction means are tested at the P = 0.05 level, using Duncan's new multiple range test as follows: lower-case letters indicate significance of nutrients within each amendment; capital letters indicate significance of amnendments within each nutrient.

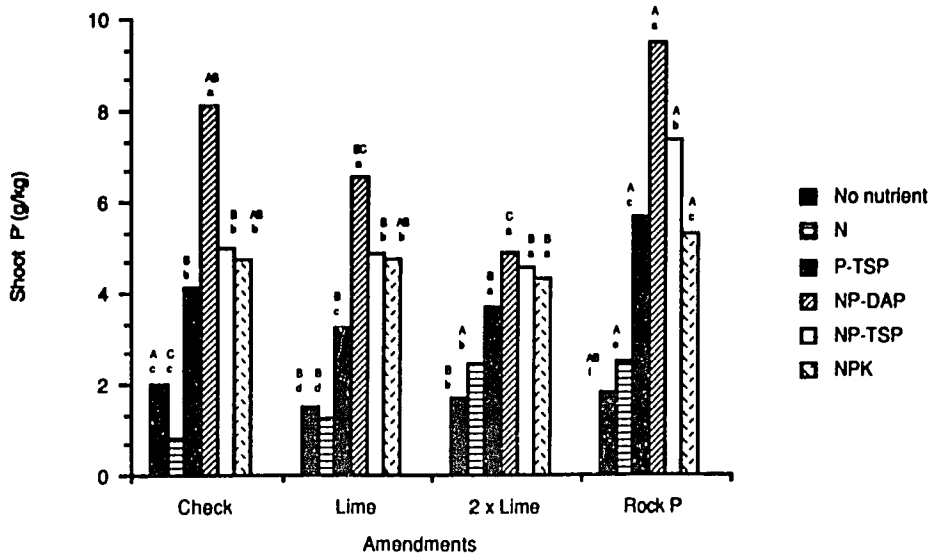

Figure 8. Phosphorus concentration in sorghum shoot (37 days old) as influenced by lime, rock phosphate, and various nutrient combinations under greenhouse conditions. Interaction means are tested at the P = 0.05 level, using Duncan's new multiple range test as follows: lower-case letters indicate significance of nutrients within each amendment; capital letters indicate significance of amnendments within each nutrient.

Variable Soil Fertility in West Africa: Characteristics of Impoverished Soils and Comparison with Fertile Soils

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In previous studies on spatial variability in Niger, soil infertility has been associated with a deficiency of plant-available phosphorus. Before attempting or prescribing a remedy, however, researchers need to understand the phenomenon more fully. We need to know what produces the localized deficiency of phosphorus, what other traits may be associated with it, how consistently the deficiency occurs, and why the depleted regions are distributed as they are. Also, since variable soil fertility is a widespread problem in the Sahel, researchers need to determine whether the same nutrient deficiency occurs wherever the variability is found.

Objective

This study sought to characterize impoverised and fertile soils associated with the phenomenon of short-distance spatial variability in Niger.

Procedures

At the end of the 1986 growing season, eight millet fields displaying substantial variability were chosen for study. These fields were located near eight widely separated villages, all within the Department of Niamey, in western Niger. To be certain that transient causes of variability would be excluded from consideration, we asked farmers in each village to identify sites that never produced well. In the course of locating these sites and interviewing the farmers, we repeatedly heard the word *gangani*, which means "crusted" in the Zarma language . Quite a number of the farmers held forth at length about their *gangani* soils, complaining of their worthlessness and of the difficulty of cultivating a field dotted with them. The Nigerien farmers distinguished the *gangani* problem from the sealing of the surface that results when an abandoned termite mound melts under rain—a phenomenon with which it is often confused by western agronomists. This native understanding of the problem was employed to help limit the focus of the present research. Villagers were asked to show not merely sites that never produced well, but *gangani* sites that never produced well.

At each village but one, a brief history of the field was obtained (at the exception, the proprietor could not be located). Two soil profiles were sampled in each field, one at a *gangani* site, and one at a site that had produced well, as evidenced by the millet stubble from the previous crop. Samples were taken at 5-cm increments, to a depth of 30 cm. At one site, complete profile descriptions to a depth of 160 cm were obtained. Soil colors were determined with the aid of a Munsell color book. Soil pH values were determined by placing 10 g (oven-dry weight) of each sample in a beaker with 10 ml of distilled water, stirring for one minute, allowing the suspension to settle for 30 minutes, and immersing a pH electrode in the supernatant. Texture, structure, and the topography at each site were also noted. Plant-available P was estimated by means of the Bray-1a extraction.

Results

A description of a typical *gangani* profile follows (all colors are for moist soil):

Ap—0 to 1 cm, sand, yellowish red (5YR 5/8), single-grained, structureless, pH about 4.5, clear boundary.

A1—1 to 4 cm, sand, reddish brown (2.5YR 4/4), subangular, blocky structure, pH 4.5, clear boundary.

Bt1—4 to 15 cm, loamy sand, red (2.5YR 4/6), weak, subangular, blocky structure, pH 4.5, gradual boundary.

Bt2—15 to 160+ cm, loamy sand, red (2.5YR 4/8), weak, subangular, blocky structure, pH 4.5.

The Ap horizon is eolian deposition. The Bt1 horizon is distinguished from the Bt2 by slight differences in color and texture, the Bt2 being a little redder and sandier. Ironstone pebbles as large as 15 cm in diameter are strewn about the surface and can be found in the A1 and Bt1 horizons. They cover less than 1% of the surface and account for less than 1% of the volume of these two horizons. The A1 and Bt1 horizons both have light-colored mottles; these are apparently pockets of the Ap horizon material that have been incorporated by termites, mice, or cultivation.

For the sake of comparison, we will describe a productive site profile about six meters away from the previously described *gangani* profile:

Ap—0 to 12 cm, sand, yellowish red (5YR 5/8), single-grained, structureless, contains several very thin and discontinuous organic strata, pH about 5.6, clear boundary.

A1—12 to 25 cm, loamy sand, yellowish red (5YR 4/6), weak crumb structure, clear boundary.

Bt1—25 to 33 cm, loamy sand, dark red (2.5YR 3/6), weak crumb structure, gradual boundary.

Bt2—33 to 70+ cm, loamy sand, red (2.5YR 4/6), weak crumb structure.

The surface elevation at this site is visibly higher, by roughly 25 cm, than the surface at the *gangani* spot. This means that although the ground level undulates slightly, the top of the Bt horizon is almost level.

In all seven cases where it was possible to talk to the proprietor of the field, we affirmed that the *gangani* sites had been barren for as long as they had been farmed. This

varied from a maximum of 17 years, to a minimum of one year.

Surface color and pH values are given in Table 3. Five of the eight surface samples of *gangani* soils had, when dry, Munsell colors of 5YR 5/6 (yellowish red), and one rated 5YR 5/4 (reddish brown). The sample from Guesselbodi had a color of 2.5YR 4/6 (red), and the sample from Kollo had a color of 10YR 7/3 (very pale brown). Samples from the top 5 cm of soil profiles at productive sites rated 5YR 5/8 (yellowish red) or 7.5YR 5/8 (strong brown), except for the sample from Guilheal, which rated 7.5YR 5/4 (brown), and the one from Kollo, which rated 10YR 6/3 (pale brown). In general, *gangani* soils tend to be redder than the productive soils, indicating that pigmentation by iron oxides is more important in the former.

Gangani soil pH values ranged from 4.0 to 5.7 (Table 4), with a mean value of 5.0 and a coefficient of variation (CV) of 12%. Productive soil pH values ranged from 5.5 to 6.6, with a mean of 6.0 and a CV of 7%. Though the ranges overlap, each *gangani* sample was more acid than its productive counterpart from the same field.

All *gangani* surface samples were loamy sands, while the surface samples of productive soils were sands. The *gangani* samples had weak, subangular blocky structure, while the productive samples were essentially structureless. Regions of *gangani* soil occurred an estimated 10 to 15 cm lower on the topography than regions of productive soil. By definition, *gangani* soils bore a hard crust, while the surface of productive soils consisted of loose sand.

Three of the *gangani* samples exhibited distinctive attributes: the sample from Kollo was a much lighter color (very pale brown) than the others; at Tillabery, the afflicted region encompassed an entire field of perhaps five hectares; and at Kona, the ground was liberally strewn with the fragments of broken clay pots.

In sum, we can describe a typical *gangani* soil as follows: 1) Munsell color, when dry, around 5YR 5/6 (yellowish red) or, when moist, around 2.5YR 4/8 (red); 2) pH in a rather wide range from 4.0 to almost 6.0; 3) loamy sand texture; 4) weak, subangular blocky structure; 5) surface 10 to 15 cm lower than that of nearby productive soil; 6) hard crust on surface; and 7) history of low crop productivity. These characteristics that can easily be identified in the field with the help of a Munsell color book, a field pH kit, and the testimony of someone who knows the field. The soil at only one site departs from this set of characteristics to an important degree: the Kollo site exhibits a very light color so different from that of the other samples as to perhaps disqualify it as a *gangani* soil.

Small-scale *gangani* sites (from four square meters to half a hectare) can be found in every field, pasture, and

Table 4. Bray extractable P from eight *gangani* sites and eight productive sites.

Depth	Gangani profiles n = 8	CV	Productive profiles n = 7	CV	Abandoned village site n = 1
cm	mg/kg	%	mg/kg	%	mg/kg
0–5	2.50	52	2.66	28	13.21
5–10	1.68	34	2.71	60	18.42
10–15	1.33	32	2.32	55	18.30
15–20	1.27	27	1.82	53	9.45
20–25	1.20	47	2.09	60	12.97
25–30	1.13	60	2.23	65	8.73

Table 3. Munsell color and pH of surface samples of paired *gangani* and productive soils.

	Munsell color (dry)		ph	
Village	*Gangani*	Productive	*Gangani*	Productive
Guilheal	5YR 5/6	7.5YR 5/4	4.43	5.56
Damari	5YR 5/4	7.5YR 5/8	5.22	6.13
Guesselbodi	2.5YR 4/6	5YR 5/8	4.00	5.4
Baleyara	5YR 5/6	5YR 5/8	5.60	6.10
Kollo	10YR 7/3	10YR 6/3	5.50	5.60
Tillabery	5YR 5/6	7.5YR 5/8	5.72	6.63
Diakinde	5YR 5/6	7.5YR 5/8	4.87	6.31
Kona	5YR 5/6	5YR 5/8	5.05	6.33
Mean			5.05	6.02
Coefficient of variation, %			12	7

tract of forest in the Sahel of western Niger. Larger expanses can also be found. Several 10- or 15-ha areas consisting of nothing but *gangani* soil supported not so much as a blade of grass. Atop the laterite plateau, where the soils are thin and gravelly, one can also find barren patches that appear to bear the seven traits enumerated above; however, further research would need to verify this assertion since the present study did not examine such soils closely.

Values for available P, determined by means of the Bray-1a extraction, are given in Table 4. Values in excess of 20 mg/kg may be considered high; between 7 and 20, medium; between 3 and 7, low; and below 3, very low. By this standard, all the *gangani* profiles and seven of the eight productive profiles have very low levels of available P. The one exception is the productive profile from the field near Guilheal, which gave much higher values for available P at all depths. This site was once a village. The relative fertility of its soil may be attributed to the deposition of bones, ash, and the other detritus of human occupation. The other productive profiles have only marginally more extractable P than the *gangani* profiles. If the Bray-1a extraction is a fair estimate of available P, the crop itself appears to have depleted each of these productive sites of whatever P had been available at the beginning of the season, since the sampling was done at the end of the growing season. Since levels of available P such as these are clearly insufficient to produce another crop, these data imply that either some process is at work that can rejuvenate the supply of available P before the next growing season or that the fertility of the productive locations must decline sharply. Dust borne by the winter wind (the Harmattan), blowing south off the Sahara Desert, appears to have a modestly restorative effect, which is amplified by the traditional practice of abandoning the field for several years between cultivations. However, this practice, known as bush-fallowing, has been all but given up in the vicinity of the study area due to the pressure of population on arable land. Consequently, the fertility status and the amount of vegetation at the productive locations are likely to decrease in succeeding years. Since all these sites were located on slopes, a loss of vegetation could cause further erosion and crusting of what soil remains.

Of particular note are the levels of Bray extractable P for the productive site in the field near Baleyara. This site had been cleared of brush only the previous year (stumps were still visible) yet the soil was already low in available P. This finding demonstrates the insufficiency of traditional bush fallowing.

Conclusion

Gangani soils occur where erosion has carried off the surface horizons, exposing the argillic horizon. Redder hue, heavier texture, more developed structure, lower topographic position, tendency to crust, and more acid reaction—all these characteristize soils of an argillic horizon. *Gangani* soils are invariably barren, but are not always sufficiently acid to mobilize Al in toxic concentrations. This finding suggests that the theory attributing spatially variable fertility to localized Al toxicity may be insufficient. The extremely low levels of Bray-1a P found in *gangani* soils appears to indicate a widespread and severe deficiency. Low levels of plant-available P are not a necessary attribute of an argillic horizon. Nor do they, in any case but one, distinguish the *gangani* soils from adjacent productive areas. Tests for P availability discovered few or no differences in P content between samples from productive and unproductive sites. Researchers concluded that available P must, therefore, be sufficient and supposed that, for unexplained reasons, the test of availability was giving misleadingly low readings. The present study suggests that the productive and unproductive sites may display no differences in levels of plant-available P because samples were taken at the end of the growing season, by which time the crop of millet had depleted the soil of virtually all available P.

Spatial Variability of Soil Chemical Properties in Sandy Soils in Niger

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Variability in crop stands over very short distances (2 to 20 m) is a widespread problem on the sandy soils of Niger and throughout the Sahelian zone of Africa. Variability in stand establishment is already visible when millet seedlings are about three weeks old, and it persists until harvest. Sand blasting, soil crusting, termite activity, high soil temperature, and low soil water content have been proposed as causes of the stand variability. The hypothesis of this work is that soil chemical problems limit early root growth and seedling establishment and make seedlings vulnerable to the harsh physical conditions.

Objective

The objective of this study was to quantify the variability of some soil chemical properties in order to identify those that contribute to the variability in crop yields.

Procedures

Two soils were sampled extensively from newly cleared plots on the International Crops Research Institute for the Semiarid Tropics (ICRISAT) Sahelian Center in Sadore, Niger, 40 km south of the capital of Niamey. Both soils were classified as Psammentic Paleustalfs; however, the Zogoti soil occurs upslope from the Labucheri soil and is redder and shallower. When the profiles were sampled for characterization, three multiple lateral samples were taken to gain an index of pedon variability. The soil characterization work was done at the Institut National de la Recherche Agronomique du Niger (INRAN) Soils Laboratory in Niamey, Niger.

Plots of approximately 1/3 ha in area were mapped on both soils, and the land was cleared by hand with machetes and rakes. Each of these plots was split into 72 subplots (6 x 8 m each), and each subplot was sampled in the center to a 100-cm depth in 20-cm increments. The variability over these 1/3-ha plots will be referred to as *macrovariability*.

On each of these soils, three pits were spaced randomly within the 1/3-ha plots. The pits were 100 cm deep, and soil samples were taken from the pit-face using a grid (100 cm x 100 cm) with grid squares of 400 cm^2 (20 x 20 cm). Thus, each depth increment was replicated five times within a distance of 100 cm. The variability over these 100 cm long pits will be referred to as *microvariability*. Other field measurements included depth to laterite bedrock, relative elevation (Labucheri soil only, using a surveying transit), and depth to very acid subsoil (defined as depth to soil with KCl pH less than 4.0).

The coefficients of variation (CVs) were calculated for each pit and then averaged for an estimated microvariability. The SAS PROC MEANS program was used to determine sample means and CVs. Semivariograms were constructed using a FORTRAN program. The semivariograms on the macroscale were calculated at four angles: 0°, 60°, 90° and 120°. The 0° angle was the east-west, downslope direction. The minimum number of couples for graphing was 20, with the exception of the microscale data, which ranged from only 3 couples at 0.8 m distance to 12 couples at 0.2 m distance. The SAS PROC NLIN program was used to determine the best-fitting asymptotic lines for each semivariogram.

Results

Both Labucheri and Zogoti soils increase in percent clay and decrease in percent sand with depth; however, the Zogoti soil has more clay in the B/A and BT1 horizons, while the Labucheri soil has more clay from the BT2 horizon down. Both soils have argillic horizons and are described as Alfisols. Both decrease in pH just below the soil surface, but the decrease is greater in the Zogoti soils.

Tables 5 and 6 list the CVs for soil characteristics in the Labucheri and Zogoti soils for the triple lateral sampling. Coefficients of variation for total N were high, in general, for both soils. This may be due to very low mean values, which could have caused the CVs to be inflated. Both soils had low CVs for pH (H_2O), pH (KCl), and percent sand; both had moderate CVs for available P and exchangeable Al. On the Labucheri soil, the highest CVs were for exchangeable Mg and percent silt, though exchangeable K, Ca, and Na also had high CVs. Exchangeable K and Na had the highest CVs on the Zogoti soil, though Mg and silt also had high CVs.

The pH, organic matter, exchangeable K, and soil-thickness CVs for these two soils are on the low end of CV ranges found in the literature (Table 7). The exchangeable Ca and Mg CVs are within the range of those reported in the literature.

The microvariance for available P was very high on the soil surface for both the Labucheri and Zogoti soils; it was actually greater than the macrovariance (Table 8). This may be due to the different analytical methods used in the laboratory measurements of P. Ion chromatography (used for microvariability samples) is less sensitive to low levels of P than the colorimetric method (used for macrovariability samples). Consequently, P was measured as zero for all samples below the 0.4-m depth. At 0.2- to 0.4-m, the Labucheri soil registered no P, but the Zogoti soil did have some measurable P at this depth. When the values for P are all zeros, the semivariogram cannot be calculated, hence the missing microscale data on the sem-

Table 5. Coefficients of variation for Labucheri soil characterization data.

Soil property	Horizon						
	Al	A2	B/A	Bt1	Bt2	Bt3	Bt4
	%						
pH (H_2O)	0.8	3.0	3.4	0.8	1.7	1.1	2.1
pH (KCl)	0.6	0.3	0.8	0.9	0.3	0.4	0.3
Ca*	15.7	0.0	0.0	24.7	20.4	36.7	20.0
Mg*	9.1	10.8	34.6	45.8	49.5	0.0	65.5
K*	9.1	10.8	34.6	12.4	15.7	43.3	44.6
Na*	0.0	0.0	0.0	24.7	0.0	0.0	0.0
Acidity*	9.8	8.6	4.4	8.2	7.4	2.2	4.1
Al*	17.8	7.2	7.2	16.2	5.1	12.4	6.9
P**	13.6	0.0	0.0	0.0	14.4	13.3	0.0
Clay	4.9	7.1	6.2	11.1	7.3	7.3	7.7
Silt	28.1	21.3	35.2	37.8	65.7	47.5	39.8
Sand	3.9	0.5	0.3	0.6	1.8	0.9	0.6
C	18.1	12.4	5.4	0.0	63.0	10.2	13.3
OM	18.3	14.4	6.3	0.0	64.1	6.0	15.1
N	102.3	86.6	86.6	0.0	100.0	83.3	44.1

*Exchangeable
**Extractable

Table 6. Coefficients of variation for Zogoti soil characterization data.

Soil property	Horizon						
	Al	A2	B/A	Bt1	Bt2	Bt3	Bt4
	%						
pH (H_2O)	30.4	2.9	2.2	3.6	1.3	1.2	1.1
pH (KCl)	1.8	1.7	0.6	3.5	0.8	0.9	1.2
Ca*	16.7	13.3	14.3	24.1	16.7	19.9	19.9
Mg*	33.3	24.7	13.3	41.7	33.3	78.7	34.6
K*	90.1	81.0	44.6	21.7	61.5	101.3	36.7
Na*	22.4	37.5	52.8	74.3	82.1	83.4	80.4
Acidity*	36.6	12.0	11.7	40.7	4.0	7.7	8.7
Al*	15.7	10.4	10.2	42.1	0.0	9.2	24.8
P**	6.4	25.8	15.1	13.3	0.0	0.0	13.3
Clay	8.0	7.1	10.5	4.5	7.6	6.4	2.7
Silt	19.7	43.3	27.8	48.0	38.0	31.3	23.8
Sand	0.6	1.5	1.6	0.9	2.1	0.6	1.4
C	10.8	22.9	201.	11.2	14.3	28.6	19.9
OM	10.5	23.3	20.8	10.6	16.7	28.5	22.9
N	134.9	44.8	28.2	54.6	125.6	155.0	119.65

*Exchangeable
**Extractable

ivariograms at the greater depths. For P, the nugget variances are difficult to determine since, without the microscale data, the pattern near the origin cannot be determined. Nevertheless, nugget variance was high for available P in several cases, especially at the soil surface, where 90% or more of the variation was random.

Table 7. Comparison of Labucheri and Zogoti CVs to those in the literature for mapping units within a soil series.

Soil property	Literature[§]	Labucheri	Zogoti
	%		
Soil pH	5–15	2–3	3–6
Organic matter	20–61	20	23
Exchangeable Ca	30–73	36–77	32–75
Exchangeable K	31–121	74–108	84–114
Depth to acid subsoil		60	80
Soil thickness	25–58		
Depth to laterite		8	21

[§] Literature values taken from: Wilding, L. P. 1988. Improving our understanding of the composition of the soil landscape. *In* Proc. of the International Interactive Workshop on Soil Resources: Their Inventory, Analysis and Interpretation for Use in the 1990s, March 22–24, 1988. Minneapolis, MN. pp. 13–39.

For the P semivariogram, the sills were a satisfactory estimate of the macrovariance in all cases except the soil surface on both soils. The Zogoti soil had higher macrovariance and sill values than the Labucheri soil from 0.2- to 0.8-m deep. On the soil surface, the Labucheri soil had greater microvariance than the Zogoti soil. The ranges for these soils are very similar, except that the Labucheri soil had a greater range at the 0.2- to 0.4-m depth, and the Zogoti soil had a much greater range at the 0.8- to 1.0-m depth.

The Labucheri soil had lower pH, lower cation-exchange capacity, less organic matter, and less N than the Zogoti soil, though the Labucheri had slightly greater available P levels. In the soil characterization data, soil pH and percent sand had the lowest CVs for both soils. Exchangeable Mg and percent silt had the highest CVs on the Labucheri soil, and exchangeable K and Na had the highest CVs on the Zogoti soil.

The KCl pH was least variable for both soils on the macroscale and the microscale. Depth to acid subsoil was more variable than indicated in the literature (Table 7); its variability is on the same scale as the factors mentioned above. Acid subsoil depth may be an important factor in understanding limitations to root growth and the resulting stand variability. If rooting depth varies in these low-fertility soils, then aboveground plant growth will also vary. Magnesium, Ca, Al, depth to acid subsoil, and P are the most variable soil chemical properties, and may, therefore, be the ones most closely related to uneven stand establishment and crop growth.

Table 8. Critical values from semivariograms for available soil P for the Labucheri and Zogoti soils.

Depth	Range	Sill	Variance: Micro	Variance: Macro	Variance: Nugget	Random variation
	m	m	%			
			Labucheri			
0.0–0.2	2262	2.00	3.568	1.067	1.808	90
0.2–0.4	177	0.611	—	0.602	0.560	92
0.4–0.6	15	0.560	—	0.530	0.070	12
0.6–0.8	9	0.337	—	0.358	0.000	0
0.8–1.0	24	0.292	—	0.267	0.050	17
			Zogoti			
0.0–0.2	2078	0.864	1.856	0.547	0.795	92
0.2–0.4	22	1.018	0.338	0.935	0.365	36
0.4–0.6	15	0.700	—	0.651	0.050	7
0.6–0.8	24	0.480	—	0.492	0.166	35
0.8–1.0	1454	0.257	—	0.234	0.246	96

Sorghum Response to Phosphorus in Sandy Soils of the Cinzana Station, Mali

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Phosphorus was found to be highly correlated with poor early sorghum (*Sorghum bicolor* [L.] Moench) growth in Grossarenic and Plinthic Paleustalfs on the Cinzana Station. Symptoms are root necrosis and leaf yellowing at the three to four leaf stage. However, no study has been conducted to determine inputs necessary to suppress symptoms of poor growth and achieve optimum crop growth and yield. This was a preliminary study upon which to base P rates for field research on the response of sorghum to applied P.

Objectives

The objective of this study was to establish a response curve to P in Grossarenic and Plinthic Paleustalfs of the Cinzana Station.

Procedures

A greenhouse experiment was designed to establish a response curve to P, using limed and unlimed unproductive soils. Ten rates of P and three replications were used. A mineral supplement (N and K) was added to each P rate, and sorghum was grown for 31 days.

Laboratory analyses were performed to determine the effects of treatments on selected soil chemical properties and nutrient concentrations in plant tissue. Exchangeable Al and H, pH, and Bray-1 extractable P were measured on soil samples. Plant samples were analyzed for N, P, Ca, Mg, Al, Mn, and Fe.

Results

Symptoms of poor growth were observed only in treatment combinations containing no P (combinations of lime levels with N, NK, and the 0 rate of P). Application of P at a rate as low as 2.5 mg/kg not only prevented symptoms of poor growth, but also increased dry matter significantly. Increasing the rate of P beyond 15 mg/kg did not result in a significant increase in dry-matter production (Figure 9). A cubic model best described dry-matter yield as influenced by P rates in both unlimed and limed soils. The regression equations are as follows:

Unlimed:

$$y = 1.17 + 0.36P - 0.0006P^2 + 0.0003P^3 \; ; \; r^2 = 0.8411$$

Limed:

$$y = 2.13 = 0.33P - 0.007P^2 = 0.00004P^3 \; ; \; r^2 = 0.7092$$

Liming significantly enhanced the effects of applied P on dry-matter yield only at a rate of 5 mg P/kg (Figure 9). Despite earlier data (100 mg P/kg), liming tended to decrease the effects of applied P at rates higher than 20 mg P/kg. Lime application significantly increased soil pH and shoot concentration of N, P, and Ca (Tables 9 and 10). Liming significantly reduced exchangeable soil acidity and shoot concentrations of Al and Mn.

Bray-1 P significantly increased with each increment of applied P (Table 11). Soil pH and exchangeable acidity were significantly influenced by the different P rates (Table 11). The rates of applied P had a significant impact

Table 9. Selected soil chemical properties as influenced by the main effect of lime in a lime x P rates (2 x 10) factorial experiment conducted under greenhouse conditions.

Treatment	Dry matter	pH (water, 1:2)	Bray-1 P	Exchangeable acidity
	g/pot	cmolc/kg	g/g	cmolc/kg
Check	4.15	5.04 b[§]	18.68 a	0.20
Liming	4.56	5.46 a	19.36 a	0.07
Interaction[¶]	S	NS	NS	S
CV (%)	16.86	4.98	11.46	36.33
Bulk sample		5.10	5.24	0.40

[§] Means followed by the same letter are not significantly different at P = 0.05, using Duncan's new multiple range test.
[¶] Lime x P rates.
S, NS: significant and nonsignificant interactions, respectively, at 0.05 level of significance.

on shoot nutrient concentration. With increasing rates of P application, shoot concentrations of N, P, Ca, and Mn were increased, while shoot Al concentration was reduced (Table 12).

Conclusions

An application rate of 15 mg P/kg of soil in a greenhouse study appears to provide adequate P for optimum sorghum growth in Grossarenic and Plinthic Paleustalfs of the Cinzana Station. This rate is slightly higher than the recommended economic rate of 20 kg P/ha for sorghum and millet (*Pennisetum typhoides*) in most soils of Mali.

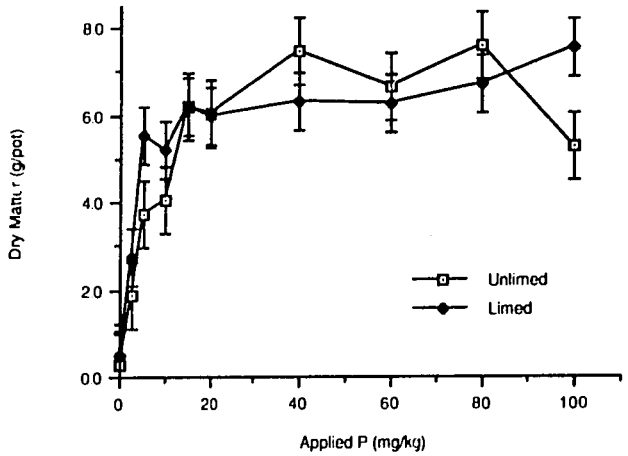

Figure 9. Sorghum dry-matter yield as influenced by lime, P rates, and a mineral supplement (N and K).

Table 10. Sorghum shoot (31 days old) mineral composition as influenced by the main effect of lime in a lime x P rates (2 x 10) factorial experiment conducted under greenhouse conditions.

Treatment	Dry matter	Selected Nutrients					
		N	P	Ca	Al	Mn	Fe
	g/pot	g/kg			mg/kg		
Check	4.15	32.50 b[§]	2.51	4.55	523 a	429	327 a
Liming	4.56	33.66 a	2.74	5.10	466 b	151	333 a
Interaction[¶]	S	NS	S	S	NS	S	NS
CV (%)	17	7	8	10	10	13	27

[§] Means followed by the same letter are not significantly different at P = 0.05, using Duncan's new multiple range test.

[¶] Lime x P rates.

S, NS: significant and nonsignificant interactions, respectively, at 0.05 level of significance.

Table 11. Selected soil chemical properties as influenced by the main effect of P rates in a lime x P rates (2 x 10) factorial experiment under greenhouse conditions.

NK§ + P	Dry matter	pH (water, 1:2)	Bray-1 P	Exchangeable acidity
mg P/kg	g/pot		ug/g	$cmol_c/kg$
0	0.85	5.11 cde	2.99 h*	0.20
N + 0	0.44	4.97 e	4.09 h	0.22
NK + 0	0.40	4.96 e	4.13 h	0.17
NK + 2.5	2.29	5.06 cde	4.48 h	0.16
NK + 5	4.63	5.03 de	5.23 h	0.15
NK + 10	4.62	5.34 abcd	7.97 g	0.09
NK + 15	6.20	5.25 bcde	11.60 f	0.13
NK + 20	6.02	5.38 abc	14.72 e	0.13
NK + 40	6.88	5.29 abcde	24.86 d	0.14
NK + 60	6.43	5.50 ab	37.59 c	0.10
NK + 80	7.13	5.54 ab	49.07 b	0.10
NK + 100	6.39	5.60 a	61.48 a	0.08
Interaction¶	S	NS	NS	S
CV (%)	16.68	4.98	11.46	36.33
Bulk sample		5.[illegible]0	5.24	0.40

§N was applied at a rate of 100 mg/kg and K at 50 mg/kg; *Means followed by the same letter are not significantly different at P = 0.05, using Duncan's new multiple range test; ¶Lime x P rates; S, NS = significant and nonsignificant interactions, respectively, at 0.05 level of signifcance.

Table 12. Sorghum shoot (31 days old) mineral composition as influenced by the main effect of P rates in a lime x P rates (2 x 10) factorial experiment conducted under greenhouse conditions.

Treatment§	Dry matter	Selected nutrients					
		N	P	Ca	Al	Mn	Fe
	g/pot	g/kg			mg/kg		
0		28.22 e	1.75	5.86	552 ab	151	340 a
N + 0		30.04 de	1.72	5.36	581 a*	191	298 a
NK + 0		28.02 e	0.81	4.13	580 a	232	273 a
NK + 2.5		33.45 bc	1.70	4.34	550 ab	407	309 a
NK + 5		32.05 cd	1.80	4.60	524 abc	363	303 a
NK + 10		30.48 de	2.14	4.60	509 bcd	376	301 a
NK + 15		33.89 bc	2.13	4.65	490 bcd	294	376 a
NK + 20		34.08 bc	2.29	4.78	482 dc	251	351 a
NK + 40		35.96 ab	3.04	4.91	492 bcd	266	395 a
NK + 60		37.17 a	3.99	4.96	458 d	321	356 a
NK + 80		36.31 ab	4.71	4.93	388 e	305	284
NK + 100		37.29 a	5.41	4.76	342 e	326	373 a
Interaction¶	S	NS	S	S	NS S	NS	
CV (%)	17	7	8	10	10 13	27	

§N was applied at a rate of 100 mg/kg and K at 50 mg/kg; *Means followed by the same letter are not significantly different at P = 0.05, using Duncan's new multiple range test; ¶Lime x P rates; S, NS = significant and nonsignificant interactions, respectively, at 0.05 level of signifcance.

Organic-Matter Dynamics and Nutrient Cycling in Tropical Agrosystems: TAMU-410

Poor soil nutrient reserve is among the major constraints limiting crop and livestock production in the drier regions of sub-Saharan West Africa. Although the importance of organic matter in supplying and conserving plant nutrients in the region's predominantly sandy, kaolinitic soils is widely recognized, quantitative data on the gain and loss of nutrients from organic sources in tropical agroecosystems are scarce.

Much experimental evidence has shown that on well-drained, sandy soils in the semiarid and subhumid tropics, crop residue mulch and minimum tillage can improve soil productivity and sustain crop yield for a longer period of time without returning land to bush fallow. However, in the semiarid region of Africa, traditional farming practices generally remove the bulk of the crop residues (i.e., sorghum, millet, maize, and cowpea) from the field after each harvest. Crop residues are used for fodder, fuel, and fence materials in the farm compound. Moreover, cowpea stover is often sold for livestock feed during the dry season. Such practices eventually deplete soil nutrient reserves and prevent the land from regenerating its natural vegetative cover when it is returned to the fallow phase.

Improving crop and fodder yields by adopting commercial production systems that use high-yielding cultivars and chemical inputs is generally regarded as uneconomical for the foreseeable future. Research aimed at developing new farming systems to include low-cost nutrient-management practices are needed to sustain optimum crop yield while conserving the soil resource base. To be successful, we need to better understand the processes and mechanisms that control the decomposition and turnover of organic matter. Nutrient cycling in tropical environments and the role of cropping systems, fallow vegetation, soil fauna, and microbial biomass as they affect cycling of nutrients, modification of soil properties, and the supply of nutrients for plant growth also require further investigation.

This project, which has not yet started, will focus on a comparative study of organic-matter dynamics and nutrient-cycling budgets in selected agroecosystems consisting of cereals and annual, perennial, and tree legumes in the cropping systems. Nutrient-cycling studies should improve our understanding of how agroecosystems operate as a unit. Such knowledge is essential for the development of sustainable and productive agricultural systems in the tropics.

Decomposition of Legumes During the Rainy Season of the Semiarid Climate of Niger (proposal)

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Poor soil fertility is a major constraint to increased food production in large areas of the Sahel. The soils in the region are predominantly sandy, have low water and nutrient-retention capacities, and are very low in organic matter. An intercropped green manure will temporarily increase the soil's organic matter and improve its physical, chemical, and biological structure. It is hypothesized that legumes intercropped with millet during the first part of the growing season will not significantly compete for water with millet, and that decomposition of incorporated legumes is sufficiently rapid to contribute to millet nutrition.

Objectives

The specific objectives of this study are as follows 1) to evaluate various legumes' contributions to millet nutrition as they decompose; 2) to quantify the effect of legumes intercropped during the first part of the growing season on available water for millet; 3) to estimate decomposition rates of soil organic matter and added plant material by release of inorganic N and carbon dioxide (CO_2); 4) to understand transformations and movement of released N; and 5) to quantify the effect of added plant material on the decomposition of native soil organic matter.

Procedures

A field experiment will be conducted in Niger, West Africa. Local millet, *Pennisetum glaucum* (L.), will be grown. Legumes will be grown as intercrop for six weeks followed by incorporation toward the millet rows. Legumes will include one commonly used in the area (cowpea), a native wild legume well adapted to the area but not used for production, and a legume cultivated in other semiarid areas. The following treatments will also be established: millet monoculture, millet in intercrop with cowpea grown to maturity, legume only, and bare soil. P fertilizer will be a second consideration in this study.

Decomposition of organic matter and incorporated legumes will be monitored by release of inorganic N and evolution of CO_2. These parameters will be related to soil temperature, soil water content, and stage of decomposition. The static chamber method and alkali absorption will be used to measure CO_2 evolution from soil and decomposing legumes. Cumulative CO_2 evolution for each treatment will be compared, and the CO_2 released from decomposing legumes estimated by difference. Any priming effect of added fresh organic material on soil organic-matter decomposition will be indicated in a prior lab experiment.

Under controlled conditions experiments will be performed with the same legumes used in the field study. Legume N will be labeled by application of $^{15}NH_4{}^{15}NO_3$. After soil organic matter and legume tops and roots decompose, the release of CO_2 and of total and labeled inorganic N will be maintained for 90 days.

Additional studies under controlled conditions may include 1) screening wild legumes for N content and growth rate during the first six weeks; 2) examining the effect of soil water content and temperature on C and N released from decomposing legumes; and 3) examining the effect of incorporated legumes and stage of decomposition on the soil's water-retention capacity.

2.

Sustainable Agriculture

Soil Acidity and Infertility: UH-1

For resource-poor farmers, lime is expensive and difficult to incorporate into the subsoil, where it is needed to detoxify aluminum. Without lime, only a limited number of acid-tolerant crops of low nutritional value can be grown. With lime, farmers can choose from a wider variety of marketable crops, minimize yield losses from drought, obtain higher use efficiency of N, P, and K fertilizers and pest control measures, produce the desired quantity of commodities on a smaller area, and extend the length of the growing season by increasing water-use efficiency.

The precise cost-effectiveness of lime application is not known because 1) the residual effect and therefore the amortization of costs over several years cannot be quantified for sound economic analysis, 2) the optimum depth of lime incorporation that depends on the amount and distribution of rainfall cannot yet be readily determined, 3) the rate of lime leaching is not yet predictable, and 4) the role of organic matter as a substitute for lime is not known. These knowledge gaps prevent the large knowledge base on liming from being used to assess the economic feasibility of liming and fertilizer use.

Diagnosing and Correcting Soil Acidity and Infertility

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Objectives

The objectives of this study were 1) to measure the long-term residual effect of lime, phosphorus, and organic matter on crop performance and the economics of production; 2) to identify the optimum depth of lime and organic matter incorporation with different water retention characteristics under dry- and wet-season farming; 3) to collect lime-leaching data to develop transport equations that will predict movement of lime in the rhizosphere.

Procedure

Lime was incorporated into the subsoil at rates of one or two tons per hectare per 10-cm depth to varying depths. The treatments were:

L0D0: no lime
L1D10: 1 ton lime/ha/10-cm depth to a depth of 10 cm
L1D20: 1 ton lime/ha/10-cm depth to a depth of 20 cm
L1D30: 1 ton lime/ha/10-cm depth to a depth of 30 cm
L1D40: 1 ton lime/ha/10-cm depth to a depth of 40 cm
L1D50: 1 ton lime/ha/10-cm depth to a depth of 50 cm
L2D10: 2 tons lime/ha/10-cm depth to a depth of 10 cm
L2D20: 2 tons lime/ha/10-cm depth to a depth of 20 cm
L2D30: 2 tons lime/ha/10-cm depth to a depth of 30 cm
L2D40: 2 tons lime/ha/10-cm depth to a depth of 40 cm
L2D50: 2 tons lime/ha/10-cm depth to a depth of 50 cm

The soil in each plot was removed in 10-cm depth increments to a depth of 40 cm and placed on plastic sheets. The 40- to 50-cm layer was tilled in place, and the prescribed amount of lime was incorporated in it by thorough mixing. Thereafter, successive layers were returned to their original positions one by one, levelled, and limed. All plots were excavated to 40 cm to eliminate the "tillage" effect on the experimental results. The treatments were replicated three times in a randomized complete-block design. After the liming treatment was completed, all treatments were fertilized with 222 kg urea/ha to give 100 kg N/ha, 150 kg TSP/ha, and 50 kg KCl/ha.

Three successful maize crops were harvested from these plots. One additional crop was destroyed by feral pigs.

The chemisty of the soil prior to liming was as follows:

Depth	pH	Al	Ca	Mg	K	Al sat.
(cm)		———	(cmol/kg)	———		%
0–10	3.77	3.28	0.71	0.36	0.08	74
10–20	3.76	3.48	0.58	0.25	0.08	79
20–30	3.74	3.78	0.78	0.31	0.06	77
30–40	3.69	3.38	0.49	0.19	0.04	82
40–50	3.72	3.30	0.50	0.20	0.04	82
50–60	3.86	3.13	0.50	0.19	0.07	80

Results

Top Growth

Grain yield and total biomass for three harvestable crops are shown in Table 1. The results clearly show that deep incorporation of lime improves crop performance. However, it is not clear whether improvement is due to the amount of lime applied or to the depth of application. For example, what would the results be if 5 tons of lime were incorporated to a depth of only 10 cm and the result compared with that of lime distributed to a depth of 50 cm? Data in an earlier experiment in which varying rates of lime were surface applied showed a potential grain yield of 4.5 tons per hectare from 5 tons per hectare lime applied to the surface 10 cm. The same amount of lime incorporated to a depth of 50 cm in the present experiment yielded 5.83 tons of grain per hectare. In fact, 3 tons of lime incorporated to a depth of 30 cm produced 5.43 tons of grain per hectare.

Root Growth

Selected treatments were sampled for root distribution at full crop growth. Data are presented in Table 2. Data show that rooting depth increased with greater depth of lime incorporation. Root zone depth for no-lime treatment was limited to 20 to 30 cm, whereas roots grew to 60 cm where liming depth was 50 cm. Most of the roots (73 to 95%) grew in the top 10 cm of the soil. However, the fraction of the total root mass growing in the subsoil (that growing below the 10-cm depth) increased as the liming depth increased. For example, subsoil root growth for the no-lime plot accounted for only 5% of the total root mass. Compared to this, subsoil root growth for the L2D30 treatment was 27% of the total root mass. Lime also affected rooting density in the subsoil. At any given depth in the subsoil, root density increased with an increase in the amount of lime.

Total root mass does not appear to be as important as root distribution. Root mass in the topsoil for the no-lime treatment was nearly as high as that for the treatment where lime had been incorporated to 50-cm depth. However, biomasss yield for the no-lime treatment was

only 33% of that for the latter. The subsoil root growth in the two cases was quite different, however. For the no-lime treatment, only 5% of the total root mass grew in the subsoil and was limited to an effective depth of 20 cm. In the case of the 50-cm liming depth, 25% of the total root mass grew in the subsoil and reached a depth of 60 cm. These data clearly demonstrate the importance of subsoil root growth for plant production. The relationship of biomass production to root growth is illustrated in Figures 1a and 1b. Maize biomass was clearly related to subsoil root growth. No relationship seemed to exist between maize biomass and root growth in the topsoil.

Soil Water

Soil water status was measured as a function of lime and depth for selected treatments. A neutron probe was used to measure soil water content, and tensiometers were used to monitor soil water pressure. For the purpose of this report, only the soil water pressure data are presented to elucidate the effects of deep liming on water availability. Temporal patterns of soil water pressure for L0D0, L2D20, and L2D50 treatments are presented in Figures 2, 3, and 4. Figure 2 shows the patterns at 22.5-cm depth. Data show that soil water pressures for the L2D50 treatment were highly negative compared to those for the L0D0 treatment.

Table 1. Effect of deep liming on corn grain and biomass yields in a Sitiung Ultisol (variable rate and depth).

Treatment	Crop I Grain	Crop I Biomass	Crop II Grain	Crop II Biomass	Crop III Grain	Crop III Biomass
	Yield kg/ha					
L0D0	1911	4332	575	1978	1054	3756
L1D10	3241	7407	1633	4349	2824	7757
L1D20	4745	11655	2736	7238	4523	10171
L1D30	5426	12973	2968	7549	5172	12905
L1D40	5400	13002	3361	8057	5506	11901
L1D50	5830	15064	3896	8989	5507	12612
L2D10	4415	10802	2523	6472	4169	9650
L2D20	4682	10550	3024	8751	5357	12267
L2D30	5254	12468	3186	7795	5383	12252
L2D40	5610	13180	3778	9902	6326	14651
L2D50	5488	13195	4577	10703	6136	14472

Table 2. Effect of deep application of lime on corn root and top growth in a Sitiung Ultisol.

Depth	L0D0	L1D10	L2D10	L1D30	L2D30	L1D50	L2D50
	Treatment						
(cm)	Root mass (g/l)						
0–10A	10.14	7.87	6.20	4.92	8.53	6.82	7.95
0–10F	8.89	9.81	10.68	8.34	9.73	11.37	12.91
0–10T	19.03	17.68	16.88	13.31	18.26	18.19	20.86
10–20	0.93	1.62	2.26	1.85	3.91	2.90	3.48
20–30	0.09	0.15	0.24	0.90	1.84	1.63	1.95
30–40	0.00	0.05	0.03	0.23	0.85	0.60	1.01
40–50	0.00	0.00	0.00	0.02	0.04	0.22	0.30
50–60	0.00	0.00	0.00	0.00	0.00	0.06	0.10
60–70	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	kg/ha						
Biomass	4,332	7,407	10,802	12,973	12,468	15,064	13,195
Grain	1,911	3,241	4,415	5,426	5,254	5,830	5,488

A: anchor roots.
F: fine roots.
T: total.

Data indicate that roots under the L2D50 treatment were extracting water much more rapidly. Pressures for the L2D20 treatment were somewhat less negative than those for the L2D50 treatment, but were significantly more negative than those for the L0D0 treatment. Data also indicate that during the early stages of crop growth, pressure patterns for the three treatments were similar.

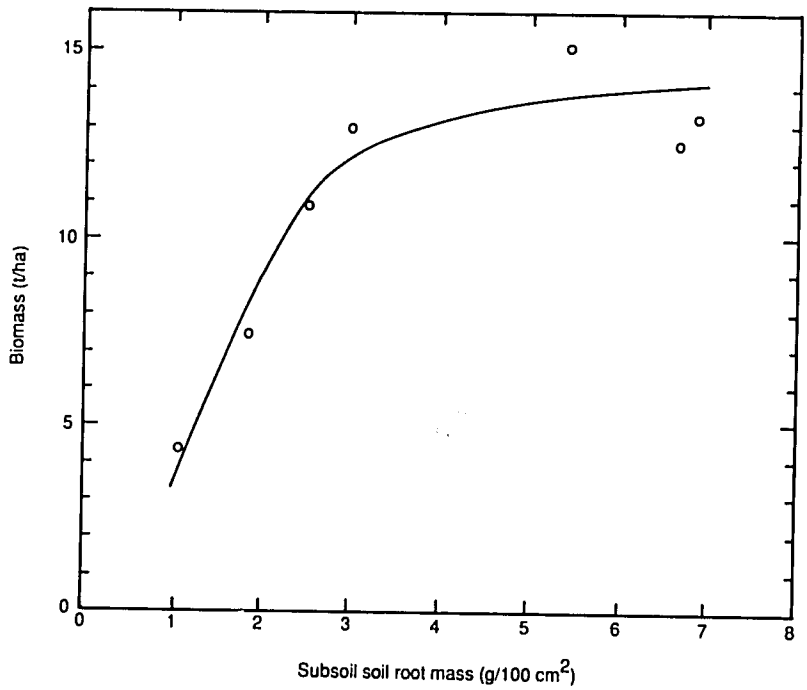

Figure 1a. Corn biomass as a function of subsoil root growth.

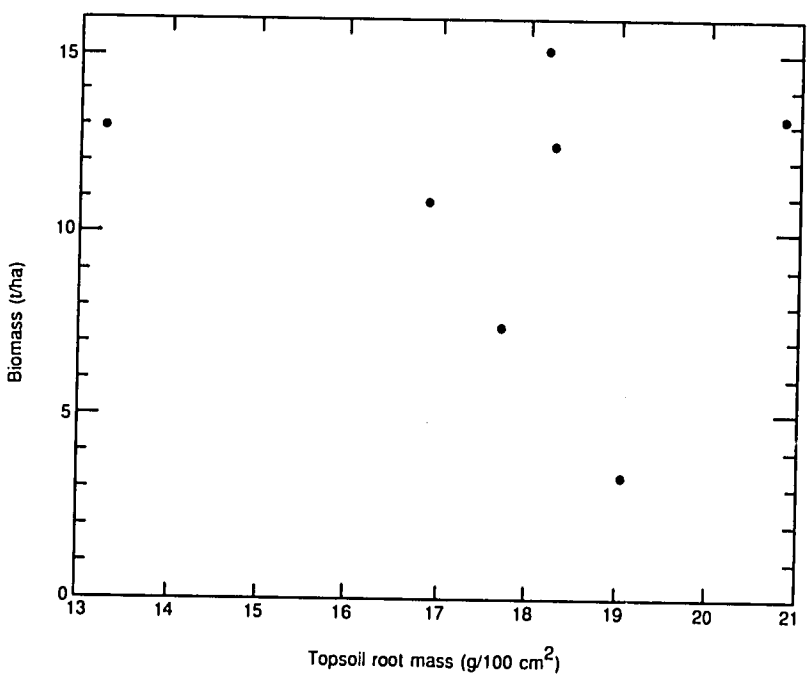

Figure 1b. Corn biomass as a function of topsoil root growth.

Sharp differences began to appear when the rooting patterns changed and differences in growth caused differential evapotranspiration demand. Pressure patterns also fluctuated with the rainfall. Rainfall data are shown as inverted bars at the top of Figure 2.

At 37.5-cm depth, pressures for the L2D50 treatment were quite negative (Figure 3). However, those for the L0D0 and L2D20 treatments were much less negative and quite similar in magnitude. These patterns seem to be related to liming depth. Although the L2D20 treatment had reasonably good plant growth, there was no added lime at 37.5-cm depth under this treatment. It seems, therefore, that liming to 20-cm depth did not influence root growth at the 37.5-cm depth. The L2D50 treatment, on the other hand, had lime distributed to 50-cm depth. More roots grew and, hence, there was more water-extraction activity at 37.5-cm depth. Pressure patterns at 52.5-cm depth (Figure 4) are quite similar to those at 37.5-cm depth, except that absolute values of pressures are smaller. Here again, the presence of lime at 50-cm depth helped roots to grow in the vicinity of 52.5-cm depth. Presence of roots at 50-cm resulted in increased extraction of water, which is quite clearly reflected in the pressure patterns.

Differences in the temporal patterns of soil water pressure at various depths, for the three liming treatments, are consistent with the root distributions presented in Table 2.

Soil Calcium

Calcium content increased at all soil depths where lime was applied. Soil distribution data of calcium, three weeks after application of lime, are shown in Figure 5. The distribution, however, was quite uneven. The treatment without lime showed very low values of calcium and a smooth distribution with almost no calcium below 20-cm. The treatment where 1 t/ha lime per 10-cm depth was supposed to have been applied to a depth of 50-cm showed increases in calcium content only up to 35-cm depth. The distributions indicate problems with the method of incorporation. Most likely, lime was not completely mixed.

Distribution of Ca after the first harvest of maize, 15 weeks after lime application,

is shown in Figure 6. The unevenness in Ca distribution still existed, although sharp bulges in the distribution decreased somewhat. There was a slight indication that there may have been some redistribution of calcium within the zone treated with lime. However, the fact that shapes of the distribution curves did not change in 15 weeks suggests that movement of lime was negligible.

Conclusions

Results from this study indicate that deep liming has a significant positive effect on maize production in Sitiung soils. Deep liming promotes deep rooting and makes available a larger volume of soil for water and nutrient absorption. As a result, plants continue to function normally even during rainless periods of several days. Both water- and nutrient-use efficiencies are increased. A shallow-rooted plant, on the other hand, cannot utilize water and nutrients stored in the subsoil. The effect is not temporary. Since movement of lime in the soil is negligible, the residual effect may last several years. Although deep liming is a labor-intensive operation, it appears to be a worthwhile investment.

Implications

Owing to its relative immobility and long residual effect, lime may be looked upon as a capital cost by agricultural development agencies. Lime acts as an inexpensive substitute for an irrigation system. This research demonstrates that the main benefit of liming is to increase water availability to crops. Deep incorporation of lime not only results in yield increases but contributes to yield stability by enabling a crop to weather drought.

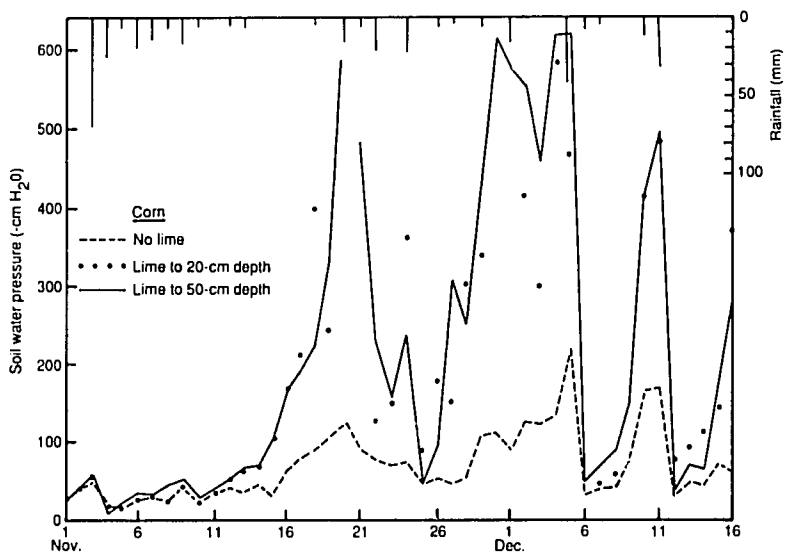

Figure 2. Soil water pressure at 22.5-cm depth as a function of time.

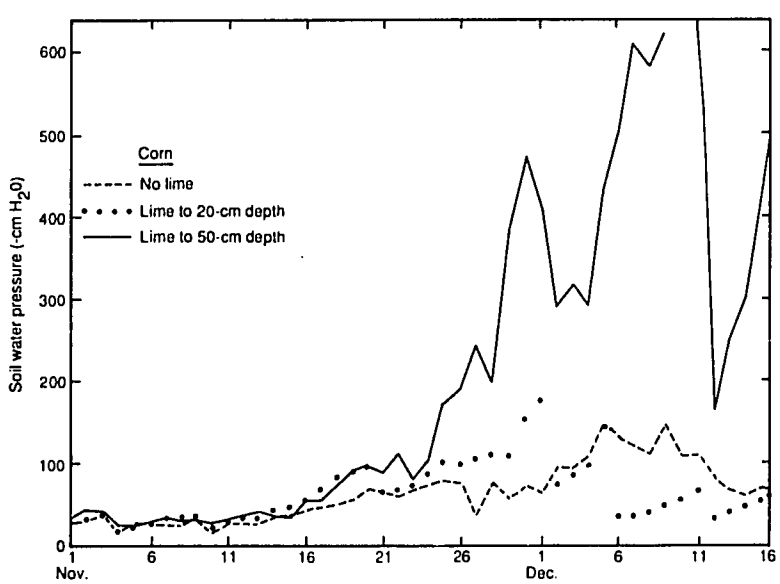

Figure 3. Soil water pressure at 37.5-cm depth as a function of time.

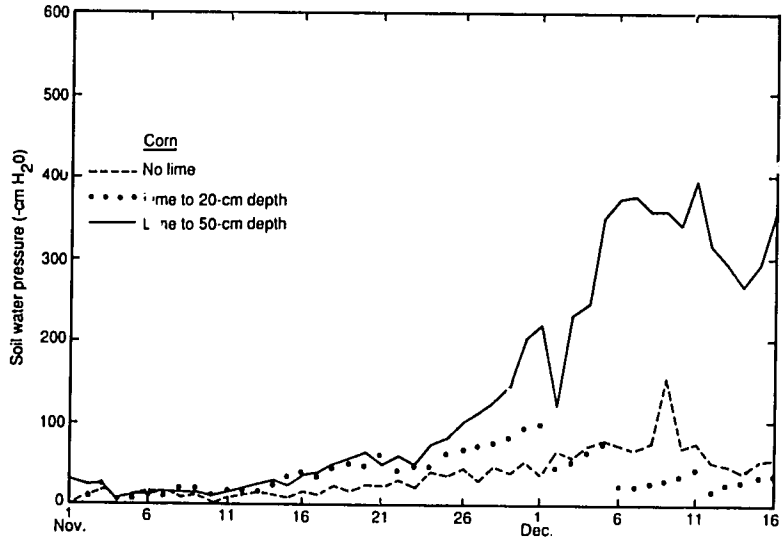

Figure 4. Soil water pressure at 52.5-cm depth as a function of time.

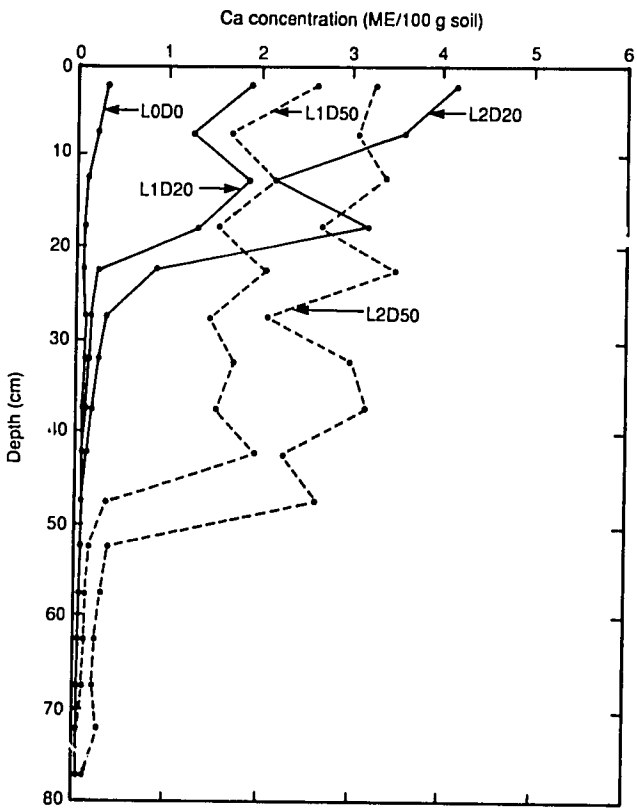

Figure 5. Soil distribution of Ca three weeks after application of lime. L0D0: no lime; L1D20: 1 t/ha/10-cm depth down to 20-cm depth; L2D20: 2 t/ha/10-cm depth down to 20-cm depth; L1D50: 1 t/ha/10-cm depth down to 50-cm depth; L2D50: 2 t/ha/10-cm depth down to 50-cm depth.

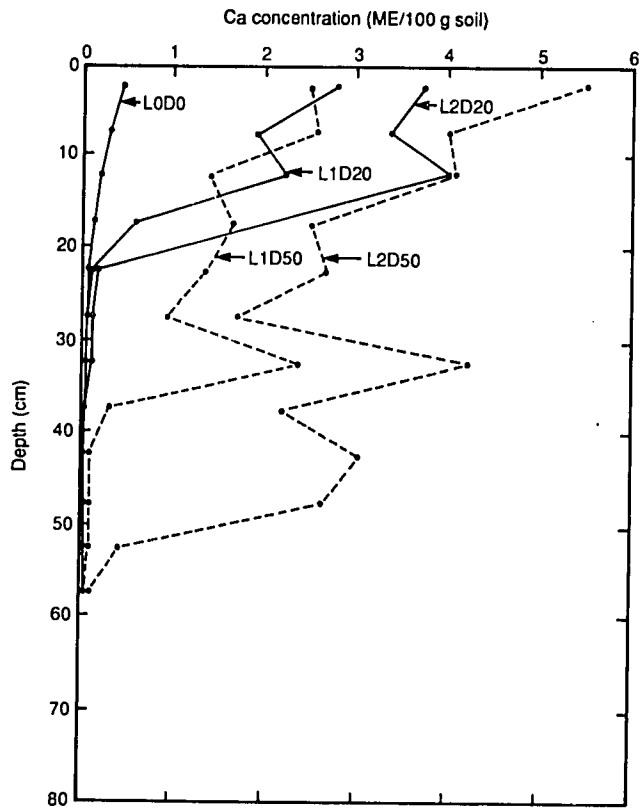

Figure 6. Soil distribution of Ca after the first harvest of corn. L0D0: no lime; L1D20: 1 t/ha/10-cm depth down to 20-cm depth; L2D20: 2 t/ha/10-cm depth down to 20-cm depth; L1D50: 1 t/ha/10-cm depth down to 50-cm depth; L2D50: 2 t/ha/10-cm depth down to 50-cm depth.

Agroforestry: UH-2

Inexpensive, locally available agroforesty and other organic resources constitute alternatives to lime and chemical fertilizers. Fast-growing, acid-tolerant, nitrogen-fixing trees and ground cover, along with other organic residues, serve as sources of nitrogen, fuelwood, fodder, lime substitutes, and windbreaks. They may also help control soil erosion. For two reasons, however, the relatively large knowledge base on agroforestry and organic residue management has not been organized in a way that helps producers make decisions and solve problems. First, until recently, information technology did not provide an efficient, user-friendly format for organizing and representing data; indeed, some confusion still exists concerning the best way to put information into rules and to encode those rules into computer language. Second, knowledge is still incomplete concerning 1) the effect of soil temperature, moisture, and microbiology on the nitrogen dynamics associated with residue decomposition; 2) the role of nutrient cycling by acid-tolerant, deep-rooted plants in managed agroecosystems (as opposed to unmanaged forests); and 3) the degree to which decomposing organic residue can complex aluminum ions.

Integration and Utilization of Agroforestry and Organic Resources in Sustainable, Low-Input Farming Systems: UH-2A

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Objectives

The objectives of this study are as follows: 1) to quantify the nitrogen-supplying capacity of nitrogen-fixing trees and cover legumes relative to a standard nitrogen source (e.g., urea); 2) to evaluate the role of nutrient recycling of trees in low-input, sustainable farming systems; and 3) to identify organic compounds responsible for detoxifying aluminum and develop procedures for estimating "lime" equivalence of green manures.

Problem-solving strategies will be developed, written as rules, and encoded into computer language. These problem-solving strategies will become available to a large audience of users.

The marked response of some crops to green manures in previous experiments in Sitiung suggests that the proper management of organic materials might reduce the need for lime and fertilizers on Sitiung farms. A series of experiments has been initiated in Sitiung to 1) determine the influence of green manures on crop yields, 2) evaluate tree and herbaceous legumes for use in Sitiung farms, and 3) incorporate information from Sitiung transmigrants in the selection and design of green-manuring systems. Findings from these studies should contribute to better management of organic materials on similar soils in Indonesia and elsewhere in the humid tropics. The identification of useful tree and cover crop species for use in intercropping or relay cropping with food crops would be an important contribution.

A methodology was developed for economic analysis of experimental data and comparison of potential changes in farming practices over multiyear periods. This analysis assesses the economic implications of crop yield increases observed in response to alley-cropping and liming. Such analysis provides a more thorough utilization of the research results than agronomic analyses alone and allows initial farmer recommendations to be developed.

Previous research in West Sumatra (Wade et al., 1988) indicated that herbaceous green manuring temporarily alleviated Al toxicity, enhanced P availability, and supplied other nutrients such as K and Mn. The research described here was initiated to compare alley-cropping, herbaceous green manuring, and liming for upland crop production on an acid soil in West Sumatra. This research focuses on Objective 2 of the overall UH-2 project.

Procedure

Alley-cropping Experiment

The experiment was planted on a Tropeptic Haplorthox soil in Sitiung Vc and laid out in a split-plot design with four replications. Main plots consisted of three hedgerows of a single tree species planted 4 m apart. Subplot size was 5.5 m x 12 m for the alley-cropped plots and 5.5 m x 6 m for the treeless plots. The harvest area of the subplots consisted of the central 3 m of the center tree hedge and 2 m to either side of the hedge for food crop yields. The harvest area for the treeless subplots was also the central 3 m x 4 m of the subplot. The treatments were as follows:

Main plots—tree species

1) *Paraserianthes falcataria* (syn. *Albizia falcataria*) (direct seeded)
2) *Calliandra calothyrsus* (direct seeded)
3) *Gliricidia sepium* (grown from hardwood cuttings)
4) No trees (control)

Subplot—liming levels

1) No lime
2) Low liming rate (375 kg lime/ha applied in December 1984 and in September 1985, but none applied in 1986, 1987, or 1988)
3) High liming rate to reduce Al+H saturation to 25% (2 t lime/ha applied in December 1984; 240 to 810 kg lime/ha, varying with individual plots, in September 1985; 500 to 1810 kg lime/ha, varying with replications, in September 1986; no lime applied in 1987 or 1988).

This report covers the crops grown during the 1986–87 and 1987–88 seasons, including upland rice and cowpeas, and the growth of the tree hedges themselves. The experiment was initiated and the trees planted in December 1984. The lime rates were broadcast over the subplots along with a blanket application of triple superphosphate (TSP) at 40 kg P/ha. Thereafter, TSP and Muriate of Potash (KCl) were broadcast and incorporated to 15-cm depth at rates of 10 kg P/ha and 25 kg K/ha before planting each upland rice or cowpea crop.

The trees were pruned in September 1985, nine months after planting, and before planting the upland rice crop at the beginning of the rainy season. The trees were cut to 40-cm stump heights, and the prunings were spread in the alleys to dry. After four days, the wood was removed from the plots. Thereafter, the trees were pruned four times per year, i.e., before planting the upland rice or the cowpea crops and during the growth of each crop. The most vigorous hedges were pruned at 1 to 1.5 m in height to reduce shading of the food crops.

Prunings made before planting the alley crops were dried in the alleys, the wood removed, and the leaf incorporated into the soil to about 15-cm depth. Prunings made during crop growth were mulched without removing the small amounts of wood produced at those times. At each pruning, samples were taken to determine leaf fraction, wood fraction, and dry-matter content. Each sample was separated by hand into leaf (leaflet and rachises) and wood (twig and stem) fractions. Tree leaf tissue samples from selected prunings were also analyzed for nutrient contents.

A local variety of upland rice was planted at a spacing of 40 cm x 15 cm in September 1986. Rice leaf samples (fully expanded new leaves) were collected for nutrient analysis at approximately 50% panicle initiation in mid-December 1986. In January 1987, one rice plant per row in each plot was measured for height, number of fertile tillers, and total number of tillers. Rice panicles were also harvested row by row to determine competition effects with the hedges. A local variety of cowpea was planted at a spacing of 40 cm x 25 cm in February 1987. The germination of seed was very poor due to diseased seed and dry weather at planting. Harvest of pods and vines was completed in May 1987. The trees were allowed to grow uncut into the dry season.

The 1987 dry season was quite severe and delayed normal pruning and crop-management practices. Hedges were pruned in October 1987 in preparation for planting upland rice. However, lack of rain delayed rice planting until November, at which time TSP, KCl, and urea were applied at rates of 10 kg P/ha, 25 kg K/ha, and 25 kg N/ha. The trees were pruned in December 1987 and again in February 1988 to reduce shading of the rice. Prunings were mulched at both of these times. The rice crop grew very poorly due to infrequent rains and a heavy infestation of rice blast. Rice was harvested in May 1988.

The trees were pruned again in May 1988, the prunings spread in the alleys to dry, and the wood removed. TSP was broadcast at a rate of 50 kg/ha and then incorporated. A local variety of cowpea was planted at a spacing of 20 cm x 40 cm in early June. Growth was very poor. Cowpeas were harvested in August 1988.

Farmer-managed Alley-cropping

A farmer-managed follow-up study of alley-cropping was initiated in November 1986 in the village of Sitiung Ve to assess farmer reactions and to obtain farmer recommendations for improvement of the system. The tree species *Paraserianthes falcataria* and *Calliandra calothyrsus* were selected for study, due to promising growth in the main alley-cropping experiment. Four farmers participated in the study. They received tree seed and planting instructions only since additional inputs might have influenced their retention of the system.

Scarified seeds were given to the farmers in sufficient quantities to plant two 25-m-long hedges of each species. The seeds were planted at a spacing of 3 seeds every 10 cm in a hedgerow and 3 to 6 m between hedgerows. The farmers were instructed that the trees could be used as fertilizer and might help to prevent erosion. Cropping practices were determined entirely by the farmers, so that they were free to adapt the system to their own requirements.

Economic Analysis of Alley-cropping

Partial budgeting and cash flow discounting were used to analyze the alley-cropping data. When implementation of a technology extends over a several-year period, as does alley-cropping, the times when costs and benefits occur determine how valuable they are. Discounting procedures can be used to "standardize the values of cost and benefit streams extending over several years to provide a proper basis for comparison" (Brown, 1979). Present values were calculated by reducing future benefit and cost streams to their present worths through discounting at an estimated discount interest rate.

Net present values can be calculated on the change in net benefits associated with a change from one treatment to another (Hogg et al., 1976). The equation used for calculating the net present value of changing treatments (trmt.) is:

$$\text{NPV of change} = \sum_{x=1}^{n} (\text{NB trmt.1} - \text{NB trmt.2}) / 1 + i)^n$$

where:

n = number of discounting periods (seasons or years)
i = the discounting interest rate
nb = net benefit

This is analogous to the marginal analysis used in partial budgeting, except that discounted changes in net benefits are compared. The change in net benefits associated with a change from the farmer's practice to another technology was calculated for each year. These changes in net benefits were then discounted at an appropriate interest rate, and the change in technology with the highest net present value was selected.

Source and Management of Green Manure

This experiment also took place in Sitiung Ve on a soil similar to that of the alley-cropping experiment. It was conducted using a randomized complete-block design with three replications. The plot dimensions were 4 m x 6 m. The experimental factors studied were the following:

Experimental Factors

Species:
1) *Calopogonium mucunoides* (CAL)
2) *Crotalaria usaramoensis* (CRO)
3) *Centrosema pubescens* (CEN)

Methods of green-manure application:
1) *In situ* incorporation (INC)
2) Cut and carry (CUT)
3) Root residue and stubble from plots that were used to produce the cut-and-carry material (RES)

Levels of Lime:
1) L0 = no lime
2) L1 = 375 kg lime/ha
3) L2 = liming to 40% acid (Al+H) saturation
4) L3 = liming to 20% acid saturation

Level of Nitrogen:

	Maize	*Peanut*	
1) N0 =	0	0	kg N/ha
2) N1 =	60	15	kg N/ha (split application)
3) N2 =	120	30	kg N/ha (split application)
4) N3 =	180	60	kg N/ha (split application)

These experimental factors were combined to produce 20 experimental treatments in four groupings of related treatments. The treatments used are listed in the box below.

This report covers the crops grown during the 1986–87 cropping season, which include the green-manure (GM) crops grown during the 1986 dry season, and then maize and peanuts grown during the following rainy season.

Green-manure crops were planted in May 1986 in rows 50 cm apart. Dry weather reduced germination, but a uniform stand was obtained by replanting gaps in the rows of green manures. The green-manure crops were harvested in September 1986 using 2-m x 4-m harvest areas, and they were incorporated according to the treatment plan. Estimates were made of litter and root residue of the green manures. TSP and KCl were applied to all plots at rates of 10 kg P/ha and 25 kg K/ha. Lime treatments were applied initially in June 1985 and were reapplied in September 1986 on only the highest lime level treatment to reestablish 20% soil acid saturation (Table 1). Soil samples taken to 15-cm depth in April 1986 indicated that the target acid saturation of 40% was achieved for the third lime rate, but that the highest lime rate averaged 27% acid saturation.

Maize (Cargill C-1 Hybrid) was planted at a spacing of 80 cm x 20 cm in October 1986. During the first two weeks of December, ear leaves were collected when 50% of the plants showed silk extrusion. The maize was sprayed several times with diazinon for insect control. Some minor damage by wild pigs occurred in early January but was corrected by slightly reducing harvest areas to exclude damaged plants. Maize was harvested in January 1987 (99 days from planting). Maize stover was removed from the plots (as is usual farmer practice in Sitiung), and TSP and KCL were incorporated on all plots at rates of 10 kg P/ha and 25 kg K/ha.

Experimental Treatments

Trt no.	Green-manure species	Application method	Nitrogen, Lime	(Code)
Group 1: (GM species and application methods)				
1)	CAL	INC	(N0,L2)	(02I/CAL)
2)	CRO	INC	(N0,L2)	(02I/CRO)
3)	CAL	CUT	(N0,L2)	(02C/CAL)
4)	CRO	CUT	(N0,L2)	(02C/CRO)
5)	CAL	RES	(N0,L2)	(02R/CAL)
6)	CRO	RES	(N0,L2)	(02R/CRO)
7)	Check (no GM)	—	(N0,L2)	(02)
8)	CEN	INC	(N0,L2)	(02I/CEN)
Group 2: (Lime response with GM also applied)				
9)	CRO	INC	(N0,L0)	(00I/CRO)
10)	CRO	INC	(N0,L1)	(01I/CRO)
11)	CRO	INC	(N0,L2)	(02I/CRO)
12)	CRO	INC	(N0,L3)	(03I/CRO)
Group 3: (Lime response with no GM applied)				
13)	Check	—	(N2,L0)§	(20 or 00)
14)	Check	—	(N2,L1)§	(21 or 01)
15)	Check	—	(N2,L2)§	(22 or 02)
16)	Check	—	(N2,L3)§	(23 or 03)
Group 4: (Inorganic nitrogen response)				
17)	Check (no GM)	—	(N0,L2)	(02)
18)	Check (no GM)	—	(N1,L2)	(12)
19)	Check (no GM)	—	(N2,L2)	(22)
20)	Check (no GM)	—	(N3,L2)	(32)

§ Nitrogen was applied to maize at the N2 level and to peanut at the N0 level in the Group-3 treatments.

Table 1. Rates of lime applied to each replication on 13 June 1985 and (for the 20% acid saturation level only) on 11 September 1986.

Rep.	Lime 1	40% Acid sat.	20% Acid sat. 13/6/85	20% Acid sat. 11/9/86	Total
I	375	1000	1604	354	1958
II	375	1396	2083	396	2476
III	375	1208	1900	278	2174

Peanuts were planted in January 1987 at a spacing of 25 cm x 25 cm with one to two seeds per planting hole. The peanuts established well and required no replanting. After several weeks, all of the zero- and low-lime plots had high rates of seedling death and leaf necrosis, but other plots had excellent growth. To determine the effects of N application on peanut yields, urea was applied on 10 February to the inorganic N treatments (18, 19, and 20) at rates of 15, 30, and 60 kg/ha. The peanuts were harvested in April 1987 using a 2-m x 4-m harvest area.

Soil and Plant Tissue Analyses

Soil samples were collected in the alley-cropping and green-manuring experiments at 0- to 15-cm depths. The samples were air dried and ground to pass a 2-mm sieve. Determinations of exchangeable Al + H were made by extraction in 1 N KCl and titrated with NaOH to the phenolphthalein end point. Separate determinations of Al were not made since Al + H levels were found to be highly correlated with Al in previous studies in Sitiung (Wade et al., 1986). Exchangeable Ca and Mg were extracted with 1 N KCl, while K and P were extracted with Mehlich I (double acid) extractant. Ca, Mg, and K were measured using an Atomic Absorption Spectrophotometer, while P was measured using a colorimetric procedure (Murphy and Riley, 1962). Effective cation-exchange capacity (ECEC) was calculated as exchangeable Ca + Mg + K + extractable-Al + H. Percentage of acid saturation was calculated as (extractable Al + H)/ ECEC) x 100. Organic carbon was analyzed using acid dichromate digestion; total nitrogen, using a semimicro Kjeldahl procedure; and pH, using a 1:2.5 soil to water suspension (Soil Conservation Service, 1972).

Rice and maize leaf tissue, green leaf manure (GLM) from the alley-cropped trees, and herbaceous green manure samples were sun dried and later oven dried at 60 °C. Samples were ground in a Wiley mill to pass a 1-mm mesh. Total elemental analysis was done at the University of Hawaii Agricultural Diagnostic Service Center using an ICP Spectrometer. Nitrogen was analyzed using a semiautomated indophenol blue colorimetric method (Suehisa, 1980).

Crop grain and straw samples were taken at each harvest to determine moisture content. Grain moisture content was measured with an electronic moisture tester, and yields were calculated at 14% moisture for upland rice, 15% moisture for maize, and 12% for cowpea and peanut. Straw samples were sun dried to constant weight. Five or six randomly selected straw samples per harvest were oven dried at 60 °C to calculate oven dry weights.

Results

Alley-cropping Experiment

Data on leaf yield, wood yield, and heights of hedges at pruning for the 1986–87 season are presented in Tables 2a, 2b, and 2c, respectively. Unlike the 1985–86 season, *Calliandra* produced more total biomass than *Paraserianthes* in the same season. However, at the first pruning in September both *Calliandra* and *Paraserianthes* produced about the same amounts of leaf and wood. This was the most important GLM application since it was the largest and preceded the first crop of the season. GLM application at this time would probably allow complete decomposition and availability of nutrients for the crops. Gliricidia produced the lowest yields of all prunings.

Yields of leaf and wood and heights of the hedges at pruning for the 1987–88 season are presented in Tables 3a, 3b, and 3c, respectively. A prolonged dry spell (May to September 1987) preceded this season of growth and delayed the first hedge pruning until October 1987. The alley crop of upland rice was not planted until November, and subsequent tree prunings were each about a month later than in the two previous seasons. As in the 1986–87 season, the highest leaf and wood yields were produced by *Paraserianthes* hedges in the first pruning, while *Calliandra* yields were highest in the three subsequent prunings (Table 3). Total leaf yields for the season were highest for *Calliandra* hedges, while total wood yields for the season were equal for *Calliandra* and *Paraserianthes*.

To provide an indication of the relationship between tree growth and soil fertility, total biomass yields (leaf + wood) were regressed on various soil test parameters. In the 1986–87 season, *Paraserianthes* biomass yields were significantly related to percentage of organic matter and to percentage of total N (Table 4). *Calliandra* biomass yields were significantly related to exchangeable Mg. *Gliricidia* biomass yields were strongly related to exchangeable Ca, extractable acidity, and to percentage of acid saturation. These regressions provide indications of the adaptability of the different tree species to sites of varying soil fertility. *Calliandra* and *Paraserianthes* both appear to be species that tolerate acidic soils with low base status. *Calliandra*, however, may respond to Mg application on such soils. *Gliricidia* is clearly responsive to Ca applied as lime.

Data on yields of upland rice and cowpea for the 1986-87 season are shown in Figure 1. The yields of grain and straw for both rice and cowpea crops increased significantly with the application of the low rate of lime (Table

5); however, yields at low and high lime rates did not differ significantly. Although *Calliandra* hedges produced more GLM, rice grain and straw yields were significantly lower than with *Paraserianthes* hedges. The mean rice yields of all treatments with trees did not differ significantly from the no-tree (control) treatments (Table 5). The interaction of lime x tree species caused significant differences in rice yields, which indicates that the rice yield responses to different tree species varied at different levels of lime application (Figure 1). Rice yields were highest at the low rate of lime for *Paraserianthes*, *Gliricidia*, and the no-tree plots, while rice yields were lowest for *Calliandra* at the low rate of lime.

Although cowpea yields were quite low due to a poor stand and drought at planting, there were significant differences in response to GLM application from the different tree species (Table 5). However, there was no significant interaction between lime rate x tree species. Figure 1 shows that cowpea yield response to *Paraserianthes* was significantly higher than to the *Gliricidia* or no-tree treatments. See Table 5 for the coefficients of variation for both upland rice and the cowpea crops. They were especially high for the cowpea crop, probably due to nonuniform stand.

Data on yields of upland rice and cowpea for the 1987–88 season are shown in Figure 2. Yields were very low due to a combination of irregular rainfall and heavy disease infestations. However, crop response to *Paraserianthes* relative to the other species was much higher than

Table 2. Growth and yields of tree hedges during 1986–87.

a. Leaf yield[§]

Tree species	Tree pruning date: Sept. 1986	Nov. 1986	Feb. 1987	Mar. 1987	Total: 4 prunings
	kg/ha				
Paraserianthes	1027	217	292	189	1725
Calliandra	1248	550	948	446	3192
Gliricidia	101	122	86	70	379
LSD (0.05)	271	123	254	96	628

b. Wood yield

Tree species	Tree pruning date: Sept. 1986	Nov. 1986	Feb. 1987	Mar. 1987	Total: 4 prunings	Fuel wood[¶]
	kg/ha					
Paraserianthes	45	508	75	3308	3198	2680
Calliandra	185	919	197	3941	3559	2640
Gliricidia	31	79	21	264	212	133
LSD (0.05)	44	113	60	1155	1075	928

c. Tree heights at pruning

Tree species	Tree pruning date: Sept. 1986	Nov. 1986	Feb. 1987	Mar. 1987
	cm			
Paraserianthes	317	95	189	89
Calliandra	264	117	200	102
Gliricidia	101	66	88	65
LSD (0.05)	42	10	25	16

[§] Yield in kg/ha was calculated on the basis of total intercropped land area, rather than yield per hedgerow.
[¶] Fuelwood is the sum of only the Sept. 1986 and Feb. 1987 harvests, since the wood was taken off the plots only at these times.

in previous seasons. Significantly lower crop yields were produced with *Calliandra* than with *Paraserianthes* (Table 6), despite the higher GLM production of the *Calliandra* hedges (Table 3). As in previous seasons, crops responded only up to the low rate of lime. However, the tree species x lime interaction for both the upland rice and cowpea crops was significant (Table 6). Yields of the *Paraserianthes* treatments were maximum at the low lime rate while yield responses for the other species increased up to the high lime rate (Figure 2). Nutrient yields from four prunings during the 1986–87 season are shown in Table 7. *Calliandra* GLM contained the greatest amounts of N, P, and Ca due to high yields of prunings. However, nutrient yields of K and Mg did not differ significantly between *Paraserianthes* and *Calliandra* due to the high K and Mg contents of the *Paraserianthes* GLM. *Gliricidia* nutrient yields were much lower due to low yields of prunings. Nutrient yields in *Calliandra* and *Gliricidia* GLM were significantly higher at the higher lime rates, while *Paraserianthes* nutrient yields were not significantly affected by lime rates.

These findings show that substantial nutrient accumulation occurred with both the *Paraserianthes* and *Calliandra* hedges. In the 1986–87 season, K in GLM represented about 40% of the annual KCl application, and the P in GLM represented 16% (*Paraserianthes*) to 24% (*Calliandra*) of the annual TSP application. Recycling of bases such as Ca, Mg, and K, which are prone to loss by leaching, may be an important benefit of alley-cropping. *Paraserianthes* maintained high nutrient yields at all lime rates, while nutrient yield of *Calliandra* and *Gliricidia* increased with lime application.

Table 3. Growth and yields of tree hedges during 1987–88.

a. Leaf yield

Tree species	Tree pruning date: Oct. 1987	Dec. 1987	Feb. 1988	May 1988	Total: 4 prunings
	kg/ha				
Paraserianthes	2423	458	884	261	4026
Calliandra	1838	783	1741	722	5084
Gliricidia	220	163	365	57	805
LSD (0.05)	490	118	327	166	780

b. Wood yield[§]

Tree species	Tree pruning date: Oct. 1987[¶]	Dec. 1987	Feb. 1988	May 1988	Total: 4 prunings
	kg/ha				
Paraserianthes	4586	673	240	177	5676
Calliandra	3517	1121	507	504	5649
Gliricidia	279	191	85	35	590
LSD (0.05)	1429	211	79	134	1647

c. Tree height (cm) at October 1988 pruning.

Paraserianthes	351.
Calliandra	269.
Gliricidia	095.
LSD (0.05)	0.74

[§] Yield in kg/ha was calculated on the basis of total intercropped land area, rather than yield per hedgerow.

[¶] Fuelwood was removed from the plots only at the October harvest, since the usual pruning schedule was delayed and the three subsequent prunings had to be applied as mulch.

In soil samples taken in February 1987 (Table 8), the acid saturation of soil from the high lime rates was higher than the desired level of 25%, but still well below the critical values reported by Wade et al. (1988) for upland rice (70%) and cowpea (55%). Wade et al. (1988) also reported critical levels for upland rice of 0.20 and 0.21 $cmol_c/L$ for K and Mg, respectively. This indicates that soil K levels were probably adequate, but that Mg was probably deficient.

Treatments with trees did not cause significant differences in any of the soil chemical properties measured, except that the *Paraserianthes* treatments had significantly higher exchangeable Mg than the other species. Lime application caused significantly higher exchangeable Ca and Mg levels, as well as lower Al+H and acid saturation levels (Table 8). The increase in exchangeable Mg at the first lime increment may be due to increased Mg uptake by more

Table 4. Correlation coefficients for total tree biomass regressed on various soil test parameters in the 1986–87 season.

Soil Test	Ranges in soil	Correlation coefficients (r)		
Parameter	Test values	*Paraserianthes*	*Calliandra*	*Gliricidia*
Al+H	0.77 – 2.58 $cmol_c/L$	0.224	0.244	0.836***
Ca	0.18 – 1.71 $cmol_c/L$	0.041	0.168	0.932***
Mg	0.03 – 0.40 $cmol_c/L$	0.385	0.627*	0.604*
K	0.09 – 0.27 $cmol_c/L$	0.275	0.062	0.204
P	2.37 – 8.63 mg/kg	0.059	0.147	0.083
Acid	29 – 80%	0.030	0.242	0.925***
Sat.pH	4.13 – 4.83	0.116	0.322	0.566
OC	1.26 – 2.27%	0.707**	0.188	0.010
Total N	0.11 – 0.23 %	0.646*	0.039	0.110

*,**,*** = significant at the 0.05, 0.01, and 0.001 levels, respectively.

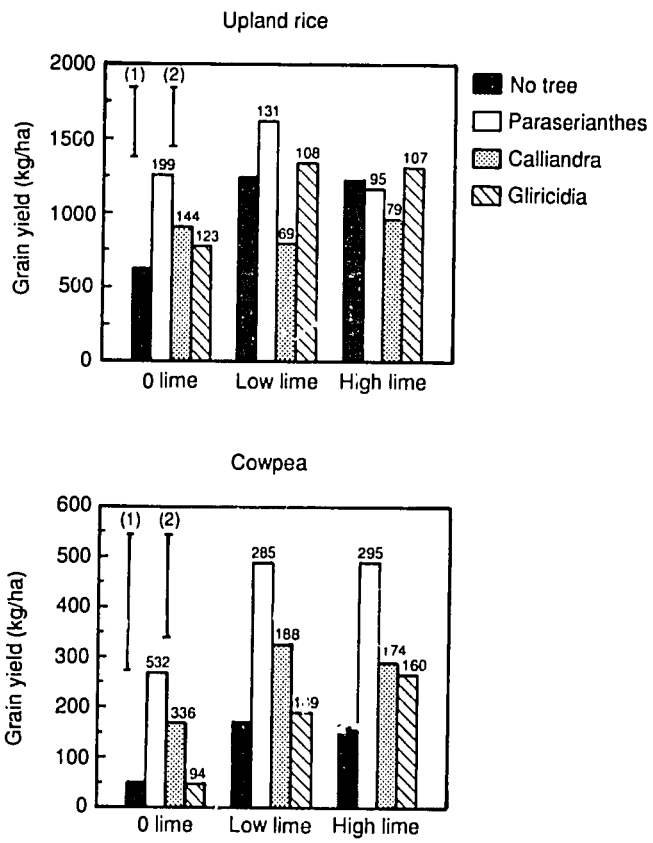

Figure 1. Upland rice and cowpea grain yields during the 1986–87 season. Numbers above bars are percentage of no-tree treatment yields at each lime level. Vertical lines are LSD (0.05) values (1) to compare species means at the same or different lime rates and (2) to compare lime means for the same species.

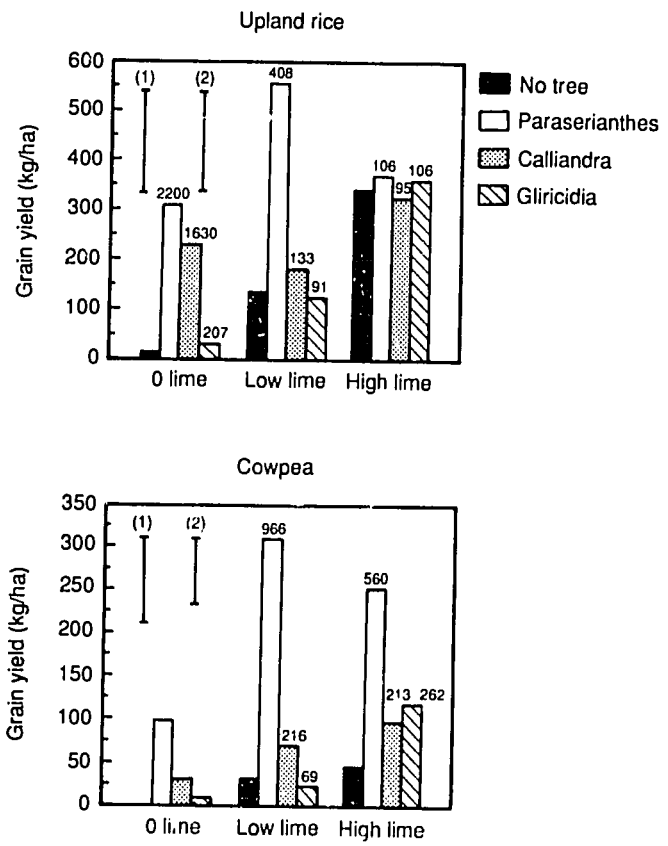

Figure 2. Upland rice and cowpea grain yields during the 1987–88 season. Numbers above bars are percentage of no-tree treatment yields at each lime level. Vertical lines are LSD (0.05) values (1) to compare species means at the same or different lime rates and (2) to compare lime means for the same species.

Table 5. Analysis of variance for upland rice and cowpea yields during the 1986–87 season.

Source	df	Upland rice Grain MS[§]	Upland rice Straw MS	Cowpea Grain MS	Cowpea Straw MS
Rep	3	24392	8767	31560	48260
Tree Spp.	(3)	444456	21650[illegible]	197452	289808 *
Tree vs No Tree	1	79571	90[illegible]52	218119	96293
GLI.[¶] vs PAR.[§§]+CAL.[¶¶]	1	4356	823045	249071	411688 *
PAR. vs CAL.	1	1249441 *	4766850 *	162134	416185 *
Error A	9	134342	595109	55012	62529
Lime Rates	(2)	549620 **	928444 *	116461 *	266223 **
Lime vs No lime	1	1042709 ***	1852040 **	232344 **	474390 ***
Low vs High lime	1	56532	4851	578	58055
Lime x Tree Spp.	6	195298 *	687431 *	3392	33929
Error B	24	72789	206816	19982	32703
CV (%) Mainplot		33	32	101	64
CV (%) Subplot		25	19	58	45

*,**,*** = significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
[§] Mean square; [¶] Gliricidia.
[§§] Paraserianthes; [¶¶] Callinadra.

Table 6. Analysis of variance for upland rice and cowpea yields during the 1987–88 season.

Source	df	Upland rice Grain MS[§]	Upland rice Straw MS	Cowpea Grain MS	Cowpea Straw MS
Rep	3	133	1690443	1301	3092
Tree Spp.	(3)	157669 **	3866963 *	92969 ***	90771 ***
Tree vs No Tree	1	112583 *	2663506	66573 *	38596 *
GLI.[¶] vs PAR.[§§]+CAL.[¶¶]	1	195636 **	4644695 *	69391 *	59501 *
PAR. vs CAL.	1	164789 *	4292689 *	142944 ***	174217 ***
Error A	9	17309	808893	7016	6939
Lime Rates	(2)	166114 **	4390688 ***	38631 ***	146175 ***
Lime vs No lime	1	252796 ***	7478596 ***	74070 ***	241803 ***
Low vs High lime	1	79431	1302780	3192	50546 *
Lime x Tree Spp.	6	49117 *	1314084 *	9860 *	7139
Error B	24	19272	469435	2731	7936
CV (%) Mainplot		53	61	93	48
CV (%) Subplot		56	47	58	51

*,**,*** = significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
[§] Mean square; [¶] Gliricidia.
[§§] Paraserianthes; [¶¶] Callinadra.

vigorous root systems and better retention on the exchange complex. Lower Mg levels at the high lime rate may be due to leaching losses after replacement on the exchange complex. Exchangeable K and available P were not significantly affected by either tree species or lime rates.

Nutrient concentrations in rice leaf tissue sampled at 50% panicle initiation during the 1986–87 season are shown in Table 9. Nitrogen concentrations in rice leaves from the no-tree and *Gliricidia* treatments were not significantly different, but both were significantly higher than *Paraserianthes* and *Calliandra* treatments at the zero lime rate. This suggests that the added N from the *Paraserianthes* and *Calliandra* GLM did not significantly increase yields. Since no nitrogen was applied to the no-tree treatments and *Gliricidia* GLM did not contribute much N (Table 7), the higher rice leaf nitrogen levels in these treatments suggest that lack of N did not limit upland rice yields. Rice leaf N concentrations were significantly higher at the zero lime rate (Table 9), which can be explained by a dilution effect, since crop growth was much greater when lime was applied.

Phosphorus concentration of rice leaves was significantly higher in no-tree treatments than in treatments with trees. This could indicate some P depletion by trees and may indicate that slightly higher P-fertilization rates are required for alley-cropping systems than for food crops without trees. The zero lime treatments were associated with significantly higher P levels in rice leaves. This also is likely to be a dilution effect, since soil P availability was not reduced by lime application (Table 8).

Concentrations of K and Mg were not significantly different in rice leaves from different tree species or treeless treatments (Table 9) as might be expected if the trees were actively recycling K or Mg from deeper soil layers to the surface. Long-term data are needed from this trial to determine whether there is, in fact, increased recycling and availability of bases under this alley-cropping system. Potassium concentrations in rice leaves were significantly higher in the zero lime treatments than when lime was applied, indicating that calcium may have interfered with potassium availability or uptake. Magnesium levels in rice were significantly lower in the zero lime treatments than when lime was applied. Since Mg was not applied to this experiment and Mg is not very mobile in the soil, more vigorous root systems in the limed plots may account for the higher Mg concentrations.

There was a strong increase in Ca concentration in rice leaf tissue with increasing lime rates. Calcium levels in rice leaves were also higher in the no-tree treatments than in treatments with trees, which is possibly due to calcium uptake by the trees. Aluminum concentration decreased in rice leaves with increasing lime rates, but there were no significant differences among tree species or in the no-tree treatments. Ca and Al levels in rice leaves were inversely related.

Table 7. Nutrients contained in green leaf manure as totals of four prunings in the 1986–87 season.

Treatment	N	P	K	Ca	Mg
Paraserianthes					
No lime	73.2	3.3	20.0	7.2	5.0
Low lime	68.5	3.0	21.3	9.0	5.8
High lime	68.7	3.3	20.5	12.4	5.1
Calliandra					
No lime	88.2	3.8	18.8	10.7	5.5
Low lime	119.7	5.2	24.2	23.1	5.8
High lime	129.3	5.5	19.8	29.7	3.9
Gliricidia					
No lime	4.8	0.3	1.0	1.0	0.5
Low lime	12.1	0.8	4.9	2.9	0.3
High lime	28.7	2.0	10.3	9.0	0.9
Species means:					
Paraserianthes	70.1	3.2	20.5	9.5	5.3
Calliand a	112.4	4.8	21.0	21.2	5.1
Gliricidia	16.2	1.1	5.8	4.6	0.6
Lime rate means:					
No lime	60.0	2.6	14.3	6.8	3.9
Low lime	66.7	3.0	16.8	11.7	4.0
High lime	75.6	3.6	16.8	17.0	3.3
LSD (0.05) between:					
Species means	26.4	1.0	5.9	4.4	1.4
Lime-rate means	ns	0.6	3.2	3.4	ns
Lime means for same sp.	28.5	1.1	5.6	6.0	1.7
Species means for same or different lime rates	35.1	1.3	7.5	6.5	1.9

Manganese concentration in rice leaves was not significantly influenced by tree species; however, there was a trend for higher Mn concentrations with *Paraserianthes* and *Calliandra* alley-cropping (Table 9). Mn levels were also significantly higher at the low lime rate than at the zero or high lime rates. This soil may be quite deficient in manganese.

Table 9 also contains sufficiency ranges for nutrient concentrations in rice leaves as reported by Ward et al. 1973 for irrigated rice. Sufficiency ranges are the nutrient concentrations associated with optimal growth under a variety of conditions. Nitrogen, K, and Ca values presented in Table 9 were low but within reported sufficiency ranges, indicating that these nutrients were not the main factors limiting rice yield. Phosphorus was probably deficient, while Mg and Mn were well below reported sufficiency ranges, indicating that they probably did limit yields. Increasing P-fertilization rates may be advisable, but Mg or Mn fertilizers are not currently available to farmers in West Sumatra.

During the 1986–87 season, a special study was conducted on the effects of competition between tree hedges and the upland rice crop. Crop growth and yield parame-

Table 8. Soil analysis (0- to 15-cm depth) of samples taken on 12 April 1986 (sampled during cowpea crop).

Treatment	Al+H[§]	Ca[§]	Mg[§]	K[¶]	ECEC	Acid Sat.	P[¶]
			cmol$_c$/L			%	mg/kg
No tree							
No lime	1.87	0.24	0.07	0.19	2.37	79	7.5
Low lime	1.45	0.83	0.16	0.22	2.66	54	5.5
High lime	0.69	1.89	0.12	0.22	2.92	25	6.0
Paraserianthes							
No lime	1.75	0.27	0.10	0.23	2.35	76	4.8
Low lime	1.11	1.27	0.26	0.24	2.87	40	4.5
High lime	0.54	1.61	0.13	0.25	2.53	22	5.8
Calliandra							
No lime	1.66	0.29	0.11	0.22	2.28	72	5.3
Low lime	1.29	0.78	0.15	0.18	2.40	54	7.0
High lime	0.87	1.58	0.13	0.18	2.76	32	7.0
Gliricidia							
No lime	1.41	0.58	0.10	0.21	2.30	63	6.8
Low lime	1.39	0.64	0.10	0.18	2.30	60	6.8
High lime	0.94	1.41	0.11	0.21	2.66	36	4.5
Species means:							
No tree	1.34	0.99	0.12	0.21	2.65	53	6.3
Paraserianthes	1.13	1.05	0.17	0.24	2.58	46	5.0
Calliandra	1.27	0.88	0.13	0.19	2.48	53	6.4
Gliricidia	1.25	0.87	0.10	0.20	2.42	53	6.0
Lime rate means:							
No lime	1.67	0.34	0.10	0.21	2.32	73	6.0
Low lime	1.31	0.89	0.17	0.21	2.56	52	5.9
High lime	0.76	1.62	0.12	0.21	2.71	28	5.8
LSD (0.05) between:							
Species means	ns	ns	0.03	ns	ns	ns	ns
Lime-rate means	0.21	0.25	0.04	ns	0.16	9	ns
Lime means for same sp.	0.43	0.51	0.08	ns	0.32	17	ns
Species means for same or different lime rates	0.40	0.48	0.08	ns	0.39	16	ns

[§] Extracted with 1 N KCl.
[¶] Extracted with Mehlich I (double acid) extractant.

ters were measured on individual rows (of 3-m length each) in the harvest area of each subplot. Five row positions were characterized in each plot by averaging measurements of two rows at each of five distances from the hedges. In the no-tree plots, all 10 rows in the harvest areas were measured. Grain yields and several components of yield were taken to better characterize this competition.

Data on yields of rice grain at each row position are shown in Figure 3a. Yields of tree species treatments at the five row positions were averaged over lime rates since neither the lime rate x row position nor the tree species x lime rate x row position interactions were significant. Yields of rows of rice closest to hedges were reduced due to competition with the trees. This yield reduction was most severe near *Calliandra* hedges, due to strong shading of the widely spreading *Calliandra* canopy. At harvest time, *Calliandra* hedges had extended out to the second row of rice, 60 cm from the hedge. *Paraserianthes* and the *Gliricidia* hedges covered only up to the first row of rice

Table 9. Nutrient concentrations in rice leaf tissue sampled at panicle initiation during the 1986-87 season.

Treatment	N	P	K	Ca	Mg	Mn	Al
		g/kg				mg/kg	
No Tree							
No lime	28.9	1.65	13.8	2.1	0.65	49	54
Low lime	23.7	1.40	14.7	4.4	1.05	75	29
High lime	24.7	1.68	12.0	6.0	1.00	47	35
Paraserianthes							
No lime	25.0	1.38	15.2	2.0	0.78	66	51
Low lime	23.3	1.25	13.0	3.8	1.08	92	38
High lime	23.8	1.25	14.9	4.3	0.80	59	31
Calliandra							
No lime	25.9	1.43	14.9	2.0	0.78	76	43
Low lime	24.6	1.38	12.2	3.6	0.93	85	37
High lime	23.8	1.38	14.9	4.6	1.00	58	26
Gliricidia							
No lime	29.9	1.55	16.8	1.7	0.55	40	44
Low lime	24.9	1.40	13.9	4.4	0.88	91	30
High lime	25.5	1.20	13.2	4.6	0.95	57	24
Species means:							
No Tree	25.7	1.58	13.5	4.2	0.90	57	39
Paraser.	24.0	1.29	14.3	3.4	0.88	72	40
Calliandra	24.8	1.39	14.0	3.4	0.90	73	35
Gliricidia	26.7	1.38	14.6	3.6	0.79	63	33
Lime rate means:							
No lime	27.4	1.50	15.1	1.9	0.69	58	48
Low lime	24.1	1.36	13.4	4.0	0.98	86	33
High lime	24.4	1.38	13.8	4.9	0.94	55	29
LSD (0.05) between:							
Species means	1.6	0.12	ns	ns	ns	ns	ns
Lime-rate means	1.2	0.09	1.1	0.6	0.23	18	10
Lime means for same sp.	2.4	0.18	2.3	1.1	0.47	35	20
Species means for same or different lime rates	2.5	0.19	3.0	1.2	0.47	38	21
Sufficiency Ranges	28–42	2–3	12–25	2–4	2–4	252–792	n/a

[§] Source is Ward et al. (1973).

(20 cm from the hedges) and reduced yields of this inner row much less.

Among the three tree species, *Calliandra* regrew most vigorously after pruning. While this is an advantage in maintaining vigorous hedges, it does increase shading of food crops. Competition for light is probably the main cause of rice yield reduction, since plots were cultivated twice a year. This cultivation destroyed tree roots in the surface 15 cm of soil and should have lessened root competition.

The distance of rice rows from hedges affected plant height (Figure 3b). The height of rice plants in the *Paraserianthes* treatments increased adjacent to the hedges, suggesting that there was moderate competition for light with the trees. Plants often respond to moderate shading by increasing in height (Eriksen, 1978). *Calliandra*, on the other hand, severely shaded the rice plants close to the hedge, causing them to shorten. The row adjacent to the hedge was completely covered at harvest. Figure 3b shows that rice height at 20 cm was significantly lower and height at 60 cm was significantly higher than at 100-, 140-, or 180-cm row distances. This indicates

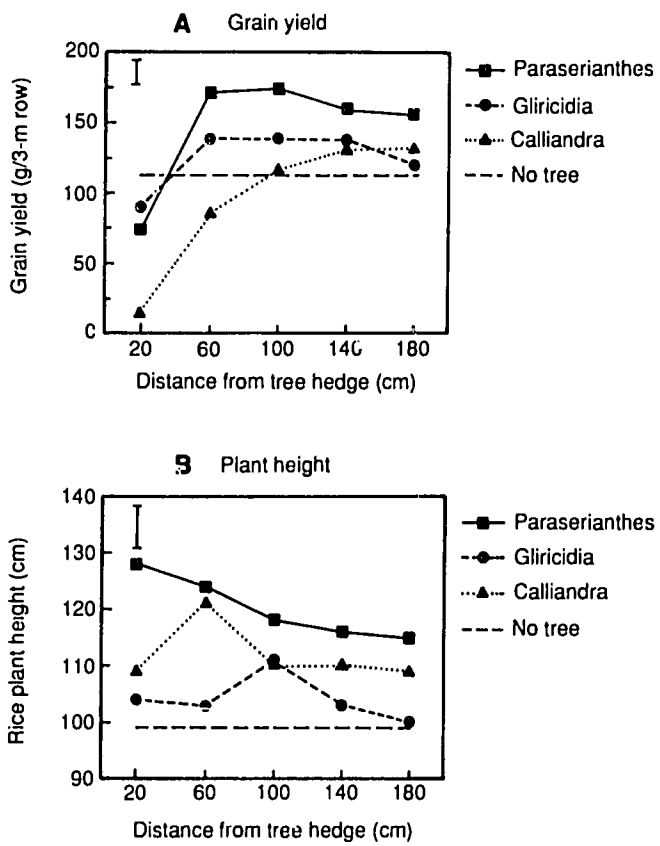

Figure 3. Effects of distance from tree hedges on rice growth and yield. Vertical lines are LSD (0.05) values to compare row position means for the same species (averaged over all lime rates).

that the first row (20 cm) was severely stunted while the second row (60 cm) was only moderately shaded.

The potential for rice yield increase if competition were minimized can be calculated by dividing the yield of rows farthest from the hedges by the average yield of all rows. According to this calculation, a yield increase of 32% for *Calliandra*, 13% for *Paraserianthes*, and 7% for *Gliricidia* is possible if competition were eliminated. Pruning hedges more frequently would reduce competition and probably raise yields. More frequent pruning would be most beneficial with *Calliandra*; however the added yield must be balanced with increased labor costs. Also, lower pruning heights of *Calliandra* hedges might increase crop yields by reducing shading.

Farmer-managed Alley-cropping

Periodic observations showed that trees had germinated well and hedges had established well on all but one farm. Growth of trees was quite variable on different sites. Young seedlings were quite susceptible to erosion damage. On the farm where hedges were slow to establish, most seedlings were lost to erosion during the first 6 months after planting, and other trees were destroyed by an accidental fire (Farmer 1 in Table 10). According to the farmer, surviving seedlings were very stunted (only 50 cm in height at 6 months) due to low soil fertility. In February 1987, one farmer planted hedges of the short-lived woody species *Crotalaria usaramoensis* in an alley-cropping system that he said would establish itself and grow more vigorously than the trees.

Two years after the hedges were planted, a survey was conducted to assess farmers reactions to alley-cropping. Of the four farmers, only one was still alley-cropping, two had removed the trees, and the fourth farmer's hedges had never established well (Table 10). The main reasons given by the farmers for removing hedges were 1) lack of time for pruning, 2) infestation of insect pests on hedges (grasshoppers, plant hoppers, and other insects), 3) loss of crop land, and 4) shading of crops.

Both farmers who removed their hedges seemed not to value the prunings as fertilizer and did not prune the hedges regularly. This lack of pruning undoubtedly caused competition with their food crops at the time hedges were removed, although Farmer 3 indicated that an east-west hedge orientation reduced shading of his crops by the hedges. Farmer 4 also indicated that insufficient seed was given to him to plant the full length of his terraces, and he felt that this would impair erosion control.

The farmer who had maintained the alley-cropping system (Farmer 2) was very happy with it. He had very perceptively developed management practices for his hedges. He pruned the hedges three times per year, just before planting a crop in August, January, and May. The prunings were mulched or, if he had time, he incorporated

them. Wood from the prunings was placed on the uphill side of hedges to dry and to act as a mechanical barrier to soil loss. The wood was later collected for fuelwood.

Farmer 2 pruned *Paraserianthes* to a 20-cm stump height the first time and cut it 10- to 20-cm higher at each subsequent pruning since he was afraid it might die if pruned too heavily. He was also trying to establish a fence with *Paraserianthes*. However, he pruned *Calliandra* to a 20-cm stump height at every pruning due to its bushy, vigorous growth habit. He was afraid that it would shade his crops too much if pruned higher. These seem to be very logical management strategies for the two different species. Farmer 2 wanted to plant more hedges, but he lacked seed. He was especially interested in *Calliandra* since it grows fast and yields the most green leaf manure and wood.

It is inappropriate to draw far-reaching conclusions from such a small sample size, but some generalizations can be made. The fact that only one farmer out of four was still alley-cropping after two years indicates that the technology may have limited appeal to farmers in this village. However, if more interaction had occurred between researchers and farmers, perhaps early problems with the system could have been solved and more farmers would have retained alley-cropping. Also, interaction among farmers could have been encouraged so that they discussed failures and shared successful management practices. Since one farmer failed to establish hedges due to erosion and low soil fertility, more attention should be paid to erosion control and fertilizing hedges during establishment. If this is not possible, then alley-cropping

Table 10. Responses of farmers in the on-farm alley-farming trial to a survey taken in 1988, two years after hedge planting.

	Sundanese		Javanese	
	Farmer 1	Farmer 2	Farmer 3	Farmer 4
Date surveyed	17 Nov.	23 Sept.	23 Sept.	17 Nov.
Slope of site	Steep	Moderate	Gentle	Gentle
Alley width	3 m	4–5 m	5–6 m	5–6 m
Alleys retained	No	Yes	No	No
Large trees retained	No	Yes (2Paraser 5.5 M)	No	Yes (2 Paraser.9m)
Crop sequence after hedge planting	peanut, peanut,[§] rice, (annual cycle)	soybean, soybean, peanut, rice	soybean, soybean, soybean + peanut	soybean + peanut,
Hedges pruned regularly	No	Yes	No	No
First pruning height				
a. *Paraser.*	2 m	6–7 m	> 2 m	
b. *Calliandra*	2.5 m	5 m	> 2 m	
Uses of hedges by the farmers		Fuelwood green manure, erosion control, fence	Fuelwood, green manure (gathered senesced leaves)	Green manure (used once when hedge removed)
Age of hedges when removed	6 months	—	1 year	8 months
Reasons for discontinuing alley-cropping	Hedge destroyed by erosion, fire. Poor tree growth due to low soil fertility	—	Lacked time to prune hedges. Hedges harbored pests	Loss of crop light to hedge. Shading of crop.
Overall attitude	Uncertain	Very Positive	Negative	Negative

[§] Hedge removal.

should not be recommended on very steep sites with highly infertile soils.

Economic Analysis of Alley-cropping

The discounting analysis of the costs and benefit streams of four selected alley-cropping treatments over a four-year-period is presented in Table 11. Since there is no universally appropriate value for the discounting interest rate (i), five values are used to provide a sensitivity analysis. Higher discounting interest rates indicate a greater preference for current over future income, as is likely with poor farmers.

A discounting interest rate of about 12% would probably apply to "progressive" farmers who are part of a cash economy and have access to government loans. A discounting interest rate of about 50% might apply to poorer, subsistence-level farmers who require relatively high initial returns on their investment in a new technology. However, differences in discounting interest rates do not reflect differences in risk aversion, which is also important to subsistence farmers but is not considered in this analysis. Given the limited data on alley-cropping, it is difficult to assess the risk involved in this technology.

Table 11 shows net present value calculations for the change from the Control to Alley, Liming, or Alley+Liming treatments at discounting interest rates of 0%, 12%, 25%, 50%, and 100%. The profitability of changing from the Control to Alley, Lime, or Alley+Lime treatments can be compared by the magnitude of the net present value of making this change. This represents the "present-day" value to the farmer of making these changes in his or her farming practices.

The change to the Alley+Lime treatment clearly results in the greatest net present values at discounting interest rates below 50%. At higher interest rates, liming alone may be most profitable. This indicates that alley-cropping with *Paraserianthes* and application of lime at an annual rate of 250 kg/ha may be the most profitable enterprise for progressive farmers, while liming may be most profitable for poor farmers who require high rates of return. This analysis is biased in favor of the Lime treatment since it was associated with high early yields followed by a general decline in the yields of all treatments. If treatment yields are averaged over the four years, the Alley+Lime treatment would be most profitable at all discounting interest rates.

These calculations for the net present value of changing do not represent the farmer's actual profit, since fixed costs were not calculated. They do, however, indicate relative profitability and the increase in profit that a farmer can expect above that obtained with current practices. It could be assumed that the farmer's current practices are profitable, or else they would be discontinued.

Data in Table 11 also indicate that the Lime treatment is more profitable than the Alley treatment at all discounting interest rates. However, the net present value of change from the Control to the Alley treatment is also positive at all five interest rates. This is important since there are areas in Indonesia (and elsewhere in the humid tropics) where lime is not available and where transportation would be costly and reliable delivery, impossible. In such areas, alley-cropping with *Paraserianthes* would be a profitable change from farmers' current practices. Since the Alley+Lime treatment was more profitable than the Lime treatment, this also suggests that alley-cropping may be profitable even in areas with less acidic soils.

Source and Management of Green Manure

Data on yields of green-manure crops grown in the 1986 dry season (June to August) are shown in Table 12. Aboveground dry-matter yields of *Crotalaria* increased with increasing liming rates and were higher than yields of *Calopogonium* and *Centrosema* at the equivalent lime rate (lime 2) in both seasons. *Crotalaria* residues (surface litter and roots) were only about 25% as large as aboveground biomass, while *Calopogonium* residues were about 50% as large as aboveground biomass. However, all green manure crops grew well and produced large amounts of dry matter, considering the dryness of the growing seasons. Apparently, all three green-manure crops are suitable for

Table 11. Net present value over four years of actual yield data of changing from the Control to Alley, Lime, or Alley + Lime treatments at various discounting interest rates.

Treatment Changed to	Discounting interest rate (%) 0	12	25	50	100
	(Rp/ha)				
Alley	151246	107731	77801	45529	19534
Lime	183672	141420	109716	71839	36480
Alley + lime	237503	168712	121273	70007	28701

growth during the dry season in Sitiung. The nutrient contributions of the green manures (Table 13) were fairly low compared to nutrient yields from trees in a related alley-cropping study (Table 7). However, the green-manure crops provided important amounts of at least N and K for low-input cropping systems.

Maize growth increased with increasing lime levels from the first few weeks of growth, but not with the addition of urea or GM (Table 14). There were no significant differences in maize yields due to the different methods of green-manure application (*in situ* incorporation, cut and carry, or root residues). However, green-manure application significantly increased maize yields compared to no green manure (Table 15). The response of maize to lime was strongly linear, and there was a significant lime x GM versus No Gm interaction (Table 16). This interaction indicates that maize yield response was significantly greater when green manure was applied.

Table 12. Green-manure biomass yields in 1986 (for the 110-day growth period of 21 May to 8 September 1986).

Green manure species	Lime rate	Aboveground dry matter	Surface litter	Root residue
		kg/ha		
Crotalaria	Lime 0	1782	—	—
	Lime 1	2806	—	—
	Lime 2	3477	346	494
	Lime 3	3651	—	—
Calopogonium	Lime 2	1590	475	347
Centrosema	Lime 2	2405	—	—
LSD (0.05)		1264		

Lime rates:
0, 1 = 375 kg/ha.
2 = liming to 40% acid saturation.
3 = liming to 20% acid saturation.

The peanut crop responded strongly to increasing liming rates (Table 14), with higher rates producing larger, greener tops and better filling of pods. Excellent nodulation was observed on most plots during harvest. However, green manures applied in September did not have a significant influence on yields. Liming significantly increased peanut yields in a linear fashion (Table 16), while quadratic and cubic effects were not significant. *Crotalaria* green manure applied before the previous grain crop significantly increased peanut yields over the lime treatments without green manure. The lime by GM versus No GM interaction was significant, indicating that peanut yield response to lime was significantly greater when GM was added than when no GM was added.

Linear, quadratic, and cubic effects of grain or straw yields regressed on nitrogen rates were not significant for any of the four test crops. There was, however, a significant maize grain yield response to the first level of inorganic nitrogen (Table 14). Response to this modest addition of 60 kg N/ha is similar to the response found by Fox, et al. (1974), who determined that on Oxisols and Ultisols in Puerto Rico, maximum maize grain yields were obtained with 67 kg of urea kg N/ha. However, response to N fertilizers is clearly related to the N-supplying ability of the soil, which was not studied. It is also interesting to note that the urea N application to the second peanut crop (at rates of 15, 30, and 60 kg N/ha in treatments 18, 19, and 20 in Table 14) caused a significant decrease in nut yields and a trend (nonsignificant) of increasing straw

Table 13. Nutrient yields per hectare in green manures harvested in September 1986.

Green manure	Lime rate	N	P	K	Ca	Mg	Mn	Cu	Zn	B
		kg/ha					g/ha			
Crotalaria	Lime 0	29	1.0	21	7.4	1.4	161	19	57	23
	Lime 1	46	1.8	27	15.8	4.0	270	28	112	42
	Lime 2	59	2.2	29	21.6	3.8	196	27	105	50
	Lime 3	46	1.7	32	17.3	5.0	133	29	93	41
Calopogonium	Lime 2	31	1.8	16	17.2	2.5	89	17	51	34
Centrosema	Lime 2	57	1.8	38	21.9	3.2	187	38	80	47
LSD (0.05)		25	ns	ns	10.3	ns	109	13	45	ns

Lime rates:
0, 1 = 375 kg/ha.
2 = liming to 40% acid saturation.
3 = liming to 20% acid saturation.

yields. Nitrogen fertilization of peanuts does not appear to be warranted, because of this yield decrease.

Soil analyses for samples taken in January 1987 are shown in Table 17. The unamended soils are quite acidic, with high acid (Al+H) saturation. Application of lime at the two highest rates achieved close-to-the-target acid saturations of 40% and 20% in both seasons. There was also an apparent increase in exchangeable Mg with increasing lime rates. This increase in Mg coincided with increasing ECEC's and might be explained by better Mg retention on the soil exchange complex.

Linear regressions of crop yields versus soil acid saturation are presented in Figure 4 for liming treatments with and without green manure. The linear responses for both the maize and peanut crops within the range of 25% to 80% acid saturations support the critical acid saturations of 28% and 29% estimated for peanut and maize by Wade et al. (1988) in Sitiung.

Conclusions

Green-manuring and alley-cropping were tested as a means of improving upland crop production on acid and infertile soils in Sitiung, West Sumatra. In alley-cropping plantings, the tree species *Paraserianthes falcataria* and *Calliandra calothyrsus* were shown to be well adapted to soils at the experimental site in Sitiung. These species produced an average of about 3 tons of leafy dry matter and about 4 tons of woody dry matter/ha/year from hedgerows at 4-m spacings. Growth of these species was good at high acid (Al+H) saturations (70 to 90%) and there was little response to lime application. *Gliricidia sepium* did not grow well in this study, producing only about 1/2 ton of leafy dry matter and about 400 kg of woody dry matter/ha/year. The poor growth of *Gliricidia* was most strongly related to low Ca availability.

Yields of upland rice and cowpea crops increased with both lime and green leaf manure (GLM) application. The highest yields of upland rice and cowpea were obtained when intercropped with *Paraserianthes* hedges. *Paraserianthes* alley-cropping approximately doubled rice yields and quadrupled cowpea yields compared to control plots. Crop response to *Calliandra* alley-cropping was less, probably due to shading competition, while *Gliricidia* hedges did not grow well enough to influence crop yields.

It is likely that part of the crop response to *Paraserianthes* alley-cropping was due to the amelioration of Al toxicity. With application of *Paraserianthes* GLM, crop yields did not decrease at the highest acid saturation levels, while without

Table 14. Yield response of maize and peanut to treatments in the 1986-87 season.

		Maize		Peanut	
Treatment	Code	Grain	Straw	Nut	Straw
		(kg/ha)			
1	(02I/CAL)	2392	3216	754	1449
2	(02I/CRO)	2530	3525	1058	1611
3	(02C/CAL)	2071	2870	874	1433
4	(02C/CRO)	2277	3362	845	1956
5	(02R/CAL)	2205	3010	713	1408
6	(02R/CRO)	1918	2821	882	1615
7	(02)	1361	2228	862	1541
8	(02I/CEN)	2520	3537	958	1622
(Lime rates with GM)					
9	(00I/CRO)	314	743	58	1133
10	(01I/CRO)	1845	2213	720	1648
11	(02I/CRO)	2111	2813	955	1637
12	(03I/CRO)	2900	3756	1268	1668
(Lime rates without GM)					
13	(20)	90	587	20	486
14	(21)	1246	1769	188	2042
15	(22)	2616	3054	658	1604
16	(23)	3906	4585	957	1700
(Inorganic N rates)					
17	(02)	1881	2808	692	1589
18	(12)	3100	3722	1005	1799
19	(22)	2712	2973	801	1902
20	(32)	3072	3619	514	2247
LSD (0.05)		985	1031	418	691
CV (%)		28	22	34	26

Code key: first number codes for N level; second number codes for lime level.

N Level	Lime level	GM species
0 = No N	0 = No lime	CAL = *Calopogonium*
1 = 60 kg/ha	1 = 375 kg/ha	CRO = *Crotalaria*
2 = 120 kg/ha	2 = 40% Acid sat.	CEN = *Centrosema*
3 = 180 kg/ha	3 = 20% Acid sat.	

GLM, crop yields decreased above critical acid saturation levels (70% and about 60% for upland rice and cowpea, respectively). If labile Al-organic matter complexes are important in reducing Al toxicity to crops, frequent application of GLM in alley-cropping would be especially beneficial. Beneficial effects of GLM addition on crop yields may be transient; therefore, the repeated application of prunings at regular intervals through the cropping season may help to maintain crop responses.

Of the green leaf manures, *Paraserianthes* also contained the highest concentrations of Mg and Mn (which were probably very deficient in the soils) and returned important amounts of plant nutrients to the soils (e.g. about 80 kg N, 30 kg K, and 6 kg Mg ha/year). Therefore, improved mineral nutrition may also explain the crop response to *Paraserianthes* alley-cropping.

The highest crop yields were obtained in the *Paraserianthes* + Low lime rate (750 kg/ha) treatment. This suggests that the beneficial effects of alley-cropping with *Paraserianthes* went beyond simply substituting for lime and may be beneficial even in areas where upland rice and cowpea crop yields are not limited by soil acidity. Economic analysis also indicated that *Paraserianthes* alley-cropping plus the low rate of lime application was the most profitable treatment. However, if lime is not available, *Paraserianthes* alley-cropping was shown to be more profitable than the control treatment, which was considered to be current farmer practice.

In a related study, *Crotalaria usaramoensis*, *Calopogonium mucunoides*, and *Centrosema pubescens* were grown as green-manure crops during the dry season in Sitiung, and the green manures were used on a rotation of maize followed by peanuts. On many farms in Sitiung, the dry season is a fallow period, so food crops were not displaced by the green-manure crops. Green-manure yields of 1.7 to 3.7 t dry matter/ha were obtained with *Crotalaria* while yields of 1.6 and 2.4 tons dry matter/ha were obtained with *Calopogonium* and *Centrosema*, respectively.

Table 15. Analysis of variance for the effects of methods of green manure application on maize and peanut yields in the 1986–87 season.

Source	df	Maize		Peanut	
		Grain MS	Straw MS	Nut MS	Straw MS
Replication	2	807182*	588522	226467*	183280
GM treatments	6	445750	549347	36310	106366
GM vs. no GM	1	1950692**	2112974*	160	3728
CAL vs. CRO	1	1659	187333	98213	396822
CAL,RES vs.INC+CUT	1	470288	774888	9763	56740
CRO,RES vs.INC+CUT	1	1401	2113	20510	2145
CAL,INC vs.CUT	1	96089	39544	67756	178400
CRO,INC vs.CUT	1	154369	179228	21456	363
Error	12	199320	309956	27615	87059

Code Key: MS = Mean square; GM = Green manure; CAL = *Calopogonium*; CRO = *Crotalaria*; RES = Root residue; INC = *In situ* incorporation; CUT = Cut and Carry.

Table 16. Analysis of variance for the effects of lime application with and without green manure application on maize and peanut yields in the 1986–87 season.

Source	df	Maize		Peanut	
		Grain MS	Straw MS	Nut MS	Straw MS
Replication	2	124174	222559	40266	118799
GM vs. No GM	1	177797	82791	520087***	24143
Lime rates	(3)	10962500***	13182700***	1282359***	1287584*
Lime linear	1	32580900***	39397900***	3829256***	1725889*
Lime quadratic	1	139492	11935	17734	1416982*
Lime cubic	1	167097	138190	86	719882
Plus or minus GM x Lime	3	777698*	456085**	60873*	279963
Error	12	225055	70739	14778	265815

Crotalaria was grown at four lime rates, to which it responded strongly, with biomass and nutrient yields more than doubling with increasing lime application.

Maize and peanut crops responded strongly to liming and less strongly to *Crotalaria* green manuring. Increases in maize and peanut yields were more strongly related to soil exchangeable Ca than to Al+H saturation. Overall, there was little response to green manure application. Also, different methods of green-manure application (grown in place, cut and carried within the field, and residue remaining after cutting) did not cause significant differences in crop yields.

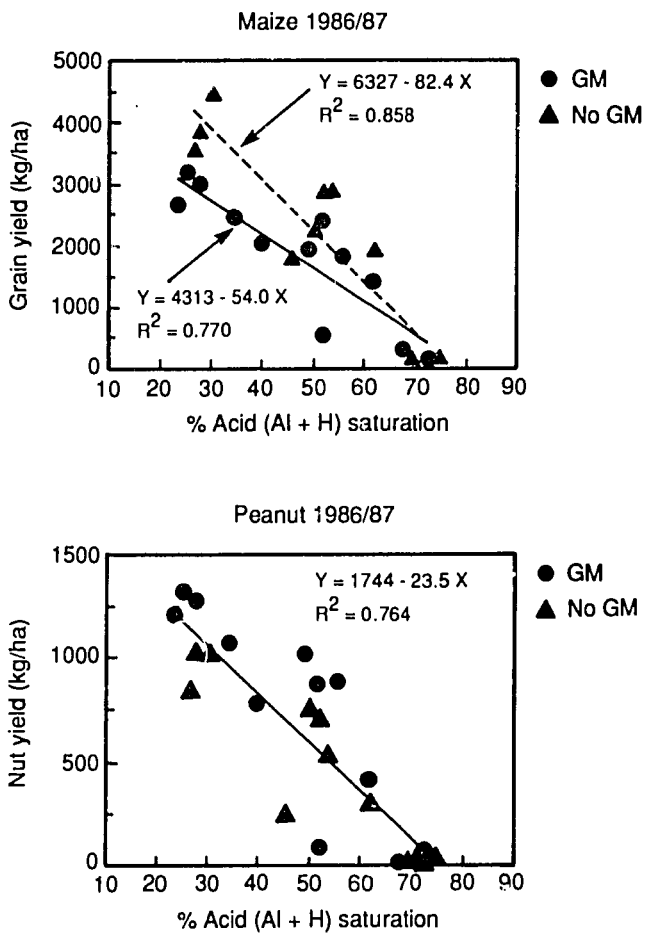

Figure 4. Crop response to percent acid saturation (Al + H/ECEC) in the 1986–87 season.

Inorganic N was also applied at four rates, and there was little or no response of the upland crops to this N during the two cropping seasons. Apparently, adequate amounts of N were available in the soil for the moderate yields. Therefore, the response of crops to the N contained in the green manures was probably limited, and the slight maize and peanut crop responses to *Crotalaria* green manure may have been related to increased availability of bases. It is also possible that the green manure additions reduced aluminum toxicity.

Overall, crop response to green manuring was slight, and the increased labor costs of this activity may make green manuring unattractive to farmers. These results are quite different from the large yield increases obtained with green leaf manure application in the alley-cropping experiment. Although the sites were fairly similar, the green-manure management experiment had a slightly more fertile and less acid soil, which may explain the lack of response to green manures. Also the amounts of nutrients contained in the green manures was slightly less than in the *Paraserianthes* GLM.

Another major difference between alley-cropping and green manuring may be the timing of application of GLM versus green manure. All of the green manure was applied at the beginning of the rainy season, while the GLM was applied in four smaller applications over the rainy season. The nutrients contained in the GLM may have been more readily available to crops at times of greatest requirement than nutrients from green manures. Conversely, the green manures were somewhat fibrous and had low N, P, Ca, and Mg concentrations, which may have resulted in some immobilization of these nutrients in microbial biomass.

The general philosophy followed in designing and managing these experiments was to set fertilizer rates and crop-management practices within the ranges of current farmer practice and to deviate from farmer practice only in experimental factors. This "farming-systems" approach

Table 17. Analyses of soil samples (0–15 cm) taken before planting peanut on 13 January 1987.

Lime rate	pH	Al+H	Ca	Mg	K	ECEC	P	Acid sat.	Org. C	Tot. N
			cmol$_c$/kg				ppm		%	
0	4.7	1.00	0.24	0.08	0.16	1.47	4.4	67	2.16	0.18
375 kg/ha	4.7	0.96	0.41	0.10	0.16	1.63	4.8	58	1.91	0.16
40% Acid Sat.	4.8	0.80	0.69	0.12	0.16	1.76	4.0	45	2.00	0.17
20% Acid Sat.	5.0	0.48	0.96	0.18	0.17	1.79	4.0	27	2.11	0.19

Extracted with 1 N KCl.
Extracted with Mehlich I extractant.

to research was intended to ensure that research results would be more readily applicable to farmers needs and resources than research conducted under high-input systems or under more controlled conditions. However, by not making blanket applications of nutrients, such as Mg, or micronutrients, crop yield responses to treatments could have been confounded with variability in availability of these nontreatment nutrients. The treatments that caused significant increases in crop yields, such as *Paraserianthes* alley-cropping, were very strong, and such technology is likely to be readily transferred to Sitiung farmers.

Implications

Alley-cropping studies indicate an urgent need to determine the pruning management of *Paraserianthes* and *Calliandra* to optimize the production of leaf and wood and yields of intercropped food crops. Less frequent prunings (1 to 2 times per year) of *Paraserianthes* should be studied to determine the effects on tree yields and longevity. In this study, pruning heights of 40 cm were maintained at each pruning. It may be beneficial to cut the hedges higher initially or to raise the pruning height at each subsequent pruning. Also, intercropping of taller-growing crops such as maize, cassava, or tree crops would allow use of higher pruning heights without excessive competition for light.

Conversely, more frequent pruning and lower pruning heights of *Calliandra* hedges should be studied to try to reduce competition with alley crops. The appropriate number of prunings per year depends on the alley crop to be grown, but prunings as frequent as monthly may be tolerated by this species. However, increased labor costs of the more frequent prunings must also be considered. Studies of alternative tree species for alley-cropping in humid environments with acidic soils is also urgently needed.

This research has shown that alley-cropping with *Paraserianthes* and possibly with *Calliandra* can increase crop yields on an acid and infertile soil in the humid tropics. However, there has not been an adequate assessment of the relevance and acceptability of this technology to farmers in these areas in Indonesia. One method of introducing and testing alley-cropping is through on-farm research, which allows adaptation of a technology to farm conditions and provides researchers and extension personnel with farmer insights on management under farm conditions. Also, evaluation under different environmental conditions allows determination of the range of applicability of alley-cropping. This should involve assessment of the physical environment and biological response to alley-cropping, as well as the resources, goals, social obligations, and economic circumstances of a farm family. Situations where alley-cropping is inappropriate or offers only marginal benefits must be clearly identified along with those situations where it is beneficial.

The results of the farmer-managed alley-cropping trial reported here provide some guidance for conducting future research. The following recommendations could help to improve the scope and usefulness of results from on-farm studies:

1) A sufficient number of farmers representing the important farming environments in a region should be involved, so that the potential for improved agricultural production with alley-cropping can be assessed.

2) Initial interactions with farmers should be frequent. Preferably this could occur in small group meetings among neighbors, so that farmers can discuss management of the hedges with researchers and with each other.

3) Periodic follow-up should be planned with each farmer, especially in the first year after planting the hedges, so that problems can be identified and possible solutions discussed. This would also provide the researchers with an opportunity to personally assess the system.

4) Sufficient seed should be given to farmers to plant an entire hillside or small drainage area, so that good erosion control is achieved. On especially steep slopes, some mechanical barriers or grass strips may need to be established along with hedges.

5) Soil from each research site should be sampled for chemical analysis and the soil profile, topography, and vegetation (or cropping system) described. This will allow determination of the range of biophysical conditions for which alley-cropping is applicable.

6) Potential interactions of alley-cropping with livestock components of the farming systems should be assessed (i.e., "alley-farming").

Integration and Utilization of Agroforestry and Other Organic Resources in Sustainable, Low-Input Farming Systems: UH-2B

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Objectives

The objectives of this study are as follows: 1) to quantify the nitrogen-supplying capacity of nitrogen-fixing trees and cover legumes relative to a standard nitrogen source (e.g. urea); 2) to evaluate nutrient recycling by trees in low-input, sustainable farming systems; and 3) to identify organic compounds responsible for detoxifying aluminum and develop procedures for estimating the "lime" equivalence of green manures.

Soil acidity problems can be readily corrected by applying lime, but lime is not always available to resource-poor farmers. Although organic matter can substitute for lime, the chemical basis for the "liming" remains unknown. In recommending organic matter as a substitute for lime, we need to know the liming equivalence of a given amount and type of organic matter. This research focuses on objective 3 of the overall UH-2 project.

Procedures

In order to test hypotheses about the influence of decomposing organic material on aluminum chemistry and toxicity, an incubation experiment was conducted in which soil-solution chemistry and toxicity were monitored over a six month (175-day) period. Two types of treatments were used. For one set of treatments, various levels of organic material were added to soils. In order to provide a range of Al concentrations and toxicities without added organic material for comparison, various levels of lime, as $Ca(OH)_2$, were added to a second set of soils. Each treatment was replicated twice. Tables 1 and 2 summarize the treatments and provide the chemical properties of the test soil.

Results

The decomposition effects of varying additions of ground cowpea on root growth, soil pH, and soil-solution Al are shown in Figure 1.

Table 1. Summary of treatments used in incubation experiment.

Treatment	Units	Levels
Cowpea	g/kg	0,5,10,20,40
Lime	cmol(OH) kg^{-1}	0,0.9,2.0,3.6,7.2,11.2

Table 2. Chemical properties of acid subsoil before and after adding $Ca(NO_3)_2$ kg^{-1}.

	Unamended	+ 5.5 mmol $Ca(NO_3)_2$ kg^{-1}
Water pH	4.0	3.8
KCl-extractable Al (cmol(+) kg^{-1})	8.4	8.6
ECEC (cmol(+) kg^{-1})	12.9	15.9
Organic C (percent)	12	12

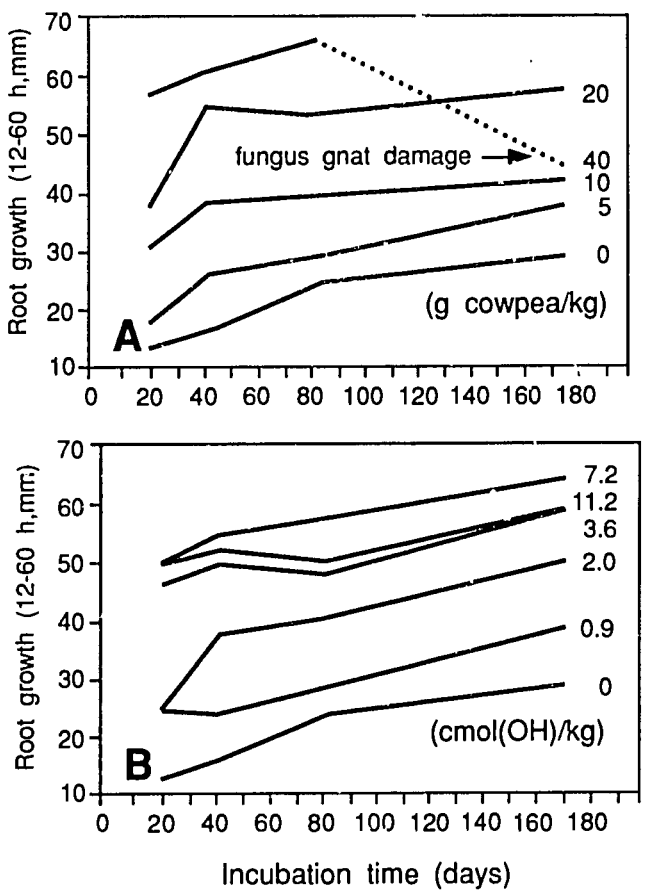

Figure 1. The decomposition effects of varying additions of ground cowpea and $Ca(OH)_2$ on root growth, soil pH, and soil solution Al (continued on next page).

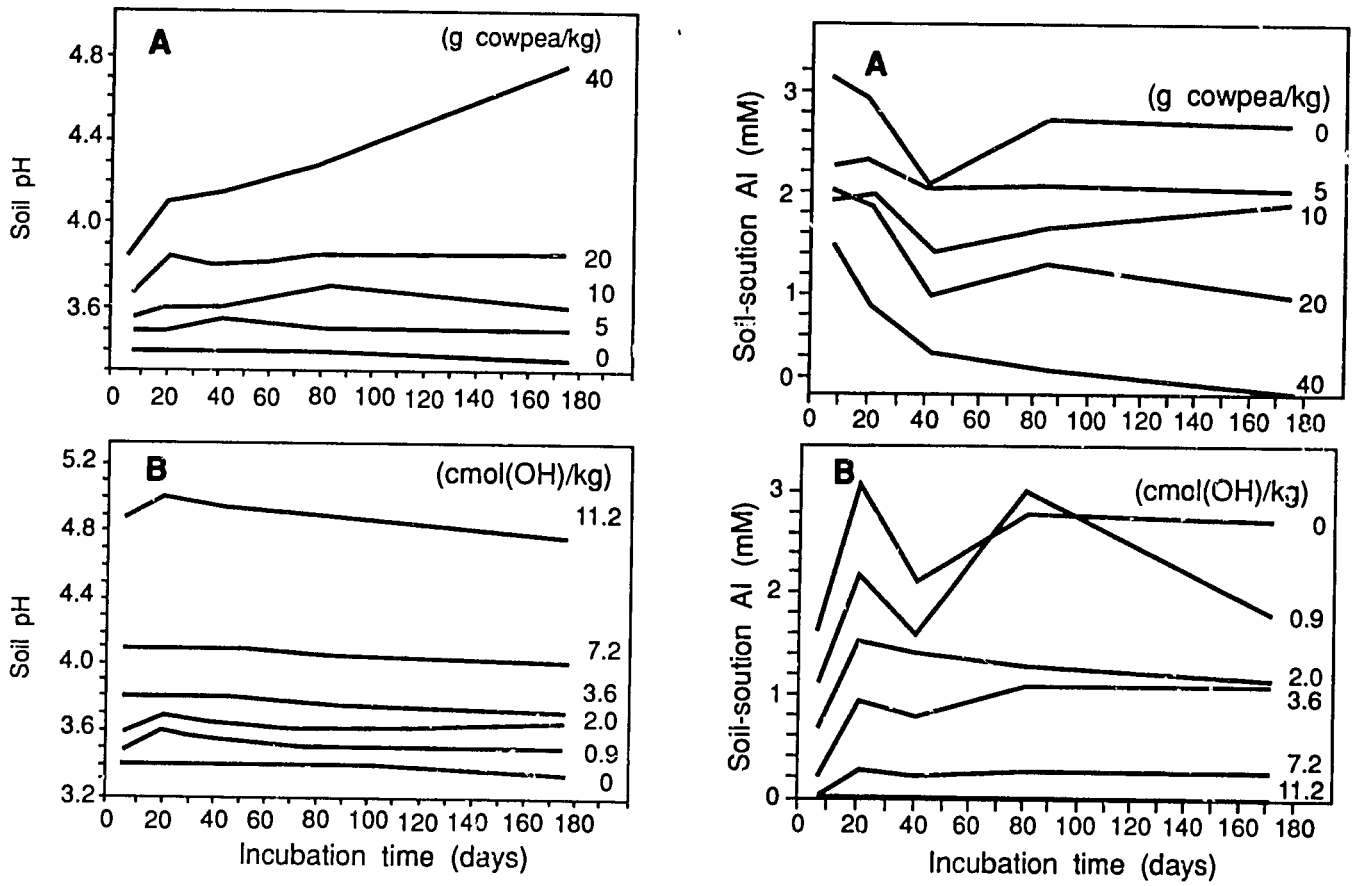

Figure 1 (continued). The decomposition effects of varying additions of ground cowpea and $Ca(OH)_2$ on root growth, soil pH, and soil solution Al.

Root Growth

Root growth increased significantly in response to added cowpea ($P < 0.001$) and lime ($P < 0.01$). Cowpea and lime improved root growth at relatively consistent rates during the incubation period. Root response to amendments of both lime and cowpea conformed to a Mitscherlitch function (Figure 2).

Soil pH and Al

Increases in root growth in response to cowpea and lime amendments were closely related to significant ($P < 0.01$) increases in soil pH and decreases in soil-solution Al and KCl-extractable Al (Figure 1). Most of the benefit to plants can be explained by the liming effect of the decomposing cowpea; reduced concentrations of toxic soil-solution aluminum are associated with reduced quantities of exchangeable Al and increased soil pH.

Although the cause of increased soil pH in response to cowpea amendments could not be determined, displacement of OH from variable-charged oxide surfaces by specifically adsorbed organic anions appears to be a reasonable explanation.

Change in Toxicity of Al

The difference in plant response to soil-solution Al in the lime and the cowpea treatments (Figure 1) indicates that intermediate concentrations of Al from soils treated with cowpea were less toxic than those from soils treated with $Ca(OH)_2$, particularly at 21 days of incubation. The difference between the two types of amendments was less at later sampling times.

The reduction of toxicity of soil-solution Al in the presence of decomposing cowpea could not be explained adequately by formation of nontoxic complexes with organic acid anions measured by HPLC. Calculated complexes with organic anions accounted for no more than 7% of the total concentration of soil-solution Al. The lower toxicity in the cowpea treatments was probably due to one or a combination of the following: 1) the formation of unidentified organic complexes, 2) the formation of sulfate complexes, and 3) the reduction of activity coefficients associated with increased ionic strength.

Lime Replacement Value

A regression function was derived to describe the ability of cowpea to substitute for lime in ameliorating Al toxicity to roots. The lime replacement value (LRV) function

$$LRV = \frac{\ln(B_l) - \ln(A_l - A_c + B_c * e^{(-Cc * cowpea)})}{C_l}$$

is a combination of the Mitscherlich functions for plant response to each type of amendment

$$Y = A - B_e^{(-C*X)}$$

where Y represents root growth and X represents amendment level. Subscripts c and l refer to cowpea and lime amendments.

The result (Figure 3) indicates that the cowpea amendment provided an effective alternative to liming and that incremental additions of cowpea were more effective at replacing lime at high levels of amendment than at low levels.

Conclusion and Implications

This study suggests that organic materials can help manage aluminum toxicity. The incubation experiment demonstrated that organic amendments can substantially raise soil pH and eliminate aluminum phytotoxicity for a longer period than was previously believed possible.

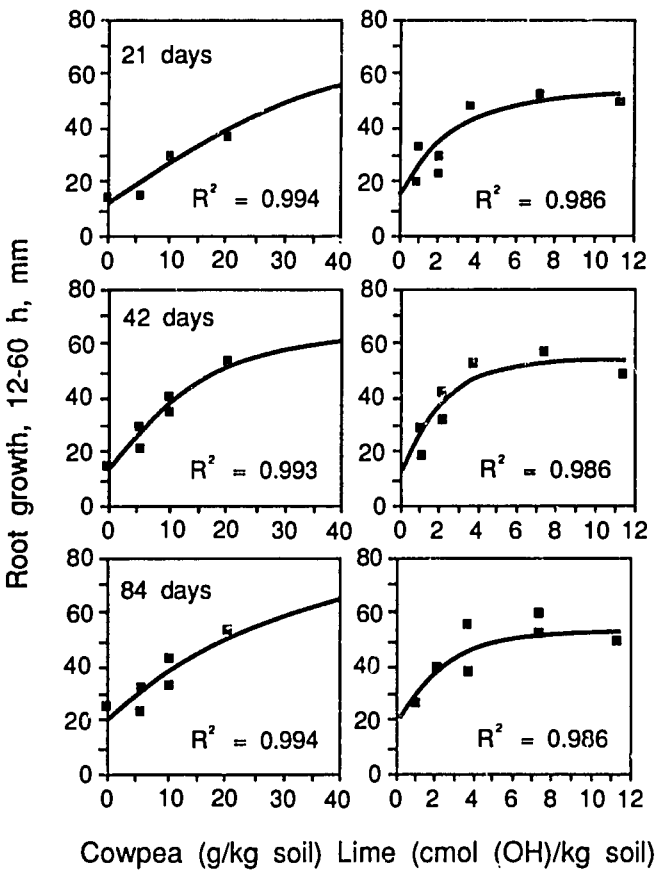

Figure 2. Root response to amendments of lime and cowpea.

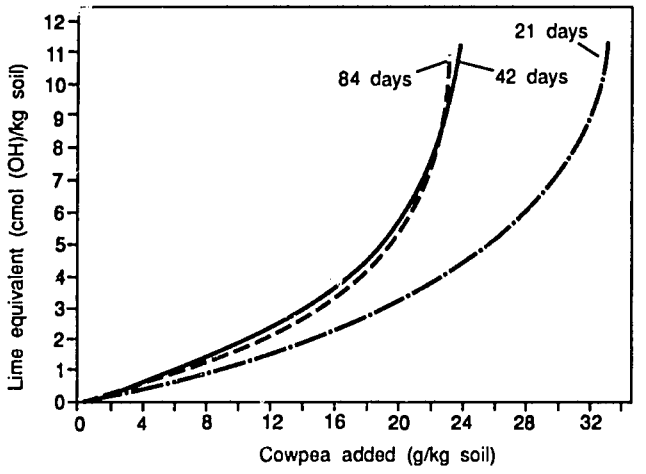

Figure 3. The effectiveness of cowpea amendments as an alternative to liming.

The long-term ameliorative effect of cowpea in this study suggests that cumulative applications of green manure or hedgerow prunings may prove more effective than a single application.

Although the ability of cowpea to produce the same effects as lime in this experiment should not be extrapolated to other combinations of soils and organic amendments, this study provides a procedure for determining optimum amendment levels and predicting benefits.

Implications for Further Research

An obvious question needing further research is what other soils will show the same benefit from organic amendments as the Kaneohe subsoil. However, the mechanism of the pH increase must be understood in order to know what soil characteristics are important. Once the mechanism for the pH increases, soils with oxidic mineralogies and high specific surfaces would probably benefit the most.

Longer studies—greater than one year—are needed to evaluate the duration of the ameliorative effect of organic amendments and the possible cumulative effects of sequential applications. Although the effectiveness of the cowpea amendments persisted and increased over a six-month period, the results should not be extrapolated to a longer period. These methods also need to be evaluated in field studies with organic-material application rates that are feasible for the local farmer.

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Soil and Crop Modeling: CU-104

In order to develop sustainable agricultural systems that conserve our water and fossil fuel resources, we must base our water- and nitrogen-management strategies on a comprehensive understanding of the physical, chemical and biological processes that affect water and nitrogen fate. Several aspects of soil and climate conditions of acid tropical savannas, such as the Cerrado in Brazil, make such an understanding a prerequisite for evaluating agricultural and environmental objectives for these regions. In the Cerrado, low water-holding capacities of the predominant soil orders (Oxisols and Ultisols) combined with frequently occurring droughts during the wet season can cause water stress and reduce crop yield. During intermittent drought, the growth and survival of the crop is largely determined by the amount of stored water that is accessible to the root system. In these highly-weathered acid soils, rooting depth is dependent on soil-fertility management, since roots are largely restricted to the portion of the soil profile where Al toxicity and Ca deficiency have been corrected by amendments. High rainfall in combination with shallow rooting and high soil hydraulic conductivity can lead to rapid leaching of nitrate below the root zone, making efficient nitrogen management difficult. However, the ability of the deeper soil to retain nitrate may make nutrients available to crops grown during the dry season. The degree to which local and regional advection may affect the water requirements of dry season crops is largely unknown, despite the interest in producing irrigated cash crops and rain-fed green manures during this period.

Field experiments in temperate regions have addressed similar issues. It remains to generalize these studies into a broadly based set of water- and nitrogen-management guidelines agronomically and environmentally appropriate to tropical acid savannas. One method of achieving this goal is to summarize our knowledge of water and nitrogen processes into dynamic simulation models of water and nitrogen fate in cropped systems and to evaluate their appropriateness to acid tropical savannas. On a scientific level, dynamic simulation models can provide a conceptual framework, integrate knowledge from many experiments, and pinpoint areas of interest. On a research management level, such models can provide support to research programs and can establish a basis for collaborative research.

Understanding Water and Nitrogen Dynamics in Cropped Acid Soils of the Tropics for Improved Management

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Objectives

The objectives of this study are: 1) to develop a comprehensive description in simulation-model form of water and nitrogen movement and nitrogen transformation in cropped soils of the acid soil regions of the tropics: a) to quantify the effects of soil physical properties upon water availability and soil water movement and their impact upon crop yield, evapotranspiration, and transient soil-water regimes in a manner useful to irrigation and crop production programs, b) to quantify the effects of soil chemical and biological properties on nitrogen transformation and transport, crop residue properties on nitrogen mineralization, and nitrate movement on base cation transport; and 2) to use the model of (1) as a guide in interpreting previous studies and in designing further experiments to aid in natural-resource assessment, agro-economic analysis, crop- and soil-management programs, and technology delivery.

Procedures

The software produced as part of this project, called GAPS (Buttler and Riha, 1987), was developed to make simulation modeling more accessible to users and adaptable to various research objectives. The program contains "user-friendly" input and output routines and allows the user to select from procedures to simulate various components of the soil-plant-atmosphere system. In addition, the user can choose from a variety of procedures with differing representations of the same component. Program structure allows the user to incorporate additional procedures into the program, linking them to procedures already present. Procedures can be selected on the basis of the data available to the user, the particular modeling objective, or the level of complexity required. Extensive documentation of the simulation procedures accompanies the software package.

Several field experiments were designed and conducted at the Cerrados Agricultural Research Center (CPAC), Planaltina, Brazil, to address key aspects of water and nitrogen dynamics in tropical acid savanna systems. These experiments were also used to test and validate models of water dynamics and crop growth.

Results

Potential Evapotranspiration

The major portion of water that infiltrates the soil in savanna cropping systems is lost to the atmosphere through evapotranspiration. Ability to estimate such losses is important for design and management of cropping systems and for water-resource planning, including irrigation design. Compared to work in the United States and Europe, very few studies on evapotranspiration have been conducted in tropical savannas, despite their large extent and potential importance as agricultural regions.

Several common approaches can be used to estimate potential evapotranspiration (PET). These include temperature-driven estimates such as the Linacre method; the Priestley-Taylor equation, which requires a measure of incoming solar radiation; the Penman-Monteith equation, which additionally requires measures of wind speed and relative humidity; and the pan method, in which water loss from a standardized pan of water is measured. All four of these methods are available as options for estimating PET in our simulation software, GAPS.

Comparison of these methods is useful 1) to evaluate how well the simpler methods, such as the Linacre, estimate PET, 2) to estimate the appropriate value to use for the Priestley-Taylor coefficient, and 3) to determine if there is significant advection by comparing the Priestley-Taylor estimate of PET to pan data or to the Penman-Monteith equation. We found that the Linacre method gives estimates of PET that are very similar to the Priestley-Taylor method using a value of 1.2 (non-advective conditions). Using a value of 1.5 in the Priestley-Taylor equation (advective conditions) results in estimates of PET very similar to the Penman-Monteith equation. We also found that regional advection could occur during the latter part of the dry season (late July and August) at the CPAC. The degree of advection appears to vary from year to year, with little occurring in 1982 and an approximately 12% increase in PET in 1983 due to this type of advection. Such advection also occurred at this time in 1988. Weather patterns related to this type of advection and their frequency of occurrence in the Cerrado are not known. Gaining knowledge in this area will be important for estimating crop water requirements on a regional and long-term basis.

Actual Transpiration

While PET sets the upper limit for water loss from soil and crop surfaces, actual evapotranspiration can be much less than PET. As the soil dries, evaporation from soil surfaces and transpiration from crops can fall below potential rates. Since reduction in actual transpiration (AT) from potential is usually associated with decreases in crop growth and yield, being able to predict actual transpiration is useful not only from the perspective of

crop water budgets but also crop production. Actual transpiration is determined from the dynamic interaction of the soil, crop, and atmosphere, so predicting AT requires consideration of this entire system.

Bulk Surface Resistance

In the Penman-Monteith equation for predicting evapotranspiration, one component, the bulk surface resistance (r_b), can limit PET in response to crop, atmosphere, and soil conditions. We characterized r_b of irrigated wheat and evaluated its use for predictive purposes. Hourly measurements of actual evapotranspiration using the Bowen ratio approach were made over an irrigated wheat field during the entire 1983 growing season. Data from four days were used to calculate r_b using both energy balance and residual methods. Crop surface temperatures predicted from measurement of wind speed and air temperature at one height above the canopy were in good agreement with infrared-measured canopy temperatures. Both the energy balance and residual methods gave similar values for r_b, which increased from time of irrigation (Figure 1). This change in r_b could not be attributed primarily to stomatal behavior, since the crop was irrigated when soil water potential at 10 cm was -70 J/kg, and, consequently, soil water status was not considered limiting to plant growth and yield. If energy transfer to the soil surface was greater than that estimated from simple radiation penetration models, which assume no sensible heat transfer, the rate of soil evaporation could have declined rapidly, affecting an increase in r_b with time from irrigation. This would mean that soil surface properties play an important role in determining actual evapotranspiration even under closed canopies, suggesting that the extent to which heat at the crop surface can be transferred to the soil may reduce crop water requirements.

In this study we also found r_b remained fairly constant during the day, until approximately 1530 h, at which time it rapidly increased (Figure 1). At the same time, latent heat loss in proportion to net radiation increased and canopy temperature decreased more rapidly than air temperature. Interestingly, this increase in r_b occurs after canopy temperatures have peaked and have actually begun decreasing relative to air temperature. An increase in r_b at this time appears to limit the cooling of the canopy below air temperature. The cause of this increase in r_b is not clear.

The Penman-Monteith equation was used to predict evapotranspiration for several periods during another crop growing season. The r_b was assumed to vary from a minimum of 40 s/m immediately after irrigation to 70 s/m immediately after irrigation. On all days r_b was assumed to equal 100 s/m after 1530 h. Predicted and measured values were similar both on an hourly and a daily basis (Figures 2 and 3).

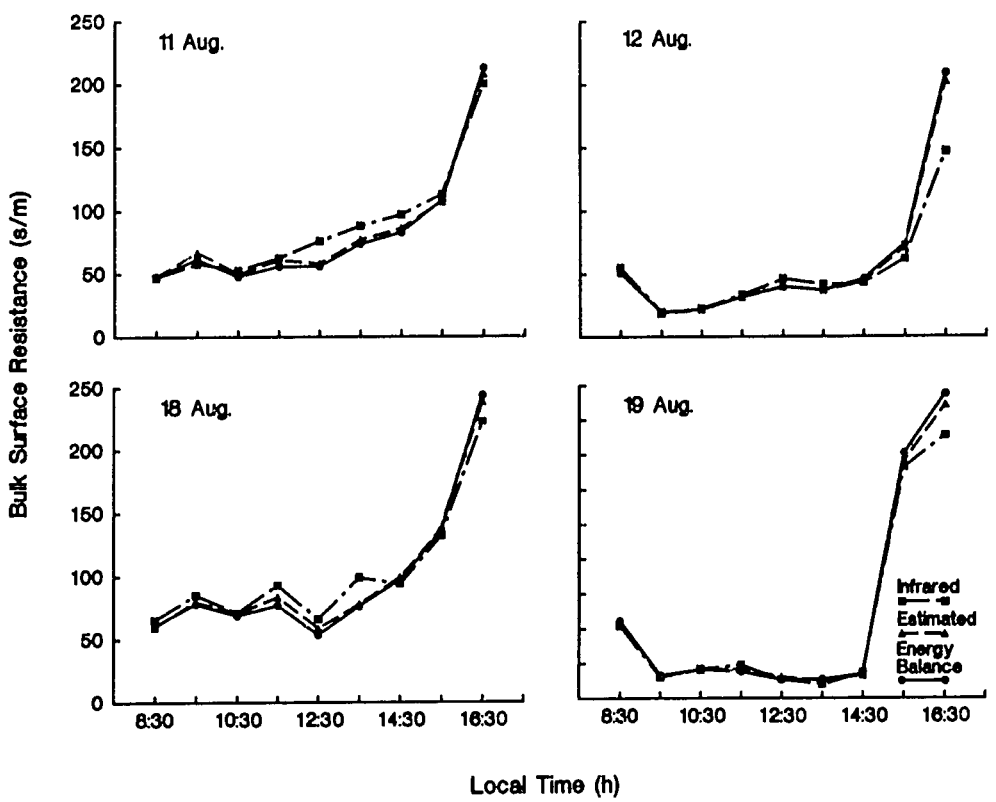

Figure 1. Bulk surface resistance as a function of time of day before (11 August and 18 August) and after (12 August and 19 August) irrigation.

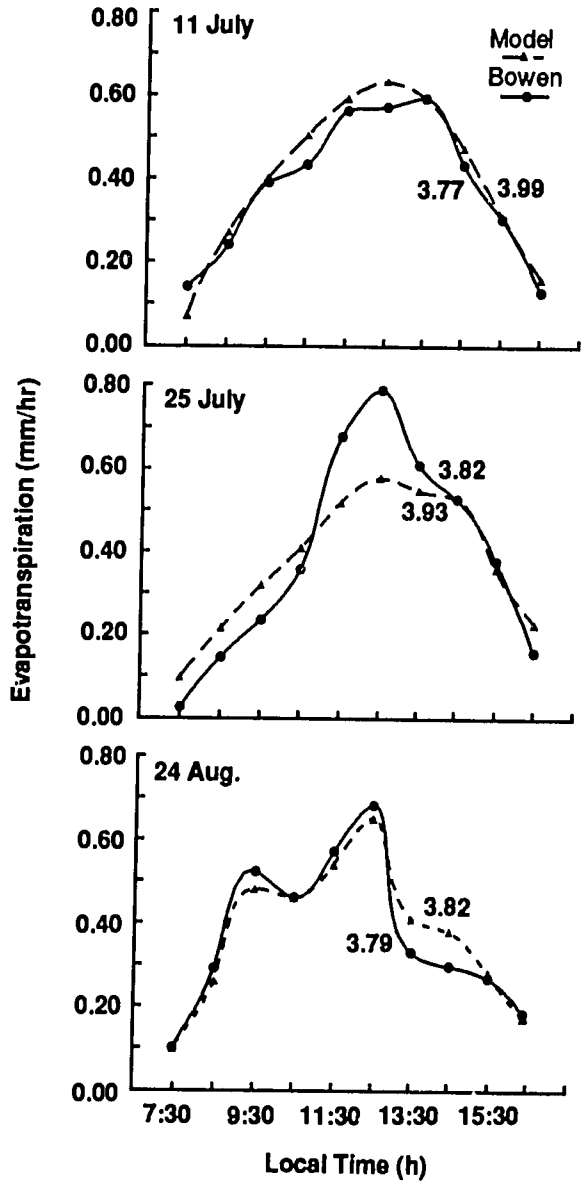

Figure 2. Hourly predicted (model) and measured (Bowen) actual evapotranspiration. Total daily evapotranspiration included.

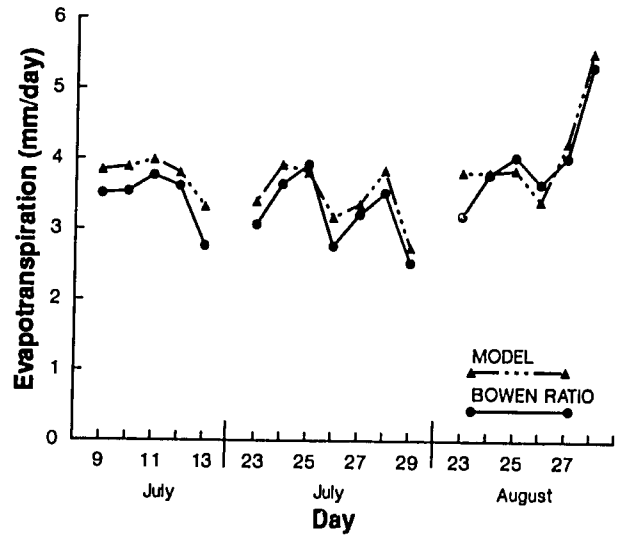

Figure 3. Daily predicted (model) and measured (Bowen) actual evapotranspiration for three crop-growth periods.

Crop Water Uptake

Since crops store very little water, crop water uptake is generally considered to equal actual transpiration. Crop water uptake can be predicted if the amount of soil water available to crops is known. One approach to predicting crop water uptake is to assume all soil water above some lower soil limit is available to plants to the depth of crop rooting. Another approach is to assume that water flows in direct proportion to a potential gradient between the soil and plant and in inverse proportion to the resistance to water flow in the soil and plant. Using this latter approach, either the plant water potential is not allowed to fall below some minimum value, or r_b is increased with decreasing plant potential, thus limiting plant water uptake. In the simulation software GAPS, both these representations of plant water uptake are available for use and have been specifically evaluated in this project. The former approach is referred to as the Tipping Bucket (TB) and the latter as the Richards Equation (RE).

A variable line source sprinkler experiment with maize was conducted during the dry season (April to September) of 1988 at the CPAC. Actual transpiration, as well as soil evaporation and drainage for a range of irrigation rates from 0.3 PET to 1.6 PET were modeled using both TB and RE methods (Figure 4). For irrigation rates less than PET (640 mm for the season), the RE method predicts slightly higher AT rates than the TB approach. Both models predict an almost linear decrease in AT with decreasing irrigation rates below PET. Both methods predict soil water content at irrigation rates less than PET very well, whereas the RE method overpredicts and the TB approach generally underpredicts soil water content at irrigation rates above PET (Figure 5). In both methods, soil water content is overpredicted toward the end of the growing season, almost certainly because our method for estimating PET (Priestley-Taylor, coefficeint of 1.2) did not account for elevated rates of PET due to advection. The close similarity between predicted actual transpiration of both methods under the entire range of irrigation treatments suggests that the concept of "plant available water," though simplistic, is very powerful.

Soil Water Movement

Prediction of soil water movement is important not only for estimating crop water uptake, as mentioned previously, but also for estimating drainage, leaching, and solute

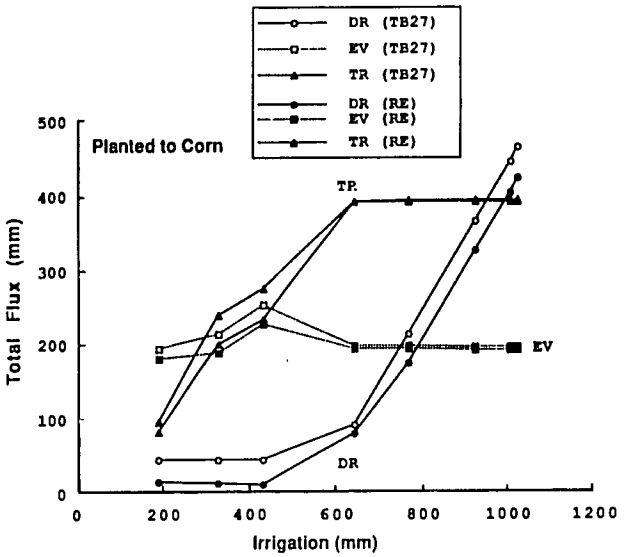

Figure 4. Predicted actual transpiration (TR), soil evaporation (EV), and drainage (DR) using the Richards equation (RE) and Tipping Bucket (TB) methods for maize over the entire crop season for a range of irrigation treatments.

movement within the profile. Both the Richards equation (RE) and the Tipping Bucket (TB) water flow models were found to predict soil profile water contents reasonably well (Figure 5, Table 1). Predictions of water fluxes over the entire growing season and even shorter time periods were very similar (Figure 4). The similarity between predicted water fluxes of both methods under the entire range of irrigation treatments suggests that the TB model, though simplistic, is very useful. Both methods have their respective strengths and weaknesses. The RE performed better in predicting soil water contents over the whole range of irrigation water treatments and is better able to predict soil profile water content distributions. Continuous drainage fluxes are predicted by the RE, whereas discrete flux events are predicted by TB.

Capacity-type flow representations such as the TB routine are used extensively in crop simulation models due to their perceived conceptual simplicity and computational efficiency. It is often argued that input parameters for the TB approach are more easily available than the parameters necessary to estimate the water content-water potential relationship needed for the RE. We found the TB water flow procedure to be very sensitive to the value chosen for field-capacity water content (Table 1). This was particularly obvious in the simulations of fallow soil conditions. Given this sensitivity, the choice of the appropriate soil water potential for field capacity is crucial to this method.

The predictions of water content and plant water uptake using the RE approach are highly sensitive to the parameters calculated for the moisture-release curve. If tested only under a narrow set of environmental conditions, this sensitivity is not always apparent. The wide range of irrigation water treatments used in this study made the sensitivity of the predictions to moisture-release parameters under certain conditions apparent. The soil moisture-release curve of the Oxisol studied resembled a silt loam on the wet end and clay on the dry end. The two-parameter function used to model the moisture-release curve did not provide a good fit to moisture-release data for these soils, when fitted over the whole range of water potentials to -1500 J/kg. If the emphasis of the modeling effort is the prediction of water flow and water contents under well-

Table 1. Summary statistics of simulated versus measured soil node water contents. Regression coefficients were obtained by regressing simulated against measured soil water contents for all eight sampling dates, for all eight sampling depths, and for the four treatments 1.6, 1.0, 0.6, and 0.3 PET. TB method used field-capacity value at 0.27 or 0.30 m^3/m^3.

	Fallow			Planted		
	RE	TB(0.27)	TB(0.30)	RE	TB(0.27)	TB(0.30)
Mean	0.279	0.274	0.304	0.282	0.275	0.301
sd:	0.026	0.003	0.005	0.031	0.006	0.019
Slope	0.808	0.99	1.21	0.87	0.71	0.917
Intercept	0.056	-0.01	0.05	0.04	0.07	0.03
R^2	0.80	0.55	0.59	0.83	0.66	0.70
s.e.Yest	0.016	0.039	0.043	0.023	0.03	0.036
s.e.slope	0.044	0.107	0.118	0.043	0.058	0.069
Measured mean:			0.278			0.261
sd:			0.026			0.038

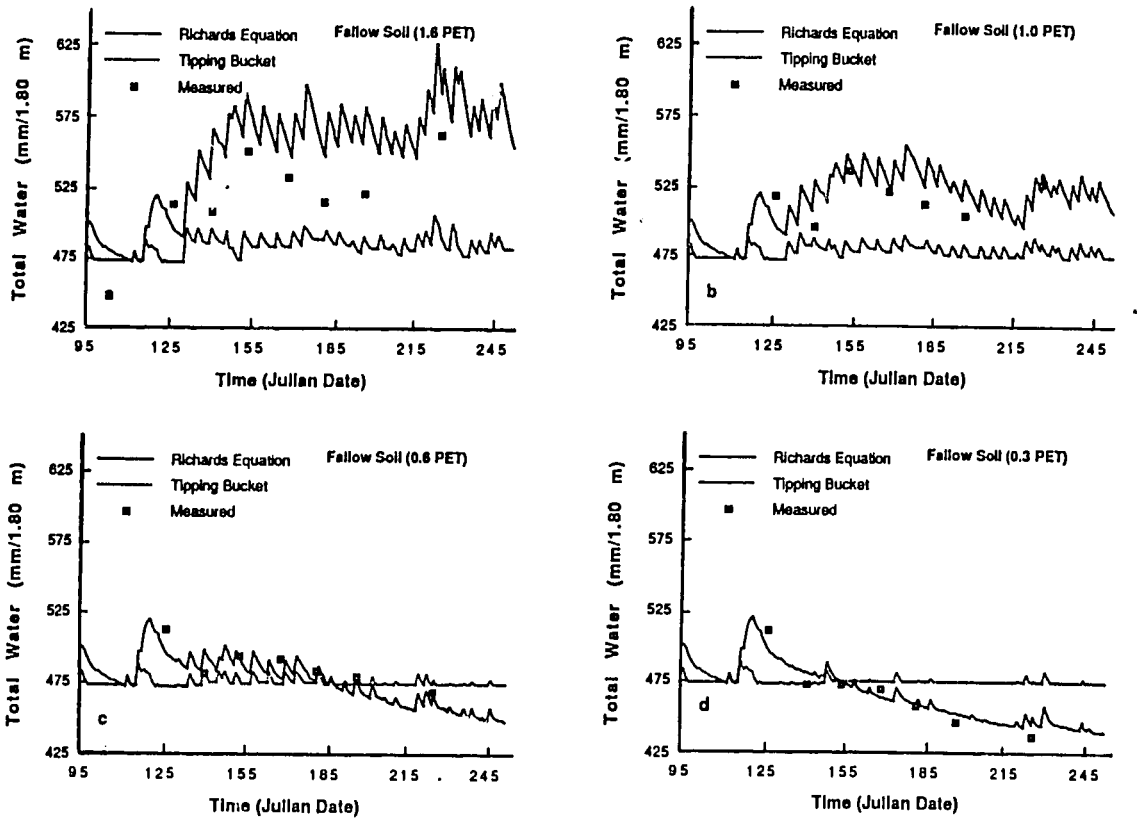

Figure 5. Measured and predicted (RE and TB) total profile soil water for four irrigation treatments over the course of the growing season.

irrigated conditions, it is advisable to use parameters fitted to the wet range (to -100 J/kg) only.

Saturated water contents never reach total porosity in the field for these soils, and the percentage of total porosity at field-saturated water contents appears to be much lower than the percentages assumed for temperate soils. A knowledge of the soil water content at saturation in the field is essential in order to predict soil water contents correctly. The effect of decreased total porosity due to compaction, and reflected in increased bulk densities, does not result in an equivalent decrease in saturated water contents under field conditions.

Maize Growth and Yield under Variable Water Inputs

In order to evaluate the feasibility of maize production and to prescribe maize management in various parts of the Cerrado region, it is necessary to understand the interactions of climate and soil with plant growth in the context of fertility treatments that affect rooting depth. Such understanding is explicitly described in dynamic simulation models of plant-environmental interactions. We wished to assess whether maize simulation models developed and tested in the temperate regions were applicable to tropical savannas like the Cerrado.

The maize model of Stockle and Campbell (1985) was evaluated because it represents physiological processes affected by water stress and is relatively simple. Components of this model were incorporated into GAPS. An experiment in which a line-source sprinkler irrigation system was used to establish a gradient of water treatments for maize was conducted in the Cerrado and used to assess the maize model. Only data from the highest level of nitrogen treatment are discussed in this section.

Dry-matter production, yield and harvest index were all highly dependent on the amount of water applied (Figure 6, 200 kg N/ha treatment). The assumptions relating to the effect of water stress on crop growth inherent in the crop simulation model appear to be generally valid when applied to a tropical acid savanna such as the Cerrado. Predicted leaf area indices and dry-matter accumulation over time compared reasonably well with measured data (Figure 7). Model predictions of final aboveground dry-matter accumulation were about 10% greater than measured production (Figure 8). Under nonstressed conditions, development of LAI during the vegetative period was slightly underpredicted (Figure 7). The leaf area ratio, which effects this prediction, may vary with variety and was found to decline over time for the variety used here. Model predictions of total dry-matter accumulation are very sensitive to the time when the period of rapid leaf senescence begins, since dry-matter accumulation stops at this stage. The thermal unit approach used to estimate this

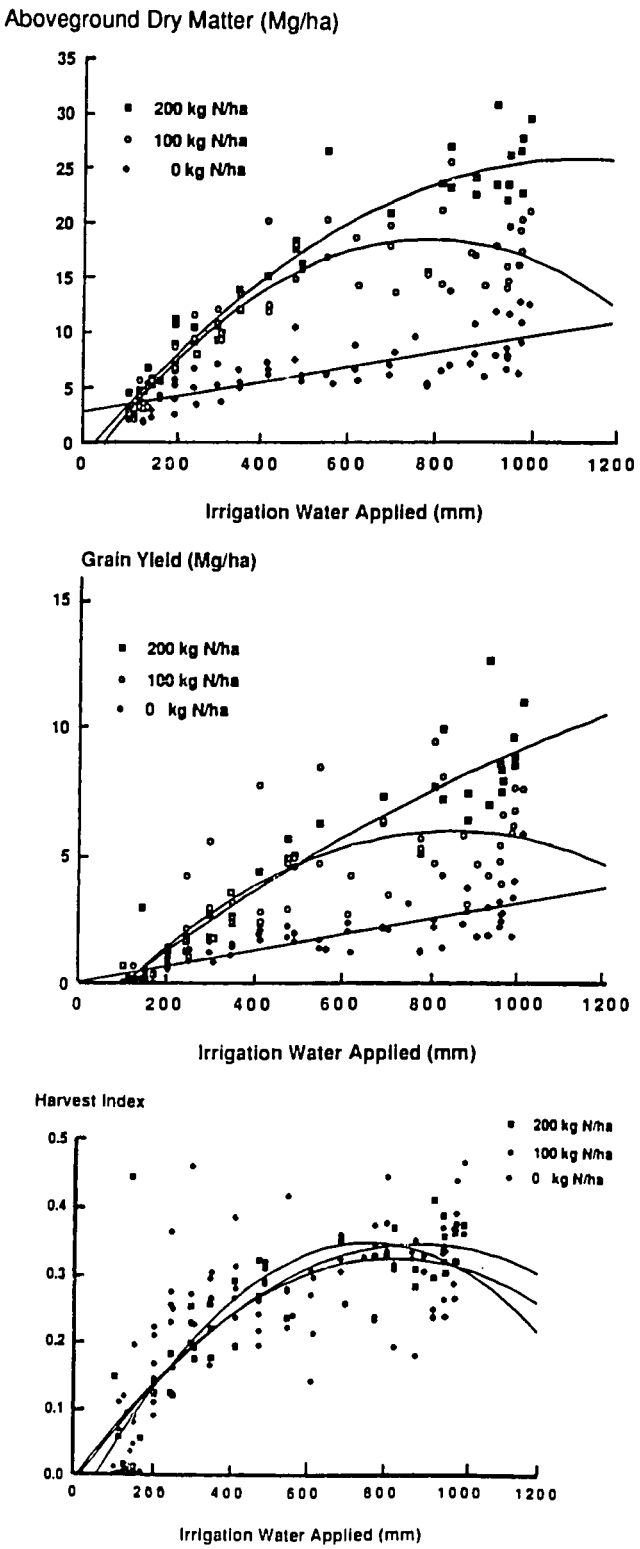

Figure 6. Measured aboveground dry matter, grain yield, and harvest index for maize under a range of irrigation treatments.

stage predicted it to within a few days of actual occurrence, but this amount of error can result in 10% error in predicted total dry-matter production. Harvest index was better related to water stress accumulated throughout the growing season than to water stress accumulated during pollination (Table 2).

Under the water regimes of this experiment, limiting the predicted maximum rooting depth obtainable to less than 1 m reduced predicted actual transpiration and dry-matter accumulation in the water-stressed treatments (0.3 PET and 0.6 PET). Predicted reductions of about 25% in aboveground dry-matter accumulation resulted when roots were restricted to a depth of 0.38 m, compared with 1.05 m. This probably represents the minimum effect of restricted rooting on growth, since in our treatment system, irrigation water for the stressed treatments was applied at low rates, and therefore the wetting front was shallow.

Maize Growth and Yield under Variable Nitrogen and Water Treatments

Efficient nitrogen management is dependent on the crop water regime, both because lack of water can reduce the crop demand for nitrogen and because excess water can cause leaching. To investigate significant nitrogen-water interactions in the line source experiment already described, we applied nitrogen fertilizer as ammonium nitrate shortly after planting at rates of 0, 100, and 200 kg N/ha.

Crop growth was delayed in the excess water treatment (1.6 PET) at the 100 kg N/ha rate and to a lesser degree in the 200 kg N/ha treatment until tassel initiation, presumably due to nitrogen deficiency caused by leaching of N below the root zone. This initial depression in dry-matter accumulation translated into reduced final dry matter and grain yields in the 100 kg N/ha treatment, but not in the 200 kg N/ha treatment (Figure 6). In the 200 kg N/ha treatment, grain yields increased to a maximum of 10 t/ha with the amount of irrigation water applied.

The 100 kg N/ha treatment had a maximum grain yield of 6 t/ha at an irrigation rate corresponding to 1.2 x PET. Without nitrogen fertilizer, dry matter and grain yields hardly were affected by irrigation (Figure 6). Although harvest index was affected by irrigation water application, it was not affected by nitrogen fertilizer rate.

Work is continuing to model the rate of nitrogen movement in the soil profile in relation to crop nitrogen uptake and the consequence of limited nitrogen availability on maize yield.

Conclusions and Implications

The task of developing sustainable agricultural systems that contribute to better management of our natural-

resource base requires a sound and thorough understanding of that base (in this case, the soils, climate, plants and water resources), the dynamic interactions of the components of the system being studied, and the response of that system to human manipulation. Such understanding is only beginning to be developed for tropical acid savannas.

This project is contributing to a better understanding of the dynamic interactions of soils, crops, climate and water. These interactions influence what type of information is deemed most important to gather about the resource base. For example, the results of this project indicate that better predictions of dry-season potential evapotranspiration for the Cerrado will require being able to predict if and when regional advection will occur due to changes in major weather systems. Also, results indicate that simple approaches to predict soil water movement for these soils will require accurate measurements of soil water content

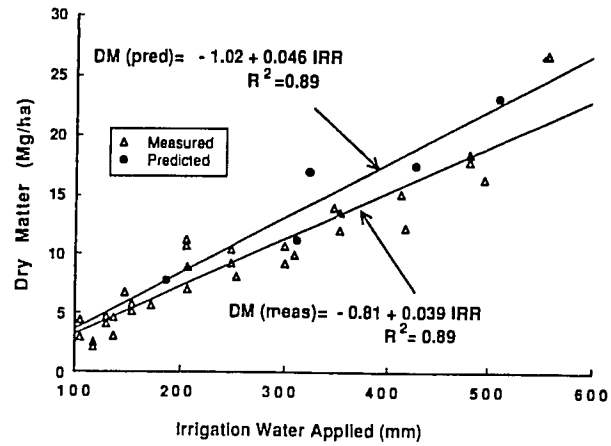

Figure 8. Measured and predicted dry-matter accumulation as a function of irrigation water applied.

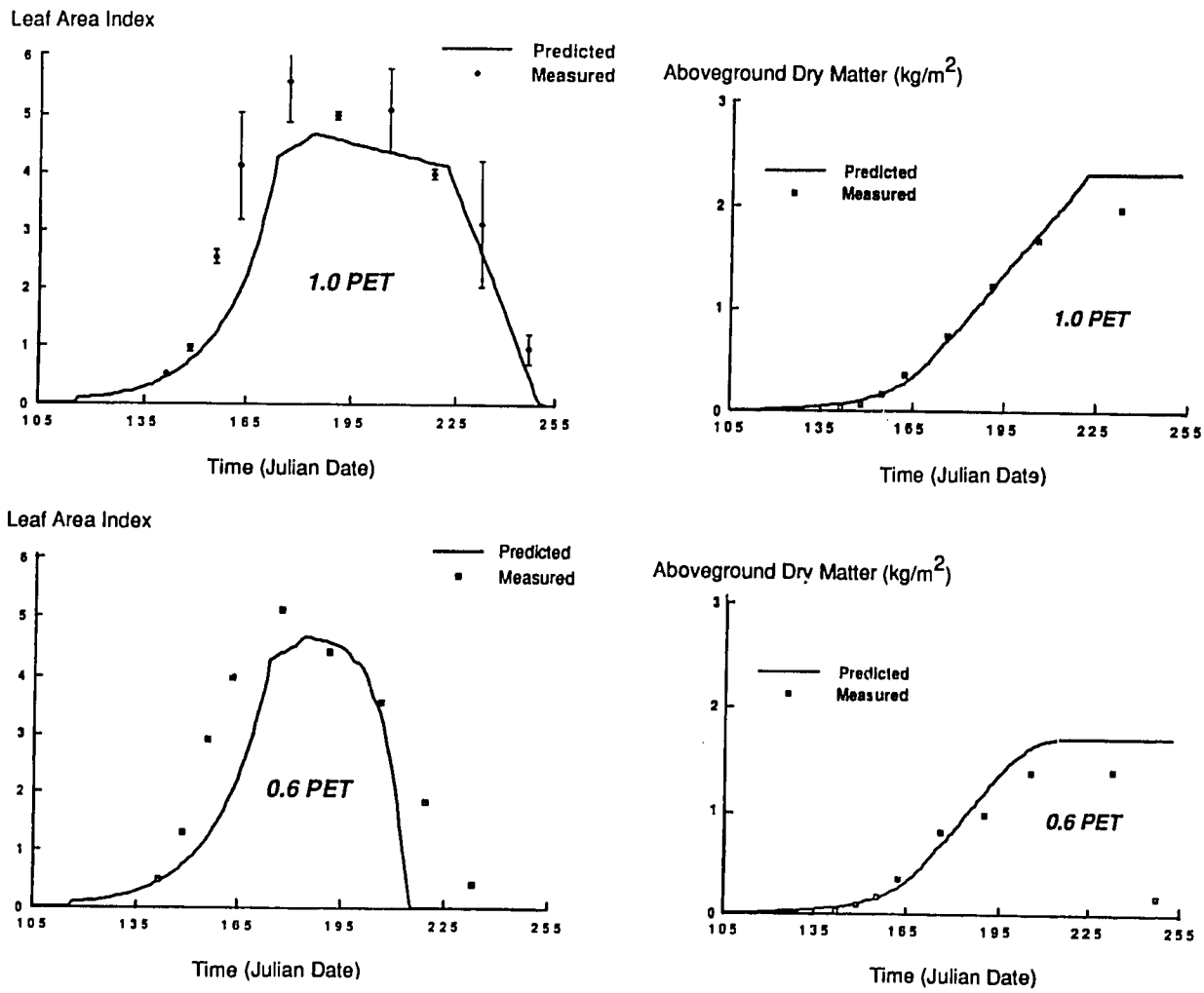

Figure 7. Predicted and measured leaf area index and aboveground dry-matter production for two irrigation treatments (1.0 PET and 0.6 PET.)

at field capacity. To use potential-driven approaches to modeling soil water movement, a two-parameter, soil water potential-soil water content relationship may suffice for irrigated systems, but not for rain-fed systems. Such results can help us decide which properties should be characterized as part of soil surveys.

Understanding the dynamic interactions of system components also can lead to insights into ways these systems could be managed more efficiently. For example, results from our crop-growth study suggest that the relationship between leaf water potential and stomatal conductance may vary with maize cultivar and significantly affect the drought response of the crop. Screening maize varieties for differences in this trait and further field testing might prove useful. Increased rooting depth will probably be more effective in increasing productivity the more highly variable the rainfall. Soil surfaces that conduct heat quickly into the soil may reduce crop transpiration.

Since tropical acid savannas, perhaps more than any other regions in the world, have greater untapped potential for sustainable agricultural production, the formation of a good knowledge base for this region seems particularly crucial. We hope to see continued international collaboration in this effort.

Table 2. Harvest index calculated from experimental data (HI_m), and predicted (HI_p) from accumulated stress during pollination and early grain filling (SI_p), and predicted (HI_t) from total accumulated stress (SI_t) (PET = potential evapotranspiration).

Irrigation (mm)	Irrigation PET	SI_p	SI_t	HI_p[§]	HI_t[¶]	HI_m
500	0.80	0.01	0.04	0.48	0.28	0.26
430	0.67	0.29	3.68	0.46	0.22	0.25
327	0.51	0.36	4.70	0.46	0.21	0.20
316	0.49	5.25	6.88	0.16	0.18	0.19
188	0.29	5.96	10.86	0.12	0.12	0.12

[§]$HI_p = 0.48 - 0.06\ SI_p$, $r^2 = 0.99$, Stockle and Campbell, 1985.
[¶]$HI_t = 0.28 - 0.15\ SI_t$, $r^2 = 0.95$.

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Cation Movement: CU-111

The use of legume green manures in cropping systems will decrease reliance on industrial nitrogen fertilizer. However, sustaining this cropping system will require inputs of other nutrients such as P, Ca, Mg, and K to meet both crop and green-manure requirements. These nutrients inevitably will be depleted from the soil as plant products containing them are removed from the land. In addition, the increased nitrogen supply from the use of green manures likely will lead to nitrate leaching, which will be accompanied by an equivalent amount of cation leaching.

Highly weathered soils of the tropics, such as Ultisols and Oxisols, contain few, if any, primary minerals. Thus the exchangeable pool of the most important plant nutrient bases, Ca, Mg and K, is the only source of these nutrients. This pool is relatively small and, if depleted, can be restored only by soil amendments. Reducing reliance on such amendments and conserving soil nutrients as much as possible will require the development of green-manure cropping systems that minimize leaching losses and promote the recovery of these nutrient bases. Although data are relatively sparse, observation of different legumes during the dry season at CPAC/EMBRAPA, Planaltina, Brazil, suggests that rooting depth among species can vary greatly. If this is true, we would expect differences in the ability of legumes to recover base nutrients from the lower portion of the soil profile. Perhaps the leaching of nutrient bases beyond the root zone can be minimized by combining a deep-rooting legume green manure with an appropriate nonlegume crop. This would be prudent from both an economic and an environmental standpoint. Legume green manures also reduce the loss of soil nutrients by furnishing ground cover that protects the soil from the impact of rain and helps maintain the infiltration capacity of the soil.

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Nutrient Balance for Cropping Systems Based on Legume Green Manures in Oxisols and Ultisols

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Objectives

The objectives of this study are 1) to develop cropping sequences using legume green manures which keep losses of Ca, Mg, K, and NO_3 to economically and environmentally sound levels, and 2) to develop models that describe the losses of Ca, Mg, K, and NO_3 under different soil and climatic regimes and to define the input data required for these models.

Procedure

An experimental area has been established at UEPAE/EMBRAPA, Manaus, Brazil. The soil and climatic regime at Manaus is nearly ideal for this study. The climatic regime is favorable for continuous crop production: precipitation is greater than potential evapotranspiration, so leaching potential is high but not excessive. The soil structure is favorable for deep rooting provided the chemical limitations are ameliorated by liming. The erosion potential is appreciable but not excessive. The Oxisols and Ultisols furnish superior experimental soils for developing cropping systems with acceptable losses of Ca, Mg, and K. This is because the total of these elements is usually small enough that any appreciable loss can be measured over a period of a very few years.

Rotations of legume green manure and corn have been implemented, and soil hydraulic properties measured. Collection of soil samples with depth have been initiated. Soil pH in water and KCl, exchangeable ions, and NO_3 analyses are being performed.

A method for describing uptake and leaching of NO_3 is being developed. Another model has been developed to describe the uptake of Ca, Mg, K, and NO_3 for individual roots (Bouldin, 1989). The resulting models will be combined and expanded to describe the uptake and leaching of these ions.

Results

The goal of this program is to collect the necessary data for a nutrient balance sheet for rotations of legume green manure and corn in the humid tropics. During the past 14 months, two corn crops and two legume green-manure crops have been grown on the experimental area. Soil water tension has been recorded in both fallow and cropped plots. Field data needed for a water release curve, and data on unsaturated conductivity have been collected. Three sets of soil samples to a depth of one meter have been collected, and some parameters have been measured. This field work continues.

Laboratory studies of soil samples taken at CPAC and Manaus showed negligible NO_3 sorption in the surface 30 cm, but sorption increased with depth. In the Manaus samples, at a depth of about one meter, 40 to 60% of NO_3-N was sorbed when soils contained about 100 kg/ha of NO_3-N.

A relatively simple water flow model has been developed as the first part of a model to describe base cation and nitrate loss. The model represents nitrogen mineralization, transport and NO_3 sorption. Experiments at CPAC have routinely included NO_3 analysis of soil samples to a depth of as much as two meters, so some of this data was used to evaluate the model. Data was taken from fallow plots in which different green manures had been incorporated at the beginning of the previous dry season (Carsky, 1989).

During the dry season, the plots were irrigated periodically, and considerable NO_3 accumulated. During the wet season, NO_3 leached fairly rapidly from the upper 30 to 45 cm of soil and accumulated below 90 cm, indicating that NO_3 was sorbed in the lower portions of the soil profile (Figure 1). Data were collected 203 to 354 days after incorporation of the legume green manure. Precipitation during this period was 134 cm. Using the model gave an estimated nitrogen mineralization of 80 kg N/ha. Leaching loss at 180 cm was 60 kg N/ha. While this model is preliminary and results should be interpreted with caution, they do indicate that NO_3 leaching was very sensitive to estimated NO_3 sorption and relatively insensitive to estimated water movement. In fact, to agree with experimental results, the model must include NO_3 sorption increasing significantly with depth. Similar results were obtained using data from both wet and dry seasons at CPAC and from Manaus.

Conclusions and Implications

Preliminary observations and model results indicate several important implications for management of N and green manures. First, anion sorption reduces the hazards of NO_3 leaching. In effect it retards the rate but does not stop leaching. Because of differences in the degree of sorption with soil depth, NO_3 tends to accumulate below 45 to 60 cm and only slowly moves beyond this point. Second, NO_3 in the lower part of the soil profile presumably will be available to plant roots growing into this zone. However, NO_3 efficiency probably will be lower for the subsoil than the upper zone because NO_3 sorption reduces the mobility of NO_3 and hence its movement toward the plant roots by mass flow or diffusion. Perhaps one green-manure crop could supply nitrogen for two nonlegume

crops with modest nitrogen demand by using the "storage capacity" associated with NO_3 sorption. Most of the current systems using green manures are based on a rotation of green manure and nonlegume crops. This means that cropping time allocated to the green manure must be approximately equal to the cropping time allocated to the nonlegume. Perhaps a rotation of legume green manure, nonlegume, nonlegume is feasible if the second nonlegume is deep rooted and the green manure adds sufficient N for both crops.

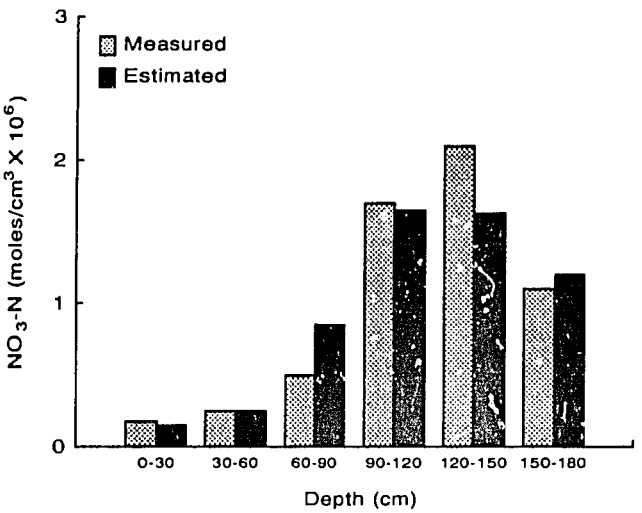

Figure 1. Measured and estimated concentration of NO_3-N in specified layers of soil at day 354.

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R. J. Carsky. 1989. Estimating availability of nitrogen from green manure to subsequent maize crops using a buried bag technique. Ph.D. thesis, Cornell University, Ithaca, N.Y.

Nitrogen Mineralization: CU-110

The previous report on this project *(TropSoils Technical Report, 1986–87)* described effects of inorganic (Ca, P, and S) and organic (green manures) amendments on sulfur availability in Oxisols. This work has been extended and broadened to investigate the effects of lime, gypsum, and green manures on soil-charge characteristics, pH, and KCl-extractable Al.

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Ion Movement in Cerrado Soils: The Effects of Inorganic and Organic Amendments on Soil Properties and Sulfur Availability

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Objectives

One objective of this research was to compare the effectiveness of green manures with lime or gypsum for increasing soil cation-exchange capacity (CEC) and reducing soil acidity and extractable Al. A second objective was to determine the impact of the various treatments on sulfur availability.

Procedure

A field experiment with three successive maize crops (two wet season, one dry season) was carried out on a Dark-Red Latosol beginning with the 1986-87 wet season. The experimental design was a randomized block, incomplete factorial containing 2 lime (0 and 3.4 t/ha) x 2 crop (with and without maize) x 3 gypsum (0, 60, and 600 kg S/ha) x 3 green manure (0, 10 t/ha of either *Canavalia ensiformis* L. or *Panicum maximum* Jacq.) treatments x 3 replications. The green manures were harvested from adjoining areas, chopped, and applied before planting the first two crops. Gypsum and lime were broadcast at the beginning of the experiment. Fertilizer N, P, and K were broadcast annually at average rates of 165, 70, and 100 kg/ha (elemental), respectively. All treatments were incorporated to 20 cm with a rotary cultivator. All data on soil properties are from plots without plants.

Laboratory experiments utilized soil collected from an untreated area adjacent to the field experiment. The 30- to 90-cm depth was used to minimize effects of the native soil organic matter. Soil was mixed 1:1 with sand and incubated at 30°C and 0.025 MPa water content in low-density polyethylene bags, either as bulk samples or in Buchner funnels. Samples in the funnels were leached with water at each sampling time after removing a subsample for analysis.

Results

Effects on Surface Charge

The Dark-Red Latosol had low surface charge. CEC decreased from 1.75 $cmol_c(-)$/kg at 0 to 15 cm to 1.30 $cmol_c(-)$/kg at 90 to 120 cm, and anion-exchange capacity (AEC) increased from 0.11 $cmol_c(+)$/kg at 0 to 15 cm to 0.82 $cmol_c(+)$/kg at 90 to 120 cm. None of the field treatments showed significant effects on either positive or negative charge. However, in laboratory incubation experiments, additions of plant material equivalent to 40 t dry matter significantly increased negative charge up to 59 d but had no effect on positive charge (Figure 1). The transitory effect of plant materials on negative charge suggests that the active organic components of the materials or active organic fractions generated during decomposition were quickly decomposed.

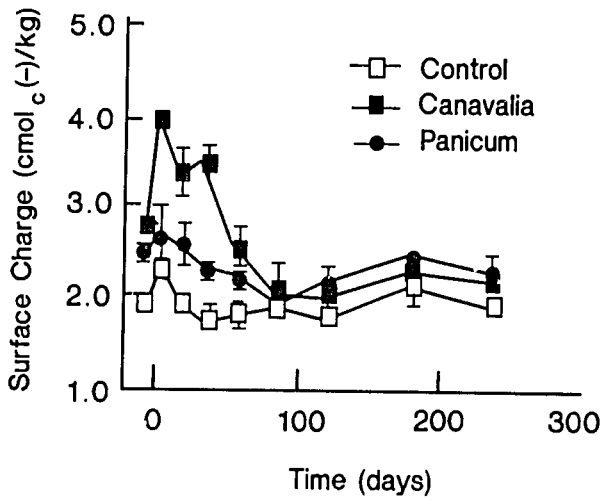

Figure 1. Effect of adding plant materials at a rate equivalent to 40 t dry matter/ha on surface negative charge of a Dark-Red Latosol subsoil incubated in the laboratory at 30°C. Bars indicate one standard deviation.

Effects on pH and KCl-extractable Al

In the field experiment, addition of lime alone or in combination with gypsum significantly increased soil pH in the 0- to 15- and 15- to 30-cm soil depths by 0.3 to 0.7 units. Gypsum alone did not significantly increase pH. Tillage resulted in a 0.3 to 0.4 unit drop in pH, which increased over the growing season. No significant effect of organic materials on soil pH was observed in the field experiment, but pH increased in laboratory incubation at rates equivalent to 40 t/ha dry matter (Figure 2). Additions of *Canavalia* caused the greatest short-term increase in pH, but *Panicum* showed a more persistent effect. Periodic leaching with water shortened the duration of the pH increase after addition of *Canavalia* but did not affect the result with *Panicum*.

Treatment effects on KCl-extractable Al followed the trends observed with pH. After three growing seasons in the field experiment, addition of lime, but not gypsum, significantly decreased extractable Al in the 0- to 15-cm and 15- to 30-cm depths of fallow plots (Table 1). Addition of the green manures tended to temporarily reduce exchangeable Al, although most of these differences were not significant (Figure 3). Nevertheless, the temporal patterns of these effects mirrored those observed in laboratory incubations (Figure 4).

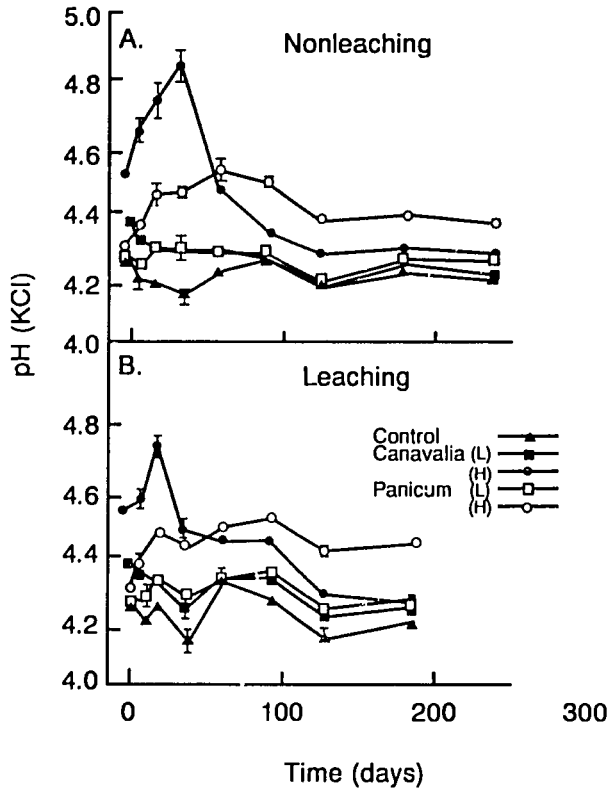

Figure 2. Effect of plant materials and leaching on pH of a Dark-Red Latosol incubated in the laboratory at 30°C. Levels L and H refer to additions equivalent to 10 and 40 t dry matter/ha, respectively. Bars indicate one standard deviation.

Table 1. Effects of lime (3.4 t/ha) and gypsum (2.8 t/ha) on KCl-extractable Al in soils 500 days after incorporation into fallow field plots.

Treatment	Soil depth (cm) 0-15	15-30	30-45
	cmol$_c$/kg		
No lime, no gypsum§	1.00a*	0.99a	0.55bc
No lime, no gypsum¶	1.12a	1.01a	0.72b
Lime, no gypsum	0.47bc	0.40bc	0.40bc
No lime, gypsum	1.26a	0.95a	0.54bc
Lime, gypsum	0.36c	0.28c	0.25c

*Values followed by the same letter are not significantly different at the 5% level.
§Value at day 0.
¶Value at day 500.

Effects on K and Ca

After three crop cycles and addition of 300 kg K/ha, the fallow plots of all treatments showed substantial leaching losses of K. In contrast to other studies, lime or gypsum reduced K loss and were most effective when added together (Figure 5). These results cannot be explained by pH effects on CEC since gypsum did not measurably alter pH, and lime and lime plus gypsum had comparable effects on pH, which increased at the end of three crop cycles from 4.6 to 5.2 in both the 0- to 15-cm and 15- to 30-cm depth increments and from 4.6 to 4.9 in the 30- to 45-cm depth increment. However, lime plus gypsum was also more effective than lime alone at reducing KCl-extractable Al in the 15- to 45-cm soil depth, perhaps increasing availability of exchange sites.

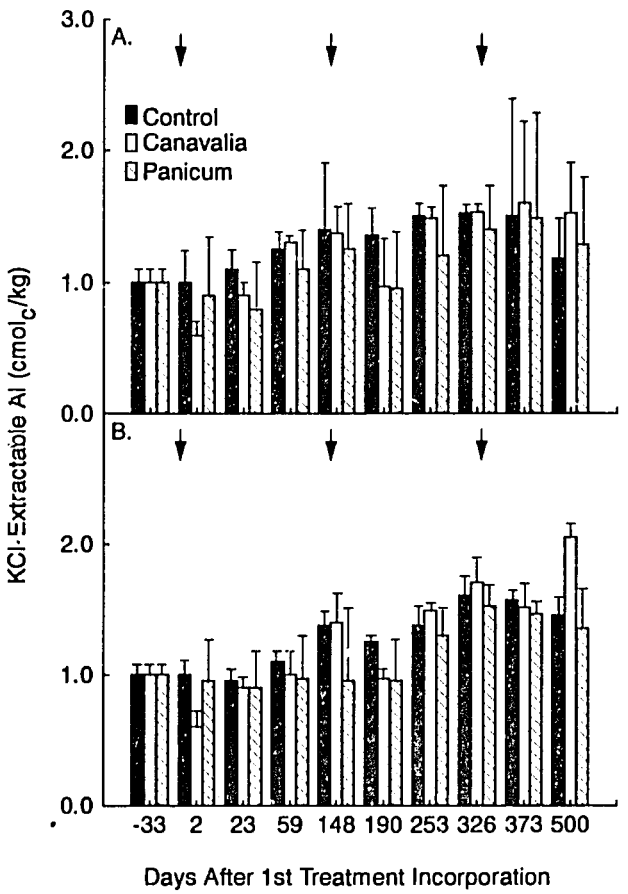

Figure 3. KCl-extractable Al in fallow field plots with and without adding plant materials (10 t dry matter/ha) with (B) and without (A) gypsum (2.8 t/ha). Arrows indicate times of tillage and plant incorporation (first two times only).
Tillage 1—Plant material incorporated.
Tillage 2—Plant material incorporated.
Tillage 3—Tillage only.
Tillage 4—Plant material incorporated.
Tillage 5—Plant material incorporated.
Tillage 6—Tillage only.

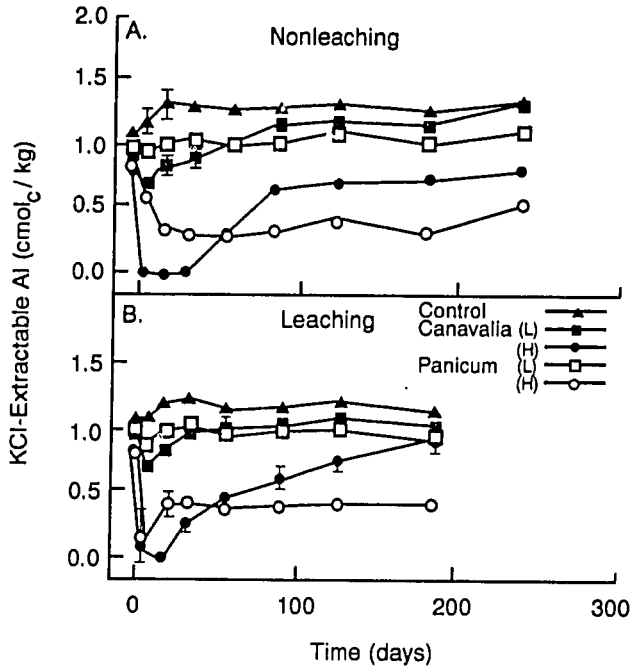

Figure 4. Effects of adding plant materials and leaching on KCl-extractable Al in a Dark-Red Latosol subsoil incubated in the laboratory at 30°C. Levels L and H refer to additions equivalent to 10 and 40 t dry matter/ha, respectively. Bars indicate one standard deviation.

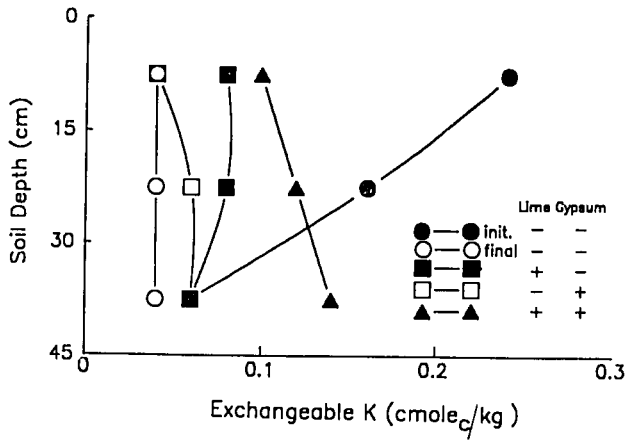

Figure 5. Exchangeable K in soils of fallow field plots 500 days after initiation of the experiment. Lime (3.4 t/ha) and gypsum (2.8 t/ha) amendments were made at the beginning of the experiment, and additions of K (~100 kg/ha) were made at days 0, 148, and 326.

Additions of green manures did not affect K levels in the field experiment, but effects on leaching of Ca and K were observed in the laboratory incubation study when the equivalent of 40 t dry matter/ha was added. Both Ca and K were added in the green manures, and periodic leaching of the soils led to greater relative loss of Ca and K from the *Canavalia* amendment than from the *Panicum* amendment. This result is consistent with the pH and surface charge differences induced by additions of these plants (Figs. 1 and 2). Evidence for preferential loss of K relative to Ca was found with the *Panicum* addition but not with the *Canavalia* addition.

Effects on Sulfate Adsorption

Adsorbed sulfate was measured as the difference between that extracted by $Ca(H_2PO_4)_2$ and KCl. To aid comparisons over a range of soil sulfate contents, sulfate adsorbed (SAD) was expressed on a proportional basis where SAD (%) = (P sulfate S – K sulfate S)/P sulfate S x 100. For results of the field experiment on the effects of lime and plant residues on SAD, see Figure 6. Additions of *Panicum* or lime reduced SAD to about 65% of the initial value, but the effect of the *Canavalia* addition was smaller and less persistent. No consistent effects of green manures in combination with lime were observed.

Effects of Nutrient Uptake and Yield of Maize

No consistent grain yield response was detected with green-manure additions. However, these materials increased total dry-matter yield by 1.3 to 3.5 t/ha. Additions of 60 or 600 kg S/ha as gypsum also increased total dry-matter yield by 0.5 to 3.2 t/ha. Maize yield response to additions of organic materials was attributed to increased K availability. With gypsum, a sulfur response was detected the first two growing seasons. Due to the diminishing residual effects of added lime, a Ca response was seen in the third growing season.

Conclusions

As expected, incorporation of lime into an acid Oxisol significantly increased negative charge and pH, and reduced KCl-extractable Al. Effects of gypsum and plant materials, however, were dependent on the rate applied. Gypsum at the 2.8 t/ha rate did not have any of the effects on surface charge, KCl-extractable Al, pH, and cation movement reported in experiments that utilized higher rates. In general, the combination of lime and gypsum was more effective than lime alone in reducing soil acidity and improving soil base status.

Green manures increased negative charge, pH, and cation retention, and reduced KCl-extractable Al and sulfate adsorption in laboratory studies when applied at rates equivalent to 40 t dry matter/ha. However, the extent and duration of these effects were dependent on the type of material applied. Microbial decomposition processes may both generate and degrade organic components, such as organic acids, which can complex with Al or provide increased negative charge. Except for the effect of *Panicum* on sulfate adsorption, effects of plant materials

added in the field at 10 t dry matter/ha were barely perceptible. However, trends consistent with the laboratory results were observed. Because the application of large quantities of organic matter is not practical, management practices that concentrate organic materials, perhaps with other amendments, might be beneficial.

Implications

The research demonstrates that adding green manures to acid soils can have a beneficial influence on several soil properties important to crop growth. Actual effects depend upon both residue type and quantity added. In general, the quantity of residue necessary for soil improvement appears to be so high as to make application impractical. Since the effects of one of the two residues studied were quite persistent, the long-term application of appropriate green manures should be investigated. Alternatively, short-term benefits may be realized in the growing season by concentrating green-manue ammendments in small soil volumes (i.e., "banding").

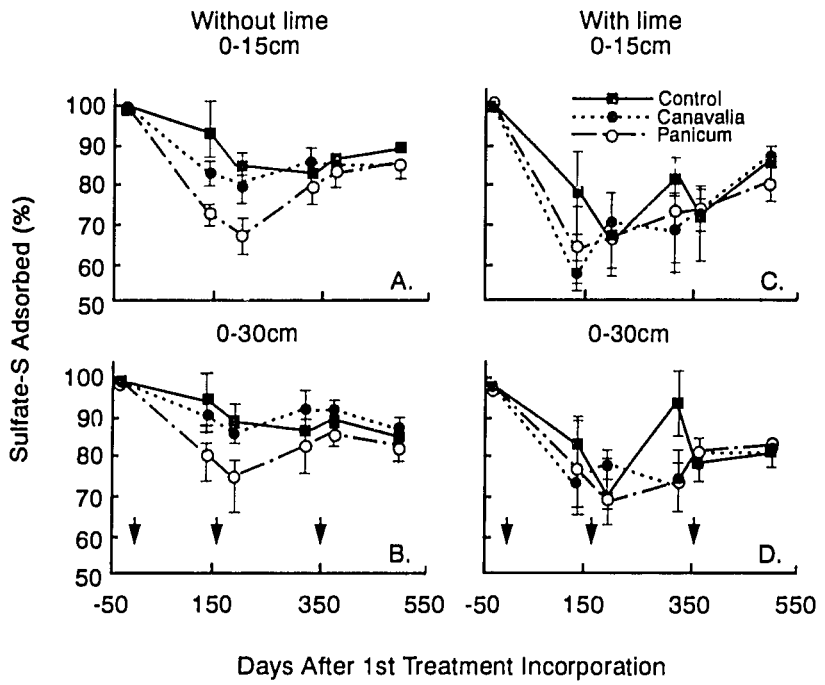

Figure 6. Effects of adding lime and plant materials (10 t dry matter/ha) on sulfate adsorption in fallow field plots following addition of gypsum (2.8 t/ha) at day 0. Bars represent one standard deviation. Arrows indicate times of tillage and plant incorporation (first two times only).

Soil and Crop Management: CU-103

Nitrogen is the nutrient that most often limits maize yields in the tropics. The N must be obtained either as commercial fertilizer or through N fixation by legume. The cost or availability of commercial fertilizers often prohibits their use; therefore, legume green manures can play an important role in supplying N. The legume green-manure crop must be able to fix and supply sufficient N for the succeeding crop(s) without large excesses. This requires that the system be balanced with respect to N fixation by the legume, rate of N mineralized by the green manure, N used by the crop, and N losses from the system. To develop systems that maximize the use of the legume green manures, N requirements and uptake patterns of the succeeding crop(s), N fixation characteristics of the legume green manure, N mineralization rates, and N losses from the system must be determined. Currently, legume green manures require relatively high management and produce some uncertainty relative to N availability and management; thus green manures are not used as intensively as they should be.

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Soil- and Crop-Management for Acid Savanna/Humid Tropical Soils Using Green Manures and Crop Residues as Nitrogen Sources

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Objectives

The objective of this project is to evaluate legume green manures as sources of N for succeeding nonlegume crops in rotations. Since the number of potential green manures is very large in relation to the number that can be tested in specific rotations, we are evaluating procedures for screening large numbers of potential green manures along with our tests in actual rotations.

Procedure

An experiment with green manures in rotations with maize was performed in the period 1986 to 1988 at Planaltina, Brazil (Carsky, 1989). The green manures were grown during the rainy season (December 1986 to April 1987), followed by maize (Cargill 111s) with irrigation (April to October 1988) and a second maize crop during the following rainy season (November 1988 to March 1989).

Results

Relevant data is listed in Table 1. The yields of the first crop of maize obtained with the two best legume green manures (*Canavalia ensiformis* and *Crotalaria striata*) were equivalent to that obtained with 175 kg/ha fertilizer N. The residual effects measured with the second crop of maize were equal to an additional 35 kg/ha of fertilizer N; the total effect was thus equal to over 200 kg/ha of fertilizer N.

Three methods of screening legume green manures were studied in several field experiments. One method, referred to here as the fallow soil method, involved establishing bare fallow plots that were treated the same as the plots cropped to maize except that no maize was planted and the plots were kept free of weeds during the period when the remainder of the plots were cropped to maize. Periodically these plots were sampled to depths of about one meter, and the inorganic N content was determined. Another method, referred to as laboratory incubation, was carried out by taking samples from field plots after incorporation of green manures and incubating samples in the laboratory for one or two weeks under ideal conditions. A third method, referred to here as the buried bag method, is similar to the laboratory incubation method described above except the incubation was carried out in the field in buried plastic bags. Periodically the bags are retrieved and analyzed for inorganic N.

All three methods have proven useful, and the results generally have been correlated with yields. Results with the fallow soil and buried bag methods are shown in Figure 1 (Carksy, 1989, p. 118, Figures 4-23).

Our experience with the screening methods has been favorable. Each has its weaknesses and strengths. With all methods, careful attention to experimental protocol is necessary. The fallow soil method is useful when it is practical to take samples to the rooting depth and where leaching beyond the rooting depth is not likely to be a problem; these problems have not been important in our experiments. Both incubation procedures require very careful sampling procedures of the soil following incorporation of the green manure and taking subsamples for the experimental incubation units to ensure that the samples are representative of the field plots. The buried bag method is useful because the temperature regime during incubation is similar to cropped field temperature, while in the laboratory method, the temperature regime is very different from the field temperatures. Studies of laboratory incubation indicated that as long as there is some degree of soil aggregation, soil disturbance encountered in

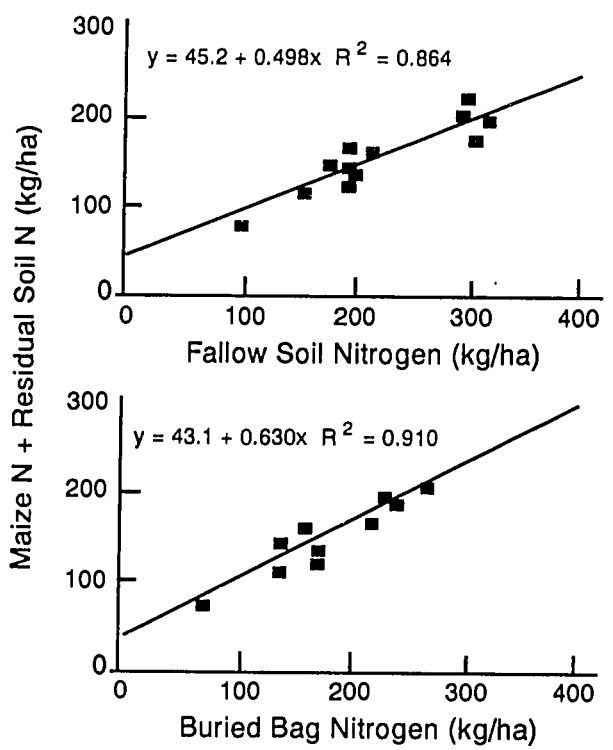

Figure 1. Relationship between the sum of the above-ground maize N and cropped soil residual inorganic N at harvest and available soil N as determined by the fallow and buried bag methods.

sampling has no effect on N mineralization. Laboratory incubations may be effective for quantifying differences in N mineralization due, for example, to soil-management practices, but do not appear to be a quantitative measure of the residual effects of a legume green manure on a succeeding crop (Klausner, Suhet, and Duxbury, 1990). In all methods, the water regimes are different from those in the cropped plots; in our experiments, severe water deficits in the cropped plots were uncommon, so effects of differential water contents were not very important.

Conclusions and Implications

One of the more useful aspects of the fallow soil method is that the time-course of mineralization and nitrification in the field can be followed if samples are taken at about every two weeks following incorporation. Our experience in several studies in Planaltina is that mineralization of N is rapid over about the first six to eight weeks and then becomes very slow. Usually mineralization is more rapid than the capacity of a developing maize crop to take up N, and thus considerable inorganic N may accumulate early in the season. Although leaching of this NO_3 from the plow layer may occur, it is "captured" by NO_3 sorption in the layers deeper than about 45 cm. The total quantity of N fixed and subsequently mineralized is equivalent to 200 kg of fertilizer N. Yields of maize using only legume green manures have reached 8000 kg/ha.

Table 1: Production of grain by two succession crops of maize, at Planaltina, Brazil, following incorporation of several legume green manures. The first crop was grown during the dry season with irrigation, and the second crop was grown during the wet season. Fertilizer N was applied to both crops, but only one green manure crop was grown.

Treatment	N added	Yield of grain		N in crop	
		Crop 1	Crop 2	Crop 1	Crop 2
	kg/ha	—— mt/ha ——		—— kg/ha ——	
Control	0	3.3	3.1	69	67
Fertilizer, 100 kg N/ha	200	5.0	5.4	119	113
Fertilizer, 200 kg/ N/ha	400	7.2	6.9	198	177
Cajanus+	229	6.9	3.9	149	86
Calopogonium§	142	6.1	3.4	186	72
Canavalia b¶	228	6.6	3.8	159	79
Canavalia e#	231	6.4	4.1	177	82
Crotalaria++	306	6.6	4.3	180	96
Pueraria§§	116	5.7	2.9	112	60
Mucuna¶¶	152	6.5	3.0	130	67

+Cajanus cajan (pegeon pea)
§Calopogonium mucunoides
¶Canavalia brasiliensis (jackbean)
#Canavalia ensiformes
++Crotalaria striata
§§Pueraria phaseoloides (Kudzu)
¶¶Mucuna aterrima (velvet bean)

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Low-input Cropping Systems: NC-2

Significant progress has been made on this project during the last five years. A low-input cropping system has been developed in Yurimaguas to serve as a transition technology between shifting and continuous cultivation for acid soils of the humid tropics. Its principal features are 1) clearing forest fallow with traditional slash-and-burn methods; 2) rotating acid-tolerant rice and cowpea cultivars and removing only the grain, thus maximizing nutrient cycling; 3) working without fertilizers, lime, or organic inputs brought from outside the field; 4) using locally available herbicides and insecticides; 5) terminating cropping after two to three years due to increasing weed pressure and deficiency of phosphorus and potassium; 6) planting a kudzu fallow to smother weeds and slashing-and-burning it after one year; and 7) subsequent options: grass-legume pastures, agroforestry, or intensively fertilized continuous cropping.

During a three-year period, five crops of upland rice and two of cowpeas were produced on soil with pH 4.5. Nutrients accumulated by crops were recyled back to the soil as follows: more than 50% of the biomass N and Mg, about 90% of the K and Ca, but only 37% of the P. Herbicide accounted for 8% of total production costs. The system was highly profitable when compared to traditional shifting cultivation. These results have aroused considerable interest by network cooperators and AID.

The questions now arising are those of sustainability. How can the system—which is presently considered transitional—be transformed into a sustainable, hi-tech version of shifting cultivation? Instead of one year of crops and 12 years of fallow, this system may produce two to three years of crops and only one year of fallow. The constraints to that possibility are clearly two: nutrient depletion and weed encroachment. There are no major soil-loss considerations because there is no tillage and because the soil surface is always protected by a crop canopy, a mulch, or crop residues.

Our germplasm base for the low-input system remains very narrow: one upland rice variety with poor grain quality and two cowpea varieties. A major effort is needed to find acid-tolerant rice varieties with good grain quality, to broaden the germplasm base of cowpea cultivars, and to search for high Al tolerance in other crops, particularly grain sorghum and sweet potatoes. Our managed fallow germplasm base is even narrower: kudzu. Other species that have shown promise in Yurimaguas and Manaus must be tested for growth pattern, weed suppression, rooting depth, and nutrient-release characteristics under acid soil conditions.

Summary of Results: Y-200A

Pedro Sanchez, N.C. State University

The second cropping period after one or more years of kudzu fallow was shorter than the first. Instead of producing seven crops in three years without external nutrient inputs, only three acceptable crops can be produced in the second go-around. Weed pressure becomes progressively worse and fertility depletion continues, probably due to net phosphorus export via grain removal. Attempting to prolong the initial cropping period with unrealistically high levels of herbicide application did not improve the performance of the second cropping period. *Mucuna cochinchinensis* was not an adequate fallow because it set seed and died in August, leaving opportunities for greater weed encroachment. Kudzu continues to be the best fallow species at Yurimaguas.

The search for corn and soybean varieties that are both high-yielding and Al-tolerant continues to produce promising results, but no solid findings. Two new upland rice lines, IRAT 120 and ITA 235, appear to perform better than traditional lines under high Al saturation and to have more desirable grain characteristics and greater tolerance to fungal diseases. Some peanut varieties appear very tolerant to Al toxicity but have low yield potential. A host of new cowpea varieties showed both Al-tolerance and high yield potential. Some promising sweet potato varieties have been identified.

A 12-crop potassium-dynamics experiment shows that returning crop residues practically eliminates the need for K fertilization in this system.

A chronological nutrient-depletion study shows that with appropriate weed management, eight crops of rice and cowpea were produced in three years without a significant response to nitrogen or phosphorus fertilization.

Central Low-input Cropping Experiment: Second Cropping Cycle: Y-210

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The objectives, procedures, and results of the first three years of this low-input system have previously been described (*TropSoils Technical Report, 1985–1986*). The low-input system consists of slash-and-burn clearing, planting acid-tolerant crop cultivars, and recycling crop residues. Five upland rice crops and two cowpea crops were harvested before the system collapsed in June 1985 (Table 1). At that time, the one-ha field was divided into eight 1250 m^2 plots.

In the current study, four treatments were randomly assigned with replicates blocking the previous fertilizer differential. The treatments consisted of 1) converting to a high-input system; 2) continuing the low-input system with conventional weed control (preemergence application of contact herbicides); 3) continuing the low-input system with full, but economically unrealistic, weed control (preemergence application of metolachlor and sethoxydim supplemented by hand weeding as needed); and 4) converting to a kudzu fallow and starting a second cropping cycle, four years after land clearing. Treatments 2 and 3 were designed to test whether weeds significantly limited crop production. Treatment 4 was designed to determine whether a short-term kudzu fallow could restore productivity to the system. An economic analysis of the system was also presented in *TropSoils Technical Report, 1986–1987*. A full history of each system with planting dates and crop yields is shown in Table 1.

The Second Cropping Cycle

System 4 follows the original concept: a first cropping cycle of seven crops lasted three years; a kudzu fallow lasted one year; and a second cropping cycle's duration was determined by crop performance, soil fertility degradation, and weed encroachment. Burning the kudzu fallow provided significant nutrient inputs from the ash (see 1986–87 technical report) and resulted in an excellent rice crop, yielding 3.9 tons/ha of grain. Weed suppression by the kudzu fallow and favorable rainfall also contributed to high yields. Crop 9 received 30-22-40 kg/ha of an NPK fertilizer. Although the fertilizer application produced no significant yield response for crops 9 or 10, a significant residual yield response was evident for crops 11 and 12 (Table 1).

With time, yields declined, and the system was then put in a second managed fallow after the fourth consecutive crop. *Mucuna cochinchinensis* was used as a fallow, but after the seeds were set in August, it died, perhaps as the

Table 1. Planting and harvesting history of control low-input experiment.

Crop no.	Crop or fallow	Planting date	Harvest date	Grain yield (t/ha)		
First cropping cycle (uniform)						
1.	Rice	9-01-82	1-17-83	2.4		
2.	Rice	2-11-83	6-11-83	3.0		
3.	Cowpea	9-07-83	11-11-83	1.1		
4.	Rice	12-15-83	4-23-84	2.8		
5.	Cowpea	5-09-84	7-21-84	1.2		
6.	Rice	9-05-84	1-02-85	1.8		
7.	Rice	2-26-85	6-30-85	1.5		
Experiment subdivided into 4 systems, 2 reps each (August 1985)						
High-input cropping (system 1)						
8.	Corn cv.	9-09-85	1-10-86	3.86		
9.	Corn cv	3-22-86	7-24-86	2.90		
10.	Soybean cv.	9-11-86	12-23-86	1.87		
11.	Corn cv.	4-11-87	8-28-87	2.31		
12.	Corn cv.	10-05-87	1-29-88	3.31		
13.	Mucuna fallow	3-14-88	3-3-90			
14.	Kudzu fallow	3-3-90	in progress			
Low-input conventional weed control for 10 crops in first cropping cycle (system 2)						
8.	Cowpea	8-19-85	10-31-85	0.58		
9.	Rice	1-09-86	5-09-86	0.09		
10.	Cowpea	7-15-86	9-25-86	0.43		
11.	Kudzu fallow #1	11-26-86	9-15-87			
12.	Rice	10-15-87	2-15-88	2.05		
13.	Rice	3-11-88	7-14-88	0.87		
14.	Cowpea	8-17-88	10-24-88	0.45		
15.	Kudzu fallow #2	11-01-88	in progress			
Extended low-input cropping with full weed control for 12 crops (system 3)						
8.	Cowpea	8-19-85	10-31-85	0.58		
9.	Rice	1-09-86	5-09-86	1.60		
10.	Cowpea	7-15-86	9-25-86	0.42		
11.	Rice	11-21-86	4-10-87			
12.	Cowpea	5-08-87	7-16-87	0.78		
13.	Kudzu fallow #1	10-26-87	11-23-89			
14.	Rice (ITA 235)	12-11-89	4-26-89	§		
15.	Kudzu fallow #2	5-9-90	in progress			
Original system 7 crops—1 fallow—4 crops, second fallow (system 4)						
				— Fertilizer Applied¶ —		
				No	Yes	LSD.05
8.	Kudzu fallow #1	8-28-85	9-13-86			
9.	Rice	9-26-86	1-22-87	3.86	3.98*	0.41
10.	Rice	2-13-87	6-18-87	1.87	2.09	0.36
11.	Cowpea	7-13-87	0-23-87	0.79	1.02	0.16
12.	Rice	10-15-87	2-15-88	0.65	1.24	0.45
13.	Mucuna fallow	3-14-88	9-01-88			
14.	Kudzu fallow #2	9-02-88	in progress			
15.	Rice (ITA-235)	12-11-89	4-26-90			
16.	Kudzu fallow #3	5-9-90	in progress			

§ Crop destroyed by disease.

¶ Fertilizer was 30-22-40 kg/ha NPK to crop 9.

result of a photoperiod problem, which would certainly limit the effectiveness of mucuna as a long-term fallow. Planted on March 14, it lasted only 5.5 months. Although mucuna reseeded itself, weed encroachment became evident. We then reverted to our tried-and-true standby and planted a kudzu fallow in September 1988. That fallow is still on the ground.

The second cropping cycle in this low input system therefore lasted effectively for three crops before yields declined below an acceptable level. The first cycle produced seven such crops. A one-time NPK application lengthened the cropping period to four crops (Table 1). Weed pressure was fairly high. Despite two hand weedings during the cropping cycle, weed biomass at harvest was 2 t/ha (Table 2). It is likely that increasing weed competition and declining soil fertility were responsible for decreasing yields.

Second Cropping Cycle after an Extended First Cropping Cycle (System 2)

A kudzu fallow was established in System 2 following the 10th crop to determine whether a short-term fallow could increase subsequent crop productivity. This was the first kudzu fallow ever planted in this treatment. The system was under continuous cropping since September 1985 (five years before) with no nutrient inputs from outside the field. After 10 months of growth, kudzu was slashed and then burned. Then, an upland rice crop was planted, and the weeding regime in this system was changed. Contact herbicide use was discontinued, and, when necessary, crops were weeded manually.

The aboveground and belowground biomass and the nutrient content of the 10-month-old kudzu fallow (just before burning) are shown in Table 3. During 10 months of growth, it accumulated large quantities of all macronutrients. The majority of these nutrients were found above the ground.

Slashing-and-burning the kudzu fallow resulted in marked improvements in topsoil chemical properties. Levels of all major nutrient cations increased by 50% or more, and Al saturation decreased by approximately 35% (Table 4).

After the rice was planted (crop 12), the field was manually weeded once to remove *Roettboellia exaltata*, a

Table 2. Distribution of weed biomass by species§ in the various low-input systems

System (Date)	Weed biomass									
	RE	TO	EP	DS	PG	CY	PT	CP	Other	Total
	t/ha									
2(10/87)	1.53								0.05	1.58
2(2/88)		0.37	0.29	0.20	0.12	0.11			0.09	1.18
3(4/87)		1.31		0.87	0.06		0.09	0.09		2.42
4(12/87)				0.35	0.41		0.93	0.22	0.17	2.08
4(1/88)		0.25		0.33	0.08		0.97	0.34	0.04	2.01

§ RE = *Roettboellia exaltata*, TO = torourco (*Paspalum conjugatum*), EP = escama de pescado (*Lindernia humilis*), DS = *Digitaria sanguinalis*, PG = pata de gallo (*Elausine indica*), CY = *Cyperaceae* sp, PT = *Panicum trichoides*, CD = *Commedlina* sp.

Table 3. Biomass and nutrient content, above and below the ground, in the 10-month-old kudzu fallow in System 2 immediately before burning, Yurimaguas, Peru, September 15, 1987, five years after clearing the forest.

Part	Biomass	N	P	K	Ca	Mg	Zn	Mn	Fe	Cu
	(t/ha)	kg/ha								
Above-ground	8.5	252	33	158	49	16	0.16	1.96	1.4	0.08
Roots§	0.44	9	1.2	3	1.5	0.5	0.002	0.02	0.27	0.01

§ Measured to a depth of 25 cm.

pernicious weed. Three months afterward, at crop harvest, weed biomass was low, on the order of 1.2 t/ha (Table 2). The grain yield of upland rice (2.03 t/ha) was comparable to that obtained in the first crop following the slash-and-burn clearing of the forest (Table 1). Reduced weed competition and improved topsoil fertility are probably responsible for the large improvement in crop production compared to yields obtained before establishment of the kudzu fallow. The positive effect of a short-term (less than one year) kudzu fallow on subsequent crops declined to less than half due to an increase in soil fertility and weeds. Consequently, the plots were again planted to kudzu. The second cropping cycle under this sequence was able to produce only one good crop of rice. Pushing the system with 10 consecutive crops during the first cycle prior to the kudzu fallow, therefore, does not seem appropriate.

Continuation of the First Cropping Cycle with Full Weed Control (System 3)

Crop yields slowly declined with time (Table 1) and the field was put into a kudzu fallow following the 12th crop (cowpea).

Yield decline was due to low levels of N and K in the soil (total N in the soil was 0.04% and exchangeable K was 0.07 cmol/L). However, even with full weed control and a highly competitive cowpea crop, weed biomass measured soon after harvest was high (2.42 t/ha) (Table 2). This suggests that after a long period of continuous cropping in a no-till system, weeds become extremely difficult to control (even with economically unrealistic prevention measures) and affect crop yields. Tillage is probably needed in order to properly control weeds as determined by Mt. Pleasant and McCollum in the 1986-87 technical report.

High-input Cropping

Corn grain yields in the 11th crop of System 1 were low (2.3 t/ha), but yields in the 12th crop (corn) were similar to previous corn yields in this system (3.3 t/ha). After the 12th crop, *Mucuna cochinchinensis* was planted as a fallow in order to reduce weed populations (Table 1). Yields for the system appear as stable as the other high-input systems at the station.

Comparisons of Weed Populations

A comparison of weed biomass at or near the harvest of the 12th crop shows that total weed biomass in System 2 was approximately half that of system 3—even though the latter received the full herbicide treatment (Table 2). The result from System 3 suggests that even with large investments in herbicides, chemical control of weeds becomes increasingly difficult to sustain. Reduced weed biomass in System 2 was probably due to the effect of the 10-month kudzu fallow which preceded the 12th crop and the effectiveness of a hand weeding approximately one month after planting.

Weed biomass was distributed among a greater number of species in System 2 than in System 3. In System 2, *Paspalum conjugatum* and *Digitaria sanguinalis*, both annual grasses, and *escama de pescado* (*Lindernia humilis*), a broadleaf herb, contributed approximately 80% of the weed biomass. In System 3, *Paspalum conjugatum* and *Digitarin sanguinalis* contributed approximately 90% of the weed biomass (Table 2). Increases in weed biomass and the shift to a weed spectrum previously dominated by grasses have been observed in low-input systems at Yurimaguas. It is not possible to determine if these differences are due to the kudzu fallow or to types of weed control. Both *P. conjugatum* and *D. sanguinalis* produce large quantities of seed; *D. sanguinalis* also reproduces vegetatively. These attributes may be responsible for their increasing dominance with time.

System 4 underwent the same weed-control regime as System 2 but had a shorter first cropping cycle. Weed biomass at the harvest of the fourth crop following a year of kudzu fallow was approximately 80% greater than in System 2, but was approximately 15% less than in System 3. This pattern probably was related to the number of cropping periods during which viable weed seeds could accumulate in the soil.

The systems' weed populations differed. *Panicum trichoides* and *Commedlina* sp. were present at very low levels in System 2 and System 3, but they composed approximately 50% and 35%, respectively, of the weed biomass in System 4. The low levels of these weed species

Table 4. Topsoil nutrients before and after burning the 10-month-old kudzu fallow in System 2, Yurimaguas, Peru, September 15, 1987.

	Topsoil (0 to 15 cm)	
	Before	After
pH	4.7	4.6
	—— cmol/L ——	
Al	1.96	1.56
Ca	0.6	0.93
Mg	0.11	0.18
K	0.07	0.22
	—— ug/l ——	
P	10	15
Zn	2.9	3.4
Mn	4.8	8.2
Fe	374	537
Cu	0.45	0.4
	—— % ——	
Al sat.	71.5	48.7

in System 3 were probably due to the herbicide regime. Metolachlor controls *Commedlina*, and sethoxydim controls all grasses. Differences between Systems 2 and 4, both of which had the same weed-control regime, were probably due to the longer time allowed for the build-up of these species in System 4. The biomasses of *P. conjugatum*, *pata de gallo* (an annual grass, *Elausine indica*), and *D. sanguinalis* were similar in Systems 2 and 4, but low in System 3, while the biomass of *D. sanguinalis* was greater than in Systems 2 or 4. Apparently, *P. conjugatum* and *E. indica* were susceptible to the herbicide treatments in System 3. The large biomass of *D. sanguinalis* in this system may be due to its ability to reproduce both vegetatively and by seed and to the greater number of cropping cycles.

Comparison of weed population dynamics during a cropping cycle in Systems 2 and 4 suggests that populations of *P. trichoides*, *P. conjugatum*, *Commedlina sp.*, and *D. sanguinalis* either maintain themselves or increase in the presence of hand weeding within a given crop cycle. Populations of *E. indica* and *R. exaltata* tend to decrease. After one manual weeding in System 2, the spectrum of weed species abruptly changed from one dominated by *R. exaltata* to one dominated by grasses and herbs similar to those found in System 4. This change suggests the following: soil seed pools of *R. exaltata* are small, *R. exaltata* immigration into the field is limited, or the seeds of this species have a different dormancy than seeds of other common weeds.

Implications

A low-input system with full herbicide-based weed control can apparently be sustained for approximately 12 crop cycles. Eventually, problems with weeds and soil fertility cause agronomically unacceptable yields. With more economically acceptable weed-control practices, productivity of the low-input system may be sustained for only seven crops during the first cycle and three during the second cycle.

Data from this study suggest that short-term leguminous fallows such as kudzu can play a valuable role in reducing weed biomass, thereby increasing crop productivity. The beneficial effect of a kudzu fallow, however, appears to be fairly short-lived. Further research is needed on the effects of different short-term fallows, on the duration of those effects, and on the timing best suited to produce an effective crop-fallow system.

The Selection of Aluminum-tolerant Corn, Rice, Peanut, Cowpea, and Sweet Potato: Y-203A

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Acid Ultisols cover large areas of the Peruvian jungle. If annual crops are to be produced in these areas, producers must apply P and lime in relatively large amounts. Because such techniques are expensive, crop varieties tolerant of Al and low soil P must be developed. This study consists of five experiments designed to develop such varieties for corn, upland rice, peanut, cowpea, and sweet potato.

Corn

Selections for Al-tolerant corn were begun in 1987: 605 families from CIMMYT (Table 1) were planted in a Yurimaguas soil with 45% Al saturation and a high P content. From them, 412 families were chosen for the next cycle. The maximum yield achieved was 5887 kg/ha by line 28-28 Across 7928 (Table 2).

Table 1. Yellow corn lines (605 total) selected for acid soil tolerance, Yurimaguas, Peru.

Total entries	Corn lines
31	Mezcla Amarilla (Pop. 26)
58	BRA 042439 (CMS 36)
12	BRA 014931 (CMS - 30)
06	18-Comp. Thai No. 01-22
60	CIMMYT-Selec.Res.Al.
40	Marginal 28
42	MB 123 C3
48	Across 7926
43	Suwan 8027
43	Pichilingue 1928
16	Across 7729
56	Across 7928
24	Setelagoas 7931
27	Pichilingue 7931
39	Across 7936
29	8136
31	Suwan x La Posta Amarilla.

Table 2. Corn grain (14% moisture) yield of the 10 best lines on a soil with 45% Al saturation and high P, (40 kg P/ha), Yurimaguas, 1987.

Entry	Genealogy	Yield
		t/ha
435	28-28 Across 7928	5.89
608	O. P. Suwan x La Posta Amarilla	5.84
610	O. P. Suwan x La Posta Amarilla	5.76
150	14-4 CIMMYT Sel. Res. Al.	5.40
340	25-36 Suwan 8027	5.19
594	O. P. Suwan x La Posta Amarilla	5.07
605	O. P. Suwan x La Posta Amarilla	5.04
565	36-12 Across 7936	4.85
429	28-22 Across 7928	4.85
234	17-21 MB 123 C3	4.76

Table 3. Corn grain (14% moisture) yield of the 10 best lines on a soil with 65% Al saturation and a high level (40 kg/ha) of applied P, Yurimaguas, 1988.

Entry	Genealogy	Yield
		t/ha
157	5-6 BRA 014931 (CMS 30)	7.12
404	132 Suwan x La Posta Amarilla	6.81
392	36-18 Across 8136	6.76
53	3-42 BRA 042439 (CMS 36)	6.69
403	O. P. Suwan x La Posta Amarilla	6.14
289	BRA 201	6.07
351	33-19 Pichilingue	5.94
38	3-21 BRA 042439 (CMS 36)	5.80
243	26-6 Pichilingue 7928	5.73
190	24-21 Across 7926	5.66

Table 4. Corn grain (14% moisture) yield of the 10 best lines on a soil with 65% Al saturation and a low level of applied P (20 kg/ha), 1988.

Entry	Genealogy	Yield
		t/ha
41	3-25 042439 (CMS 36)	6.65
155	17-24 MB 123 C3	6.32
53	3-42 BRA 042439 (CMS 36)	6.29
38	3-21 BRA 042439 (CMS 36)	6.22
392	36-18 Across 8136	6.14
62	4-14 042439 (CMS 36)	5.92
30	3-10 BRA 042439 (CMS 36)	5.82
398	O. P. Suwan x La Posta Amarilla	5.72
148	15-31 Marginal 28	5.53
141	15-24 Marginal 28	5.39

In 1988, the 412 selected families were planted on a soil with a 65% Al saturation and given two P treatments (20 and 40 kg P/ha); 337 families were selected for the 1989 cycle. Line 5-6 BRA 014931 (CMS 30) with 7118 kg/ha (Table 3) and line 3-25 BRA 042439 (MCS 36) with 6550 kg/ha (Table 4) excelled in 1988. Only the yields of the 10 best families out of the 412 selected are shown in Tables 3 and 4. Lines 23, 53, and 392 had good yields at the 20-P and 40-P levels. This result implies the need for a simultaneous selection to both Al and P stress.

In 1989, the 337 previously selected families were evaluated on a soil with high (65%) Al saturation and low P. Grain yields were generally high, even though plot size was small. Results are therefore promising; they will be included in the next technical report.

Upland Rice

In the first evaluation cycle (1985 to 1986), 100 lines from IITA were tested on acid soils. Of these lines, 62 were evaluated in a preliminary yield trial (1986 to 1987) on acid soils. The 39 best lines were then evaluated in two types of trials in 1987 and 1988: a uniform yield trial (UYT), in which the yields of the 39 lines were compared to the Carolino variety on soils with an Al saturation percentage of 51%; and a trial in which yields of the 20 best lines were evaluated on limed (34% Al saturation) and nonlimed (77% Al saturation) soil.

Based on the results of UYT, seven lines superior to the Carolino variety were selected (Table 5). The yields of the 10 best varieties in the liming-response trial are shown in Table 6.

During 1988 and 1989, the ten best lines from the two prior trials (UYT and the liming-response trial) were included in an advanced yield trial on a soil with a 60% Al saturation. The yields of the four lines that compared best to the Carolino control are shown in Table 7.

Table 5. Rice lines selected from a uniform yield trial (UYT) on a soil with 51% Al saturation, 1987-88.

Lines	Yield[§]
	t/ha
Tox 854-101-3-201-1-1-1	2.70
DJ 12-539-2	2.16
ITA 235	2.04
PL 110	1.72
RAU 4072-13	1.69
SERATUS MALAM	1.65
ITA 128	1.64
Carolino (control)	1.58

[§] Average of three repetitions.

Samples from the four lines were also analyzed for milling quality. The results can be seen in Table 8. Line TOX 854-101-3-201-1-1-1 had the best yield, but also a low milling quality (% whole grain). Consequently, this line was dropped in favor of lines IRAT 170 and ITA 235.

During 1989 and 1990, we intend to establish validation plots with ITA 235 on soils differing in percentage Al saturation. Using technology developed at the station, we will compare the results with those obtained from both the Carolino variety and farmers' traditional technologies.

The rice lines IRAT 170 and ITA 235 appear to perform better than the traditional Carolino variety on acid upland soils. They produce more grain, are tolerant to local fungal diseases, and have good milling qualities.

Table 6. Lines selected in a liming-response trial, 1987-1988.

Lines selected	Yield§ with lime (34% Al sat.)	Yield without lime (77% Al sat.)
	t/ha	
ITA 128	2.08	1.65
IRAT 170	2.07	1.63
ITA 235	1.76	1.00
ISA 6	1.75	1.21
IRAT 104	1.73	1.19
ITA 139	1.73	1.17
ITA 125	1.72	1.26
ITA 182	1.62	1.32
IRAT 161	1.49	1.30
Carolino (control)	1.38	0.71

§ Yields with and without lime are the average of three repetitions.

Table 7. Lines selected in an advanced yield trial (AYT) on a soil with 65% Al saturation, 1988-1989.

Lines selected	Yield§
	t/h
Tox 854-101-3-201-1-1-1	3.05
ITA 128	2.45
IRAT 170	2.31
ITA 235	2.28
Carolino (control)	0.93

§ Average of four repetitions.

Table 8. Analysis of milling quality.

Lines selected	Clean grain (% of total)	% Grain (whole)	% Grain (broken)
Tox 854-101-3-201-1-1-1	74.19	54.60	19.54
ITA 128	76.27	67.50	8.77
IRAT 170	76.77	66.26	10.51
ITA 235	74.04	63.10	10.94
Carolino (control)	73.42	55.50	17.92

Samples tested in a Miller No.2 Mill, *El Porvenir* Agricultural Experiment Station, Tarapoto.

Peanuts

The trials were conducted on a sandy, well-drained upland soil whose chemical characteristics are shown in Table 9. Grain yields differed significantly among varieties, but there was no response to liming, nor were there any interactions between varieties and liming (Table 10).

Highest average grain yields were measured for the Rojo 4 (0.92 t/ha) and Rojo rastrero (0.82 t/ha) varieties. Rojo rastrero showed greater stability in acid and limed soils. In limed soils, average grain production was 35% of the unshucked yield. On nonlimed soils, this figure was 24%. The low shucking percentages in both cases are probably caused by the absence of Ca fertilizer on the plots.

Relative grain yields indicate that the Rojo rastrero variety appears to tolerate acid soil conditions, but it has a low yield potential. The other varieties were sensitive to acid soil and had a low yield potential.

Cowpea

The experiment was carried out on an acid upland soil with a sandy-clay texture, good drainage, and characteristics similar to those described above.

Before planting the 1987 experiment, we applied an average of 1.6 t/ha of dolomitic lime in the limed treatment to reduce Al saturation to 20%. In the 1988 trial, neither lime nor fertilizer was applied.

There were no statistically significant differences among varieties or liming treatments (Table 11). Hence, most varieties were tolerant of soil acidity. Variety IT63 S-689-4 (1.04 t/ha) had the highest 1988 yield. Also, the varieties were tolerant to pests *Crisomelidae* and diseases *Thanatephorus cucumeris*.

Sweet Potato

Twenty varieties of sweet potatoes were tested. Sixteen varieties were selected from a sweet potato germplasm trial conducted on limed soils since 1984. Three varieties were obtained from a previous study conducted at the Yurimaguas Experiment Station. One high-yielding

Table 9. Soil chemical characteristics of the peanut evaluation trial.

Lime	Depth	pH	Acid.	Ca	Mg	K	P	Al sat.
	(cm)		———	cmol/L soil	———		mg/L	%
Limed	0–20	5.3	0.5	0.88	0.43	0.13	11.2	26
Unlimed	0–20	4.7	1.5	0.34	0.13	0.14	15.1	71

§ Average of three repetitions; samples were obtained prior to planting.

Table 10. Absolute yield, relative yield, and shucking percentages of 16 peanut varieties evaluated* in unlimed and limed soils, Yurimaguas, Peru. 1988.

	Grain yields (t/ha)*			Shucking %¶		
Variety	Limed (26% Al sat.)	Unlimed (71% Al sat.)	Average	Limed (26% Al sat.)	Unlimed (71% Al sat.)	Relative yield§
V1 Rojo Rastrero	0.87	0.76	0.82ab	41	43	87
V2 Rosado (COPSA) S-44-68	0.43	0.23	0.33 cd	42	40	53
V3 Argentina	0.58	0.14	0.36 bcd	48	27	24
V4 Dakar	0.33	0.08	0.21 d	35	14	24
V5 Cuba 15607	0.64	0.23	0.44 bcd	44	20	36
V6 E-412	0.37	0.11	0.24 d	31	23	30
V7 *Castaño Masizea*	0.68	0.02	0.35 bcd	28	4	3
V8 Rojo 4	1.46	0.38	0.92a	43	21	26
V9 ICGS (E) - 22	0.40	0.10	0.10 cd	27	21	25
V10 501	0.23	0.04	0.14 d	25	10	17
V11 2339 Flarunner	1.05	0.39	0.72abc	66	55	37
V12 Improved Span	0.47	0.19	0.29 cd	42	17	21
V13 Blanco Tarapoto	0.61	0.34	0.48abcd	18	27	56
V14 E-290	0.36	0.05	0.21 d	15	7	14
V15 *Rosado Cañete* S-47-68	0.65	0.41	0.53abcd	50	46	63
V16 Local control	0.32	0.02	0.17 d	11	2	6
Mean	0.59	0.21		35	24	

* Treatments followed by the same letter are not significantly different at the 5% level.

$$\text{¶Shucking percentage} = \frac{\text{Grain yield}}{\text{Total yield}} \times 100$$

$$\text{§Relative yield} = \frac{\text{Grain yield in unlimed treatment}}{\text{Grain yield in limed treatment}} \times 100$$

Table 11. Absolute and relative grain yield of 16 varieties of cowpea evaluated on acid (unlimed) and limed soils, Yurimaguas, Peru, 1988.

Variety	Limed (23% Al sat)	Unlimed (74% Al sat)	Relative yield
	t/ha		%
V1 IT82D-789	1.15	0.95	83
V2 IT82-E16	0.71	0.73	103
V3 IT82 E-18	0.84	0.84	100
V4 IT82 E-32	0.73	0.76	104
V5 IT82 D-885	0.57	0.60	105
V6 IT82 D-875	0.78	0.60	77
V7 CNC x 252-1E	0.76	0.67	88
V8 BRI-POTY	0.53	0.72	136
V9 IT82 E-9	0.98	0.74	76
V10 VITA 3	0.88	0.76	86
V11 IT83 S-689-4	1.04	1.01	97
V12 CNC x 0434	0.67	0.44	66
V13 CNC x 105-8F	0.69	0.74	107
V14 IT83 D-442	0.91	0.82	90
V15 TESTIGO 1 (VITA 7)	0.80	0.74	93
V16 TESTIGO 2	0.76	0.86	113

variety, introduced from North Carolina in 1983, was also included.

The sweet potatoes were planted in a newly cleared secondary forest. Fertilizer was applied at a rate of 80 kg N (urea), 80 kg P_2O_5 (supertriple phosphate), and 160 kg K_2O (KCl) on a per hectare basis, half applied at 15 days and 30 days. Liming treatments were 2 t/ha and no lime.

Table 12 indicates that the yields of most varieties were higher in limed soil (the soil analysis is shown in Table 13). Some varieties performed well in limed and unlimed conditions: GEM, Pelican Processor, NC 213 221-9, L3-66, Ecotipo #1, and Impala. In others, tuber yields and shoot fresh weight were greater in nonlimed than in limed soils: Centennial, Kander, CAL-461, Taiwan 57, GEM, and Pelican Processor.

Under acid soil conditions, Pelican Processor and GEM had the greatest tuber yields; shoot yields were greatest in Jewel.

The higher root yields obtained by some varieties in acid soils suggest that these cultivars tolerate acid soils. Al saturation in these soils was fairly low, under the critical level (51%) for sweet potatoes.

Table 12. Fresh root and shoot yields of 20 varieties of sweet potatoes under unlimed and limed soil conditions, Yurimaguas, Peru.

	Fresh root yield		Fresh shoot yield	
	Unlimed	Limed	Unlimed	Limed
	kg/ha			
Nemagold	6943	9667	16223	11733
Centennial	10510	7223	16777	14557
Kander	10110	9557	17667	12777
Julian	10133	10490	16110	16110
CAL-461	10490	6987	16557	12000
Taiwan 57	10910	9567	14690	15467
GEM	17463	10823	15156	13443
Pelican Processor	19223	15333	15600	9110
US - 700	12367	5667	8777	6443
Jewel (NC - 240)	9087	10823	11223	11600
nc - 213 X 221 - 2	8890	9890	3557.	2820
nc - 213 X 221 - 9	16423	17276	10823	10110
l 3 - 66	16787	17177	10643	12223
Ecotipo #1	13777	16710	7310	10890
Impala	11910	14823	8800	9400
Mafutha	8643	9043	11267	12667
Navarro	5777	9667	500	9557
Juan de Dios I	11333	13443	10443	10557
Juan de Dios II	8443	10523	17000	17223
Jewel	9087	15267	12443	23443

Table 13. Chemical characteritics after lime application of soil in sweet potato study.

	pH	Acid	Ca	Mg	K	P	Al sat
Unlimed	4.6	2.4	1.65	0.41	0.21	4.14	51
Limed	4.7	1.5	1.90	0.65	0.17	3.10	35

The Search for Field Tolerance to Aluminum Toxicity in Soybean: Y-203B

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Latin American soybean varieties, although carrying indigenous-sounding names like Paraná or Tropical, are really pioneering stock only one or two generations removed from their U.S. forebears. U.S. (and thus Latin American) soybean varieties trace most of their ancestry back to a small germplasm base of only 15 Chinese land races. Because of the photoperiod sensitivity of the species, these land races were collected in China at approximately the same latitudes where soybeans are currently grown in the U.S. Soils in China at these latitudes are not Al toxic (pH > 5), so few if any of the old land races originally brought to the U.S. were adapted to Al-toxic soils. Fifty years of soybean breeding in the midwestern U.S. has made no impact on the Al tolerance of the U.S. germplasm because Al is not a problem there. Even in the southern U.S., where acid soils occur, the common practice of liming in experimental plots makes it improbable that breeders could have selected for Al tolerance in their yield trials. Thus it is likely that little variability for Al tolerance exists in the genetic materials available for farmers in the western hemisphere. Incontrovertible field tolerance to Al in soybean has never been demonstrated on tests with rigorous plot protocol with appropriate statistical analysis.

Objectives

Given the poor prospects of finding Al tolerance in soybean of U.S. extraction, we have begun a program to evaluate exotic Oriental plant introductions that have no common ancestry with U.S. cultivars. Because one such plant introduction appears to be Al tolerant in our laboratory experiments, we are attempting to validate its Al tolerance through field tests in Yurimaguas, Peru, and Orange, Virginia, USA. If field Al tolerance is documented in this exotic type, then we hope to expand the field program to examine other promising sources from the Orient that have been identified in our N.C. State University lab. This work is part of our overall breeding goal to transfer Al tolerance to productive soybean varieties for the Southeastern United States.

Preliminary Study in Yurimaguas and Virginia

Genetic materials for this study were PI 416937 and Essex. PI 416937 was introduced from the USDA soybean germplasm collection; it is native to Japan and exhibits Al tolerance in solution culture. Essex is a U.S. variety sensitive to Al in solution culture. The biomass of the genotypes was compared on limed and unlimed soil. Locations were chosen because of their high native Al levels (Table 1). Each plot consisted of three 2-m-long rows with 0.4- or 0.75-m spaces between rows at Yurimaguas and Orange, respectively; 1 m of bordered row from the center of each plot was harvested for weighing at approximately 35 days after planting. Planting dates were early-to-mid June in Orange and early November 1988 and early September 1989 in Yurimaguas. In each test, two replications of whole plots (liming treatments) were employed, and in each subplot, duplicate plots of the genotypes were enlisted to improve the precision of genotypic means.

Results and Discussion

All preliminary results indicate clearly that the PI produced a larger plant than Essex in the highly Al-saturated plots (Table 1). This important finding indicates that the PI may be a useful control genotype in future field programs designed to evaluate Al-tolerant soybean germplasm. However, when one assesses the larger question of how to breed new cultivars adapted to highly Al-saturated soils, the picture is not clear. Although the PI was larger than Essex, uncontestable field tolerance to Al was not demonstrated in these experiments. From the breeder's viewpoint, the definition of Al tolerance in the PI could be demonstrated by the PI's relative superiority to Essex in highly Al-saturated soils as compared to their performances on limed soils. In a statistical sense, this means that one must detect a genotype x lime interaction if one is to say that Al tolerance has been demonstrated in the experiment. Unfortunately, no significant interaction was detected because the PI tended to be larger than Essex in the limed as well as the unlimed plots.

The presence or absence of a genotype x lime interaction plays a critical role in the choice of a breeding methodology to develop Al-tolerant cultivars: presence indicates that testing in highly Al-saturated soils is absolutely necessary in the early phases of breeding, while absence indicates that testing unlimed plots of the same soil type is sufficient. These alternative testing methods present different logistical difficulties. Limed plots are generally far more accessible to the breeder.

The lack of a genotype x lime interaction in this study may reflect a lack of true Al tolerance in the PI, or it may simply reflect a lack of precision in our current field tests, specifically in the limed plots. Further tests of the PI and Essex are under way at Yurimaguas to gain the precision necessary to distinguish between the two possibilities. Once this initial phase of testing has been completed, we hope to evaluate a wider array of germplasm to assess more accurately the extent of Al tolerance in the soybean germplasm.

Selection of Advanced Lines

This report includes two cropping cycles (1987 and 1988) carried out on an upland acid soil having a sandy texture and good drainage. Soil chemical characteristics are shown in Table 2.

The experimental design was a split-plot with three repetitions. The experimental units consisted of four rows, 0.4 m long and 0.60 m apart. Treatments were as follows: 1) whole plots: with and without lime; 2) sub-plots: 10 varieties including the control.

Dolomitic lime (165 kg/ha) was applied to the limed treatment prior to the start of the 1987 trial in order to reduce Al saturation to 20%. No lime was applied in 1988. Crops were planted on July 27, 1987, and July 11, 1988, using a planting stick and a spacing of 0.60 m between rows and 0.20 m within rows, with six seeds planted per hole. At the thinning stage, three plants were left per hole (250,000 plants/ha). Crops in both cycles were fertilized with 25 kg N, 26 kg P, and 33 kg K/ha. The Piha-Nicholaides (1981) method was used to evaluate Al tolerance.

There was no statistically significant difference due to varieties or liming during the first year, but in 1988 there was a statistically significant response to both liming and soybean variety (Table 3).

Most varieties had low yields under acid conditions except for the Cristalino variety, which had a yield of 1.21 t/ha. Yields in the nonlimed treatment were as much as 48% lower than those in the limed treatment.

Relative yields indicate that most varieties were sensitive to acidity and had low production potentials. The exception was variety TG x 854-02-D-A, which was acid tolerant, but low yielding.

Under acid soil conditions, Cristalino (1.10 t/ha), TG x 713-09D (1.10 t/ha), and TG x 297-15F produced accept-

Table 1. Biomass of two soybean genotypes at 35 days after planting in limed and unlimed soil at two field sites.

Location	Year	Genotype	Limed	Unlimed	Control
			—— kg/ha ——		%
Yurimaguas, Peru	1988	Pi	7975	4600	58
		Essex	9250	3225	35
	1989	PI	3225	2200	68
		Essex	2725	1450	53
Orange, VA, USA	1988	PI	720	390	54
		Essex	630	340	54
	1989	PI	1149	770	67
		Essex	1047	670	64

Al saturation for limed and unlimed plots was 48 and 87%, respectively, for Yurimaguas, Peru, and 11 and 61%, respectively, for Orange, USA. Biomass was determined on a fresh-weight basis at Yurimaguas and on a dry-weight basis at Orange.

Table 2. Soil chemical characteristics of the soybean evaluation trial, Yurimaguas, Peru[§].

Year	Lime	Depth	pH	Acid.	Ca	Mg	K	P	Al sat.
		(cm)		———— cmol/L soil ————				mg/L	%
1987	Limed	0–15	5.2	0.5	0.98	0.45	0.08	8.3	24
		15–30	5 1	0.8	1.00	0.51	0.04	7.1	34
	Unlimed	0–15	4.5	1.5	0.47	0.17	0.08	9.5	68
		15–30	4.4	2.4	0.43	0.14	0.04	7.7	78
1988	Limed	0–20	5.4	0.5	1.03	0.51	0.10	13.9	23
	Unlimed	0–20	4.7	2.0	0.32	0.12	0.10	16.2	78

[§] Average of three repetitions; samples were obtained before planting.

able grain yields in the 1988 trial (Table 3). TG x 713-09D and Cristalino varieties also responded to liming and had the highest average (1.59 and 1.56 t/ha) grain yields.

Relative yields indicate that all varieties were sensitive to soil acidity and had low production potentials. However, the Bilox variety exhibited acid tolerance and low potential yield. Soybean yields decreased by about half when topsoil Al saturation increased from 24 to 78%.

Table 3. Statistical significance of the grain and relative yields of ten soybean varieties evaluated on acid (unlimed) and limed soils, Yurimaguas, Peru, 1988.

Soybean variety	Grain yield (t/ha) Limed	Grain yield (t/ha) Unlimed	Relative yield[§]
	(23% Al Sat.)	(78% Al sat.)	
TG x 539-5E	1.94 ab	0.87 efg	45
TG x 573-1E	1.31 cde	0.75 fg	57
Cristalino	2.03 a	1.10 cdefg	54
TG x 854 D-1	1.04 defg	0.86 efg	83
TG x 713-09 D	2.07 a	1.10 cdefg	53
TG x 297-15F	1.60 a bc	1.00 defg	63
Bilox	0.71 fg	0.60 g	85
IAC-2	1.46 bcd	0.69 g	47
Tropical	1.84 ab	0.66 g	36
Jupiter	1.22	0.74 fg	61
Mean	1.52	0.84	

$$^{\S}\text{Relative yield} = \frac{\text{Grain yield no lime treatment}}{\text{Grain yield lime treatment}} \times 100$$

Evaluating Individual Nutrient Constraints in Low-input Cropping: Y-215

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The low-input cropping system is currently perceived as a transition technology between shifting cultivation and permanent agriculture. Current results suggest that the system collapses after three years and approximately seven continuous crops because of increased weed pressure and P and K deficiencies. After a subsequent one-year kudzu fallow, weed populations are largely reduced and soil fertility improves. A possible alternative to the present system would be to replace one of the three crops per year with an acid-tolerant and fast-growing legume cover crop, thus suppressing weeds and recycling nutrients susceptible to rapid downward movement into the subsoil. Such changes might lengthen the period of continuous cultivation in low-input systems and alter the type and sequence of nutrient constraints.

Objectives

The objectives of this study were 1) to monitor soil-fertility dynamics during continuous low-input cropping and 2) to evaluate the extent to which the cropping period can be prolonged by the annual inclusion of a legume cover crop in rotation with rice and cowpea.

Procedures

A long-term experiment was initiated at Yurimaguas in 1986. Thirteen treatments with four replications, in a randomized, complete-block design, were planned. In addition to an absolute check and a crop-residue removal treatment, crop response to N, P, and K will be evaluated by three treatments for each nutrient (levels 0, 1, and 2). Two additional treatments, with and without 0.5 t lime/ha, will evaluate crop response to Ca. With the exception of the absolute check and crop-residue removal treatments, all other treatments will not be initiated until yields, as well as soil and plant analysis data from preceding crops, suggest that an N, P, K, or Ca deficiency is likely to occur in succeeding crops. After a yield response to a given nutrient is obtained, blanket fertilizer applications will be made to all other plots, except those for the absolute check, to avoid confounding individual nutrient responses.

Low-input practices that concentrate forest biomass nutrients in ash, use acid-tolerant species, require no tillage, and promote crop-residue return after harvest will be maintained as general management practices. To ensure accuracy in monitoring available soil P, however, fertilizer-P inputs will be broadcast and incorporated with a two-wheeled rotary tiller. Weeds will be controlled manually to avoid confounding yield response to treatments with weed competition.

The 10-year-old secondary forest on the Ultisol was cleared in October 1986 by slash-and-burn and initially planted to rice without any additional treatments. Seven more rice and cowpea crops and one legume cover crop were then planted in the sequence shown in Table 1. Varieties used in all crops were Africano for rice and *VITA 7* for cowpea. *Mucuna conchichinensis* was used as the legume cover crop because it tolerates acidity, provides 100% ground cover within 30 days, and achieves maximum aboveground biomass production within 105 days (flowering stage) from planting in Yurimaguas.

Changes in surface (0 to 15 cm) soil acidity parameters during three years of cultivation are shown in Figure 1 for the absolute check treatment. One week after the forest was burned, soil pH increased by 0.2, and Al saturation decreased by 26%. However the liming effect of the ash

Table 1. Sequence of crops and time after burning for cultivation of each crop.

Crop	Time from planting to harvest
	Months after burning
Rice	0.3 – 4.9
Rice	5.6 – 9.8
Cowpea	10.4 –12.8
Rice	13.8 – 17.2
Rice	18.4 – 22.3
Cowpea	23.3 – 26.0
Mucuna cover crop	26.3 – 29.9
Rice	30.1 – 34.4
Cowpea	35.6 – 37.8

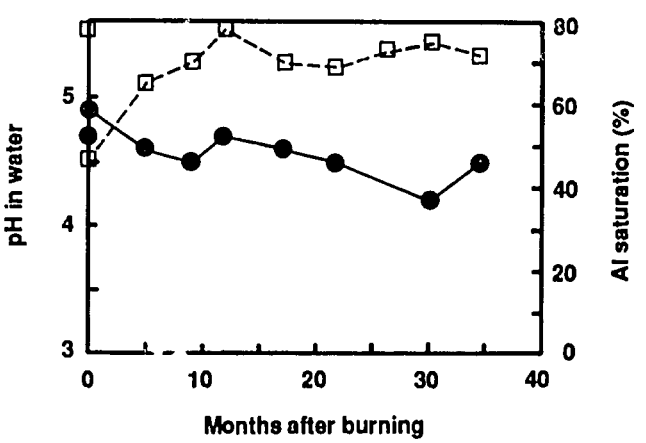

Figure 1. Surface soil pH and Al saturation in the absolute check treatment during three initial years of low-input cropping.

lasted only for the first two rice crops. Twelve months after the forest was burned, both pH and Al saturation were at the same levels observed before burning.

Mean grain yields, across all treatments, are shown in Figure 2 for each successive crop. Cumulative yields during these three years of cultivation were 6.9 t/ha of rice and 1.4 t/ha of cowpea. After the first crop, treatments designated for N received 0, 30, and 60 kg of N/ha in all subsequent rice crops. All other treatments, except the absolute check, received 30 kg N/ha in the third rice crop. However, this blanket N application was discontinued in subsequent rice crops, because there was no significant yield response to N. Nevertheless, in all rice crops, yields with 60 kg of N/ha were consistently greater than those with lower N rates (Table 2): the cumulative yield difference between the 0- and 60-kg N/ha rates was 1.2 t/ha.

Treatments designated for P were initiated during the first cowpea crop with applications of 0, 22, and 44 kg P/ha. In the subsequent crop, the same P rates were reapplied to the P treatments, and 44 kg P/ha was applied to all other treatments, except for the absolute check. Modified Olsen soil P levels for the three P treatments are shown in Figure 3 as a function of time after burning. Phosphorus additions by ash and/or by transformations in soil "pools" raised the forest's available soil P to 11 mg/L from the initial level of 4 mg/L. By five months after burning, however, available P had declined to 5 mg/L. Despite the low level of soil P maintained for the remaining crops that received no P, yields for neither rice nor cowpea were increased by fertilizer P inputs (Table 3). These results suggest that the critical soil P level of 10 mg/L—used in Yurimaguas for determining fertilizer P inputs under mechanized continuous cultivation—may be excessive for rice and cowpea under low-input cropping.

Establishment of the mucuna ground cover was severely affected by leaf-cutting ants. At the time it was cut and placed as a mulch for the subsequent rice crop, the range among plots in percentage ground cover and aboveground mucuna biomass was 10 to 100% and 0.2 to 3.0 t/ha, respectively. In the subsequent rice crop, there was a significant correlation between grain plus residue dry matter and aboveground mucuna biomass among those plots which previously had received only a blanket application of 44 kg P/ha (Figure 4). In an attempt to evaluate how the N contributed by the legume cover crop influenced subsequent rice yields, researchers did not plant mucuna on the N treatments. However, rice showed no significant yield response to fertilizer N inputs. Soil data for acidity, exchangeable bases, and P—taken before and after the subsequent rice crop—could not explain the correlation between rice and mucuna dry matter.

Surface-soil K levels in the absolute check and crop residue removal treatments are compared in Figure 5. Potassium inputs from the ash after burning caused a fourfold increase in soil K for both treatments. With subsequent cultivation and K removal in harvested grain, soil K in both treatments declined progressively. After two years of cultivation, however, soil K after crop residue was removed declined to half the value obtained when crop residues remained in the field. Grain K export in the seven initial crops was similar for both treatments, 37.7 kg/ha for the absolute check and 39.7 for the residue removal treatment. However, removal of residues for the same crops resulted in an additional export of 162 kg K/ha. Depletion of soil K after residue removal is considered the main cause of the significant yield reduction in the final cowpea crop. Yields for this treatment were 0.3 t/ha as opposed to 0.5 t/ha in the absolute check.

Results suggest that the critical soil P level for rice and cowpea in Yurimaguas Ultisols may be considerably lower than the level used in mechanized cultivation of corn, soybean, and peanut. Further investigations are needed to delineate the beneficial effect of mucuna mulch on subsequent rice yields. With appropriate weed manage-

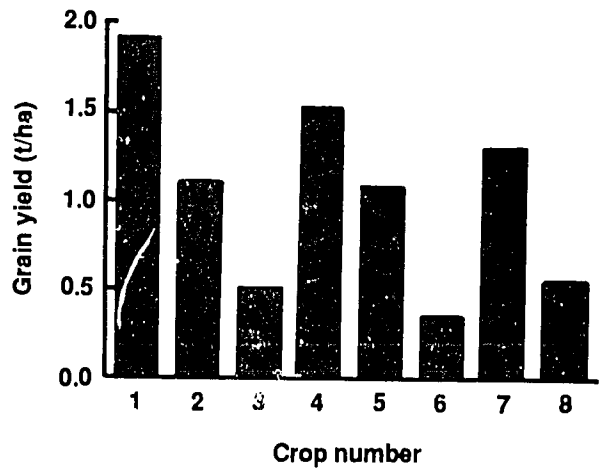

Figure 2. Mean rice and cowpea yields for eight initial crops in the low-input experiment.

Table 2. Grain yields for four consecutive rice crops as a function of N rates applied to each crop.

Applied N	Rice crop 2	3	4	5
kg/ha	yield t/ha			
0	1.24	1.53	1.13	1.31
30	1.17	1.60	1.16	1.28
60	1.44	1.82	1.38	1.77
LSD.05	NS	NS	NS	NS

ment, eight crops of rice and cowpea were produced in three years without obtaining a significant response to N or P fertilizer inputs. An adequate supply of native soil K was prolonged by allowing crop residues to remain in the field. Four similar experiments are currently under way in Bolivia, Brazil, Costa Rica, and Peru as part of the RISTROP network. Comparisons of crop performance and soil nutrient dynamics among the five locations will help to delineate the appropriate range of soil conditions and length of cultivation for this transitional cropping system.

Table 3. Grain yields for six consecutive crops of rice and cowpea as a function of P rates applied to crops 3 and 4.

Applied P	Crop Number 3	4	5	6	7	8
kg/ha	yield t/ha					
0	0.5	1.3	1.1	0.2	1.3	0.5
22	0.7	1.4	1.1	0.4	1.6	0.6
44	0.7	1.5	1.1	0.3	1.2	0.6
LSD .05	NS	NS	NS	NS	NS	NS

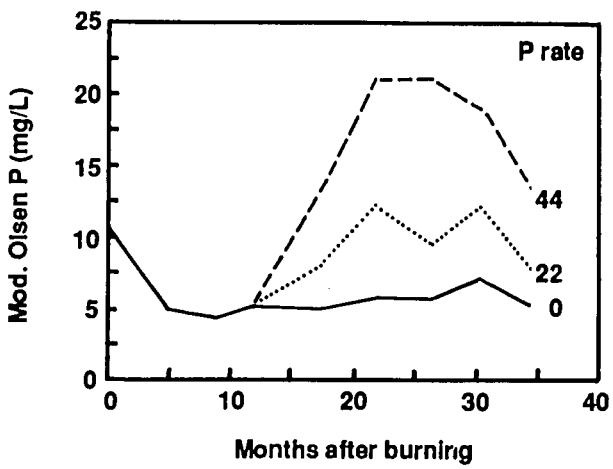

Figure 3. Available soil P dynamics for fertilizer P rates applied to the first cowpea crops and the subsequent rice crop.

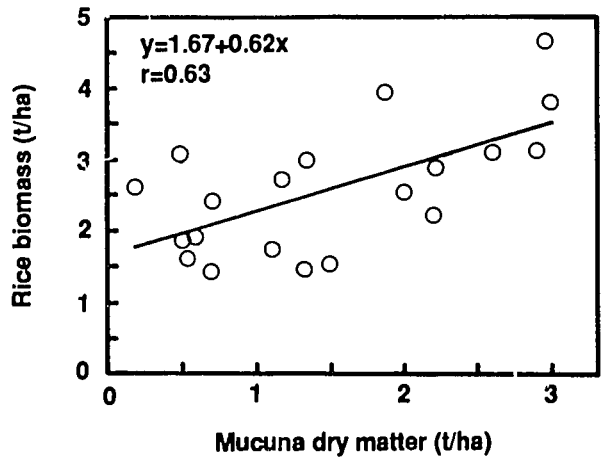

Figure 4. Relationship between dry matter of mucuna aboveground mulch and grain plus straw of the subsequent rice crop among plots with uniform management.

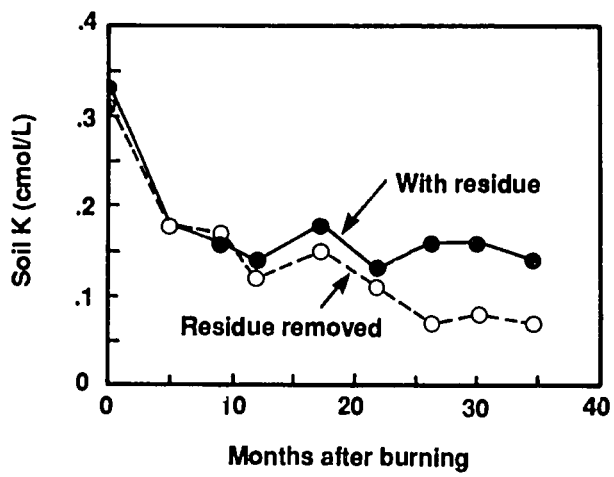

Figure 5. Soil K dynamics comparison between low-input treatments with and without removal of residues for eight consecutive crops of rice and cowpea.

Legume-based Pastures for the Humid Tropics: NC-3

Using pastures for dual-purpose (beef-milk) production is one of the most widespread management options in the humid tropics and one with a bad reputation as an ecosystem degrader. This reputation is well earned in cases where high-fertility requiring grasses are planted and no legumes or fertilizers are used. When this happens, grazing pressure increases as pasture productivity declines, leading to economic collapse and ecological damage. CIAT's Tropical Pastures Program has collected a large number of grass and legume ecotypes adapted to acid soil conditions. We have put together the most promising CIAT selections in grazing trials established in Yurimaguas and Pucallpa and continue to acquire improved material on a routine basis.

The central grazing experiment (Y-302) is one of the longest running replicated grass-legume grazing trial based on low-input concepts in the humid tropics. While some mixtures have remained persistent and have been responsible for large gains in animal weight, others have become unstable after a few years of grazing. Even under controlled experimental conditions, we have observed that animal weight loss probably resulted from lack of legume persistence and subsequent low pasture quality. We are now facing a problem of reduced pasture persistence after a few years of grazing. The problems of sustainability at early stages have been resolved, but the key problems are low pasture quality (not quantity).

There is very little knowledge about how nutrient cycles operate in these pastures and what fluxes are involved. Pastures behave very differently from crops in their interactions with soils. The acid-tolerant species we use are highly productive, deep-rooted perennials, subject to an accelerated root recycling process caused by frequent defoliation and trampling. Earlier estimates from experiment Y-302 show that approximately 80% of the P and over 90% of the K and Ca added as maintenance fertilization are cycled back to the soil. The phosphorus level contrasts sharply with the 37% recycling obtained with low-input cropping. We have discovered that many of the soil fertility changes occur in the 0- to 5-cm layer and that by sampling from a 0- to 15-cm layer, we have been diluting these effects.

The grazing animal is the driving force in nutrient recycling. Grazing pressure (animal liveweight units per unit of forage on offer) and resting periods are the main management tools. Increased grazing pressures result in more trampling, more animal excreta, possibly faster root turnover because of defoliation, but less litter accumulation.

Longer rest periods alter the grass and the legume balance. They also build up the litter layer and perhaps slow root turnover. Differential palatability of the grasses and legumes will alter the amount consumed by animals and hence the composition of the litter layer. There is no quantitative assessment of the processes in improved, acid-tolerant pastures in the humid tropics. We have started experiments about the cycling of nitrogen, carbon, and potassium under grazing. There are indications that soil organic-matter contents are improving with time in grazed pastures. We are also continuing to evaluate new germplasm accessions.

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Summary of Results: Y-300B

Pedro A. Sanchez, N.C. State University

A pure legume pasture of *Centrosema pubescens* 438 continues to produce the highest and most consistent levels of animal production after eight years of grazing. A mixture of creeping relatively unpalatable grass (*Brachiaria humidicola*) and legume (*Desmodium ovalifolium*) has also produced sustainable results with simple management practices. Other grass-legume mixtures—*Brachiaria decumbens, Desmodium ovalifolium x Brachiaria dyctioneum*—have proven to be unsustainable or difficult to manage at Yurimaguas.

Under a drier climate (1500 mm rainfall) and clayey Ultisols at Pucallpa, Peru, the mixture of *Brachiaria decumbens* with *Desmodium ovalifolium* provided as much nitrogen to the pasture biomass as an application of 300 kg N/ha/year of urea to the pure grass. Animal intake also suggests the same relationship. Over a 30-month grazing season, the inclusion of the legume provided about half the nitrogen consumed by the animals, the rest coming from recycling of the grass components. Only about 1/3 of the legume contribution was via direct intake. The rest was contributed by the enhanced nitrogen content of the grass. Of the remaining 2/3, only about 10% was due to N transfer through legume litterfall to the grass. The remainder is assumed to be legume-N recycled via animal excreta and root turnover.

A culture solution experiment indicates that—under low carbohydrate supplies similar to that after defoliation—the more rustic *Brachiaria humidicola* is able to accumulate either NO^-_3 or NH^+_4 in larger quantities than the less rustic species, *Brachiaria brizantha*. This feature may be part of the mechanism for adaptation to poor environments.

The Century model for soil organic-matter dynamics was modified for Yurimaguas conditions using the long-term experiment data. Simulation predicts that roots are primarily responsible for maintaining organic carbon in the topsoil. Sustainable pastures have increased topsoil organic-matter contents in Yurimaguas.

Studies on potassium dynamics provided some new insights: specific adsorption of K by small quantities of 2:1 clay minerals in predominantly kaolinitic soils holds large quantities of K in the subsoil, confirming similar findings from Oxisols of Colombia. This K could otherwise be lost by leaching. Leaching losses in a clipped *Brachiaria humidicola* x *Desmodium ovalifolium* field were negligible even with K applications as high as 150 kg K/ha in well-drained soils with 2700 mm of rainfall during 15 months. Potassium recycling by cut pastures with residue returned was extremely efficient. Potassium recycling under grazing was surprisingly less efficient; leaching in localized urine spots was suspected of causing a major overall loss in the system on the order of 30 to 90 kg K/ha/year. Maintenance applications of potassium may be needed to counteract that effect.

Overgrazing causes a crash in the endogenic earthworm population, while adequate grazing pressures may allow earthworms to decompact the topsoil.

Three ecotypes of *Desmodium ovalifolium* were found to be more palatable than CIAT 350, and several accessions of *Centrosema pubescens* and *Centrosema acutifolium* show agronomic promise at Yurimaguas. A farmer in Schucshuyacu is experimenting with these improved pasture technologies.

Persistence of Grass-Legume Mixtures under Grazing: Y-302

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Pedro A. Sanchez, N.C. State University

The central grazing experiment is now on its ninth year. Pasture persistence with simple animal management and maintenance fertilizer applications has been documented in previous reports and is now sufficiently demonstrated. Compared with native pastures, the combination of high animal gains and high stocking rates allowed low-input pastures to produce high levels of beef production in the seventh, eight, and ninth years (Tables 1, 2, and 3). Animal management continues to consist of a simple alternate grazing system: 28 days of grazing and 28 days of recuperation, with two fixed stocking rates at periods of maximum and minimum precipitation. Animals used in this trial are two-year-old steers weighing 160 to 190 kg; they are typically crosses of Brown Swiss and Cebu. In 1988, two lots of animals were used.

Unsustainable Mixtures

One important modification was to discontinue maintenance fertilization after February 1987. Continuous maintenance fertilization improved topsoil conditions (see previous technical reports), and since nutrient exports by animals are thought to be low, we determined not to fertilize for a time.

Of the six mixtures, the associations of *Desmodium ovalifolium* with either *Brachiaria decumbens* or *Brachiaria dyctioneura* show disappointing animal performance despite high biomass production. In general, animals gain weight once they are introduced from native grasses (besides initial compensatory gains), and after the animals graze for three to four months, average gains diminish and cannot be restored in the *B. decumbens* x *D. ovalifolium* mixture (Figure 1). Photosensitivity has been blamed for this syndrome, but to date no research has been done on the subject. Some animals seem to be more affected than others, but skin lesions have not been evident. In an effort to alleviate this condition, the *B. decumbens* x *D. ovalifolium* association was burned during November 1987 and was left to recuperate during 1988. The grass recuperated well, but the legume had to be reseeded during 1988. Only light grazing was allowed during that year. During 1989, the syndrome appeared again despite a 14-day rotation and high animal stocking rates aimed at supplying a high-quality forage.

Table 1. Animal production, grazing periods, and percentage of legume in five pastures under alternate grazing in 1987. Grazing period: January 30 to December 4.

Association	Stocking rate		Liveweight gains		Legume content
	Rainy season	Dry season	Total prod.	Indiv. prod.	
	—— an/ha ——		kg/ha/yr	g/an/day	%
C. pubescens (pure)	3.3	3.3	574	566	100
B. humidicola *D. ovalifolium*	5.5	5.5	764	423	62
B. decumbens *D.ovalifolium*	5.5	5.5	231	135	14
A. gayanus *S. guianensis*	3.3	3.3	458	451	9
A. gayanus *C. macrocarpum*	3.3	3.3	615	667	31

Table 2. Animal production, grazing periods, and percentage of legume in five pastures under alternate grazing in 1988.

Association	Grazing period	Stocking rates		Liveweight gains		Legume content
		Rainy season	Dry season	Total prod.	Indiv. prod.	
		—— an/ha ——		kg/ha/yr	g/an/day	%
C. pubescens (pure)	1/20–12/21	4.4	4.4	771	537	100
B. humidicola *D. ovalifolium*	2/18–12/22	5.5	4.4	782	485	52
B. decumbens *D.ovalifolium*		pasture recuperation after burn				
A. gayanus *S. guianensis*	1/18–12/12	4.4	3.3	802	599	9
A. gayanus *C. macrocarpum*	2/16–12/13	5.5	3.3	611	468	40

Sustainable Mixtures

The association of *B. dyctioneura* with *D. ovalifolium* was discontinued in 1989 because two lots of animals lost considerable weight in 1988.

In the case of *B. humidicola* x *D. ovalifolium*, productivity and a good legume grass balance were maintained without negative effects on animal performance (Figure 1). Two years after the last maintenance fertilization, Al saturation had increased, and Ca and Mg contents had diminished (Table 4). Also, there were differences in soil chemical composition among blocks despite homogeneous fertilizer and animal management during the last nine years. The effect on animal performance was not clear; animal gains have been sustained (Tables 1, 2, and 3).

Percent legume content appears to decrease with time in the *B. humidicola* x *D. ovalifolium* mixture. Legume stability over time may be a good indicator of sustainability since it appears that the legume is preferred by the animals and thus tends to dominate in the long run. In the *B. humidicola* x *D. ovalifolium* association, the decrease in legume presence could be attributed to the lack of maintenance fertilization (Figure 2).

For the *A. gayanus* x *S. guianensis* association, legume content dropped from an average 36% in 1986 to less than

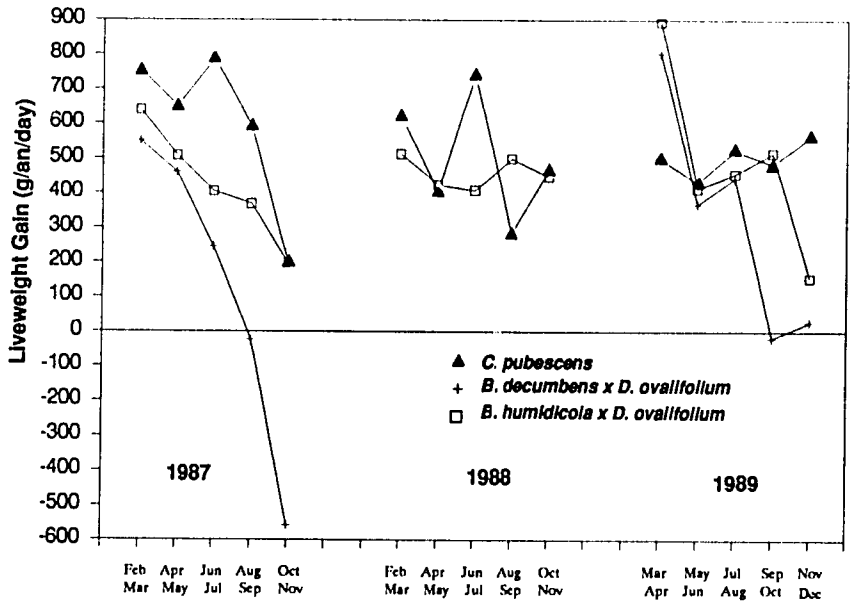

Figure 1. Average daily gains of a pure *C. pubescens* stand and two associaltons of *D. ovalifolium* with *B. decumbens* and *B. humidicola*.

Table 3. Animal production, grazing periods, and percentage of legume in five pastures under alternate grazing in 1989. Grazing season: March 10 to December 12.

Association	Grazing years	Stocking rates: Rainy season	Stocking rates: Dry season	Liveweight gains: Total prod.	Liveweight gains: Indiv. prod.	Legume content
		—— an/ha ——		kg/ha/yr	g/an/day	%
C. pubescens (pure)	8	4.4	3.3	574	479	100
B. humidicola *D. ovalifolium*	7	5.5	4.4	584	492	18
B. decumbens *D.ovalifolium*	9	5.5	4.4	433	308	16
A. gayanus *S. guianensis*	9	5.5	3.3	468	389	4
A. gayanus *C. macrocarpum*	6	4.4	3.3	577	544	46

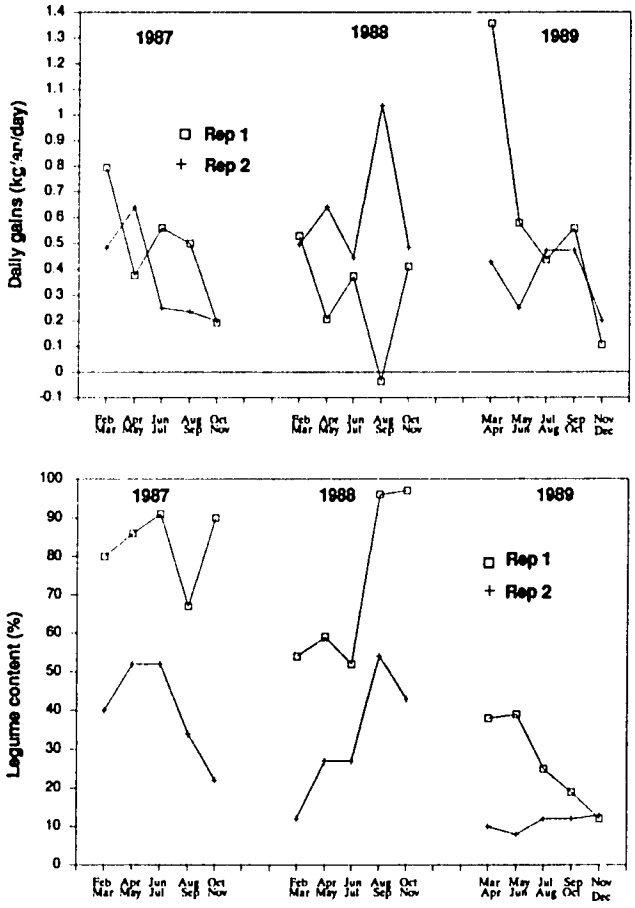

Figure 2. Average daily gains and legume content (%) of the two reps in the *B. humidicola* x *D. ovalifolium* association.

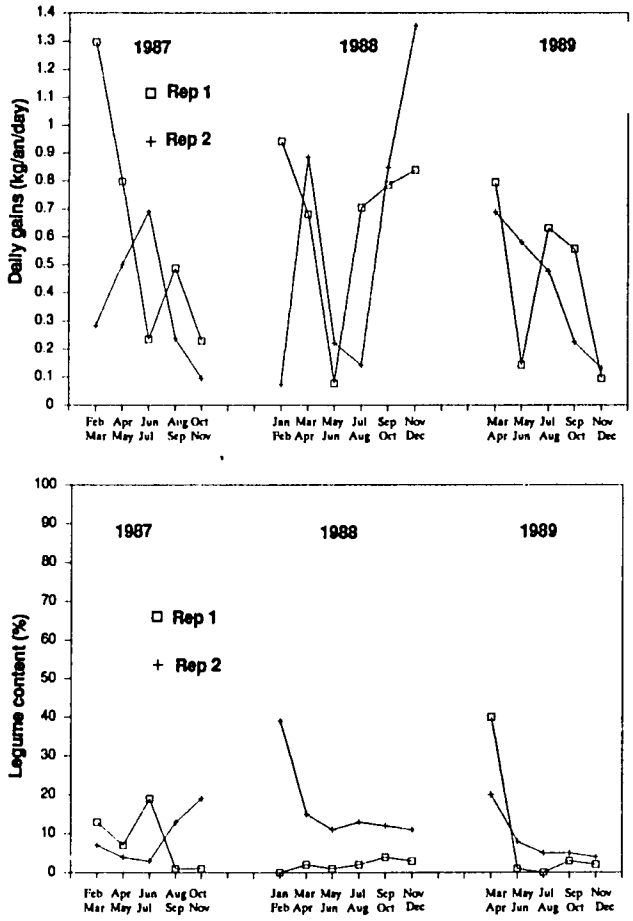

Figure 3. Average daily gains and legume content (%) of the two reps in the *A. gayanus* x *S. guianensis* association.

Table 4. Fertility status of the topsoil (0 to 15 cm) of four pastures after eight years of grazing.

Association	Year	Rep	pH	Olsen P	— Exchangeable — Ca+Mg	K	Al	Al sat
				mg/L	——— cmol/L ———			%
C. pubescens	87	1	4.3	12.2	1.46	0.17	2.57	61
(pure)		2	4.5	13.9	2.04	0.26	1.62	41
	88	1	—	14.2	1.25	0.21	2.88	66
		2	—	12.7	1.45	0.30	1.84	51
A. gayanus	87	1	4.6	11.1	1.09	0.09	3.30	76
C. macrocarpum		2	4.6	10.2	1.36	0.08	0.92	39
	88	1	—	11.2	1.24	0.17	3.96	74
		2	—	8.7	0.93	0.10	1.18	53
A. gayanus	87	1	4.6	14.5	1.12	0.19	2.38	65
S. guianensis		2	4.6	11.3	1.98	0.10	2.24	52
	88	1	—	13.6	1.15	0.21	2.13	61
		2	—	9.2	1.59	0.14	2.24	56
B. humidicola	87	1	4.6	16.1	1.40	0.14	1.08	41
D. ovalifolium		2	4.8	13.7	1.96	0.26	1.11	33
	88	1	—	16.0	1.22	0.19	1.20	46
		2	—	13.4	1.24	0.16	1.38	50

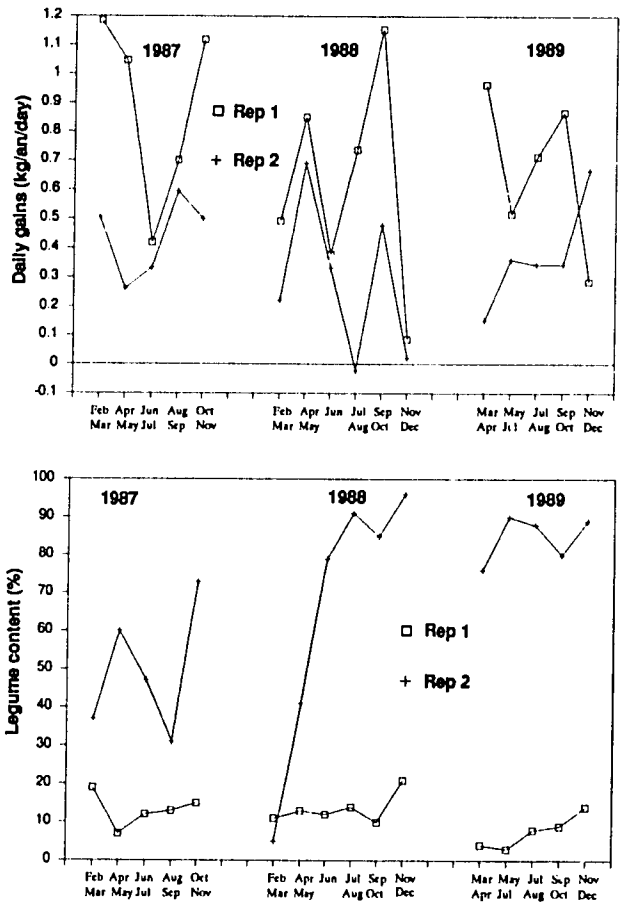

Figure 4. Average daily gains and legume content (%) of the two reps in the *A. gayanus* x *C. macrocarpum* association.

5% in 1989. It is not clear if the decrease in legume percentage is due to a lack of fertilization, since *S. guianensis* is not a true perennial and since the legume declined even when the pasture was fertilized in 1987 (Figure 3). Still, low animal performance (1989) is likely to be related to the low legume content in this treatment (Figure 3, Table 3).

The two repetitions of the *A. gayanus* x *C. macrocarpum* association show contrasting botanical composition and soil characteristics (Figure 4 and Table 4). The legume is now dominant in repetition 2, and the grass is likely to disappear from the association during 1990. In this case, legume persistence appears to be related to soil chemical conditions (Table 4). With higher Al saturation, the grass tends to dominate, even though animals prefer it; with a lower Al saturation, the legume dominates.

This suggests that a low Al saturation may be required in order to maintain the legume component. The difference in animal gains between grass and legume-dominated paddocks strongly indicates that animals prefer grass, but it also indicates that they will not lose weight despite the lack of a grass.

A pure legume stand can be grazed, as in the case of *C. pubescens*, which was the best overall performing pasture (Tables 1, 2, and 3). It is not clear what is the correct proportion of legume in a pasture, but legume contents of 50% or higher do not appear to reduce animal weight gains. However, legume contents less than 10% will reduce animal weight gains over time, as seems to be the case with *A. gayanus* x *S. guianensis* (Figure 3). The loss of *S. guianensis* often results in invasion by other forage species and weeds, but this loss may be overcome by weeding, which requires between two and three man-day/ha/year.

Nitrogen Contribution of the Legume to a Grazed Pasture: Y-308A

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Pedro A. Sanchez, N.C. State University

Leguminous plants can derive most of the N required for their nutrition from an association with *Rhizobium* or *Bradyrhizobium* bacteria possessing an N-fixing system. Portions of this fixed N are transferred to the grass via four main pathways: 1) direct animal ingestion of legume, 2) recycling of the ingested legume via excreta, 3) leaf litter, and 4) decomposition of legume roots and nodules. The relative contribution of each pathway to the transfer process is of particular importance in the humid tropics. High cost and limited availability of N fertilizers prevent their use for beef or dual-purpose cattle production. Legumes can play a key offsetting role, but low palatability of most tropical legumes and year-round grass growth are believed to hinder legume use in the humid tropics as compared with seasonal ustic regimes where grass growth stops during the dry season, as is the case in the savannas. These factors make management of mixtures more difficult than for grasses alone in udic moisture regions.

Quantifying the N contributed by legumes under field conditions is difficult. The effects of uneven distribution of animal excreta on the field, localized gaseous or leaching N losses, and the competition of legumes for N uptake make interpreting N output data in any one pathway difficult. Measurements are further complicated in a grass-legume mixture because the associated grass response must also be measured. Competitive and non-competitive interferences must be taken into account when interpreting the grass response.

An alternative to quantifying the legume N contribution is to estimate the difference between the N yield of the grass-legume mixture and the grass alone, without N fertilizer. This difference expresses the net legume N contribution to the mixed sward and is independent of interferences between components of the mixture. When this contribution is compared with N fertilizer response from pure grass swards, an estimation of its value in nitrogen fertilizer equivalents (NFE) is obtained.

The N contribution of the legume *Desmodium ovalifolium* Wall to its associated grass *Brachiaria decumbens* Stapf was estimated in the humid tropics near Pucallpa, Peru. Treatments consisted of grass-legume mixtures stocked at two grazing pressures (herbage allowances were 3 and 4 kg dry matter per 100 kg bodyweight per day for the high grazing pressure [HGP] and low grazing pressure [LGP], respectively), and grass alone topdressed with 0, 150, and 300 kg N/ha/yr at the low grazing pressure. All treatments were grazed for 2.5 years. The design was a randomized complete block with three replications. The effect of *D. ovalifolium* was measured on the herbage mass, on the N concentration of *B. decumbens*, and in the N yield of the sward.

Inclusion of *D. ovalifolium* did not increase herbage mass (Figure 1) but did increase ($p < 0.01$) the N concentration of *B. decumbens* (Figure 2) and the total N yield of the sward (Figure 3). No significant difference between grazing pressures was detected. Nitrogen fertilizer equivalents (NFE) of *D. ovalifolium* inclusion were 206

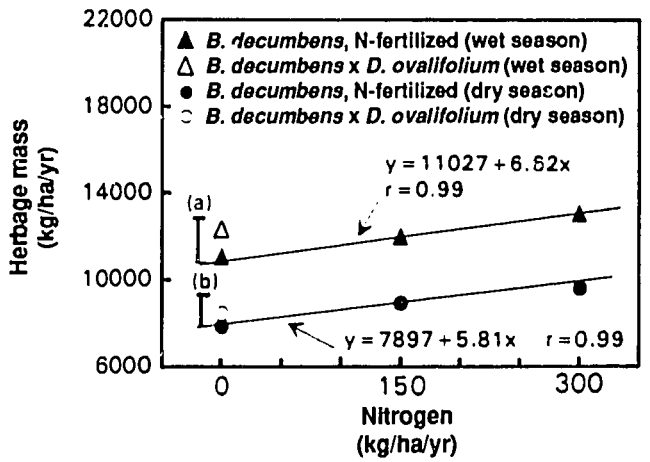

Figure 1. Mean herbage mass production, as affected by N fertilization and by the inclusion of *D. ovalifolium*. Herbage mass for the mixture treatments is the average of HGP and LPG treatments. Least significant differences (0.05) for the comparison of *B. decumbens* with no N added to the mixture are shown for (a) wet season and (b) dry season (dry season: June–September; wet season: October–May).

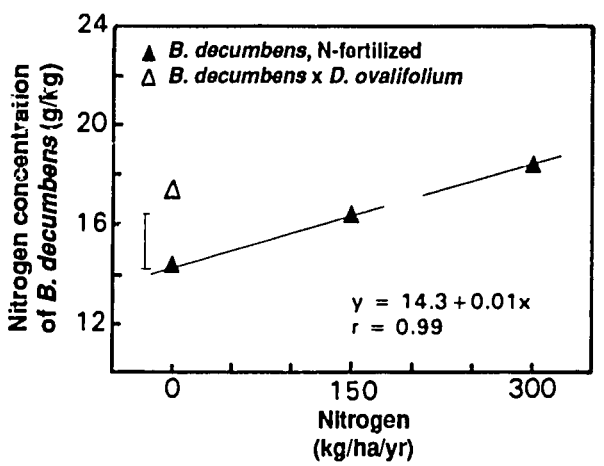

Figure 2. Nitrogen concentration of *B. decumbens* as affected by N fertilization and by the inclusion of *D. ovalifolium*. Nitrogen concentration of the mixtures is the average of the HGP and LGP treatments. Least significant (0.05) difference for the comparison of *B. decumbens* with no N added to the mixture is shown. Mean of 14 grazing cycles.

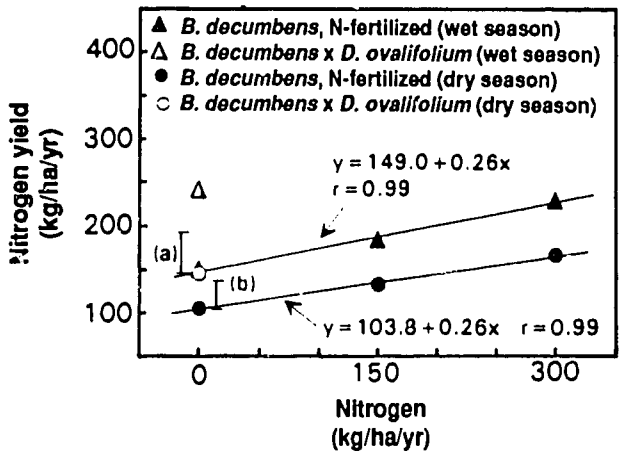

Figure 3. Mean N yield of the sward as affected by N fertilization and by the inclusion of *D. ovalifolium*. Nitrogen yield for the mixtures is the average of the HGP and LGP treatments. Least significant differences (0.05) for the comparison of *B. decumbens* with no N added to the mixture are shown for (a) wet season and (b) dry season (dry season: June–September; wet season: October–May).

and 282 kg N/ha/yr for the N concentration of the mixed grass and for the total N yield of the sward, respectively. The *B. decumbens* response to N was significant but small. The effect of *D. ovalifolium* on the herbage mass and on the total N yield of the sward appeared to be independent of the legume percentage in the sward. Legume content of the sward approached an equilibrium level of about 50% after one year of grazing and remained stable afterwards (Figure 4). The increase in N concentration in the associated grass, therefore, was the major effect produced by including the legume in the mixture.

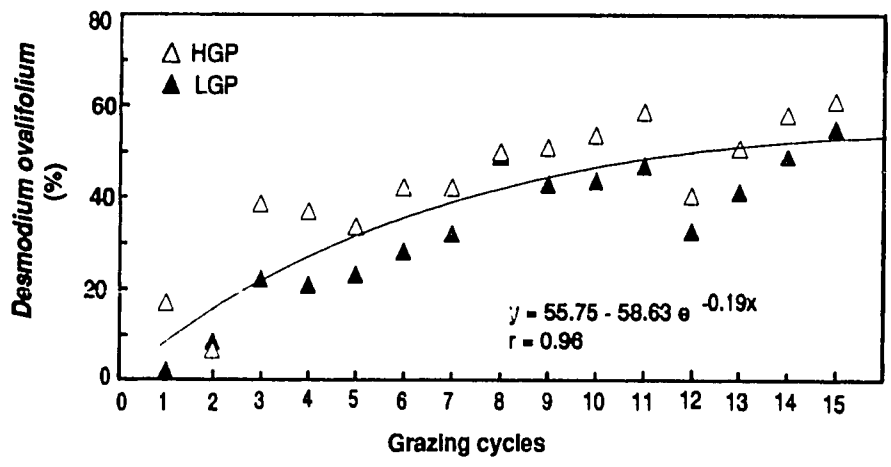

Figure 4. Changes in *D. ovalifolium* herbage mass percentage in the sward through the grazing cycles.

Nitrogen Contribution of the Legume to the Grazing Animal: Y-308B

Miguel A. Ara, N.C. State University
Pedro A. Sanchez, N.C. State University

Improving the N intake of grazing animals contributes to the animal gains that result from N fertilization of pastures or from the inclusion of a legume. Improving the N intake also increases the amount of N returned to the soil after animal requirements are met. With the increasing concern for the nutrient recycling ability of agroecosystems in the humid tropics, it is important to estimate the amounts of potentially recyclable N consumed by grazing animals. It is also important to know how these amounts are affected by fertilization or legume inclusion and by management practices such as grazing pressure.

The role that legumes play in improving the N quality of the diet, and consequently in the potential of N recycling via animals, is still obscure. In a few circumstances, legumes have significantly increased the dry-matter yield of pastures. In the high productivity environment of the humid tropics, pure grass swards show high dry-matter productivity, and they support relatively high stocking rates, thus allowing more efficient nutrient recycling. On the other hand, low palatability of most tropical legumes may reduce the fixed N in the animal pathway of the N cycle.

Objectives

The purpose of this study was to test the following set of hypotheses.

1) Including a legume in a grass pasture increases the N concentration of the grazing animal's diet at a level comparable to that caused by adding N fertilizer to the grass monoculture. The degree of the dietary N enrichment of the mixed pasture should be directly proportional to percentage of legume in the diet.

2) Any grazing management practice that tends to decrease species selectivity (such as increasing grazing pressure) from a relatively unpalatable legume-based pasture would increase legume utilization and dietary N enrichment

3) The percentage of N in the herbage mass consumed by grazing animals would be higher in pure grass pastures than in mixed pastures grazed by animals with a strong preference for the grass, especially if the proportion of legume and the difference in N concentration between the two components are high.

Procedures

To test the above hypotheses, we used the grazing experiment described in the preceding section. Ten steers ranging from 150 to 250 kg of liveweight were previously selected from the experimental animals and esophageal-fistulated in June 1985, using the surgical procedure and the sleeve-type silicon cannulae. However, after several sampling attempts, the cannulae proved completely inoperative and extremely fragile, so they were replaced with removable plugs (type 3c) as described by van Dyne and Torell. Two fistulated steers were randomly assigned to each of the five treatment areas, where they grazed for the whole experimental period (January 1986 to June 1988). Both fistulated and intact animals rotated through the replicates within treatments. They were weighed every 15 to 27 days, i.e. immediately before they changed paddocks. Intact animals were used to balance the liveweight allotted to each paddock based on the herbage mass and the desired grazing pressure.

Diet selected by fistulated animals was sampled daily from the 5th to the 10th grazing day from June 1987 to June 1988. At each sampling date, fistulated animals were subject to an early-morning (0500 to 0900 h) fasting period and returned to their respective paddocks for a 20-minute sampling period. Extrusa samples, after being collected, were drained of excess saliva and frozen. Samples were thawed, thoroughly mixed, and botanical composition estimated using the microscopic point-hit technique. In this procedure, about 300 g of plant material was placed in a 20 x 35 cm plastic tray and examined under a binocular microscope with magnification of 15x and with a center-point in one eyepiece. A board equipped with a guide rail allowed the sample to be examined at regularly spaced points (hits). At each point, the particle immediately under the center-point was identified as grass or legume. After 400 points were identified, the percentage was calculated from the number of points that were identified as grass or legume.

Dry-matter intake was estimated for each treatment and for each grazing period by using the average liveweight gain of the grazing animals. The N concentration of the herbage for the mixtures was obtained from the total mean of N concentrations of *B. decumbens* and *D. ovalifolium* adjusted for the respective percentages in the sward. The N content of the sward was calculated from the average N concentration and the herbage mass of the sward. The potential N return in the excreta of the grazing animals was calculated from the N intake values after 17% of the N retained by the animals had been considered.

Results

D. ovalifolium increased the dietary N concentration and estimated N intake of the grazing animals in amounts comparable to the addition of 518 and 330 kg/ha/yr of N fertilizer, respectively. There was no significant effect from the different grazing pressures, so the mean results are shown in Figure 1. Selectivity index values, obtained from the botanical composition of the diet, consistently

indicated preference for *B. decumbens* (Figure 2). The percentage of *D. ovalifolium* in the diet showed little correlation with the *D. ovalifolium* percentage in the sward (Figure 3). *D. ovalifolium* inclusion significantly improved the N quality of the diet, in spite of the preference for *B. decumbens* (Figure 4). Animals grazing the grass-legume mixture averaged 226 kg/ha/yr of dietary N intake, representing an estimated 187 kg N/ha/yr returned to the soil via excreta.

Conclusions

D. ovalifolium's N contribution to the mixed sward was clearly evident in the dietary N concentration and N intake of grazing animals, despite the low legume utilization. In

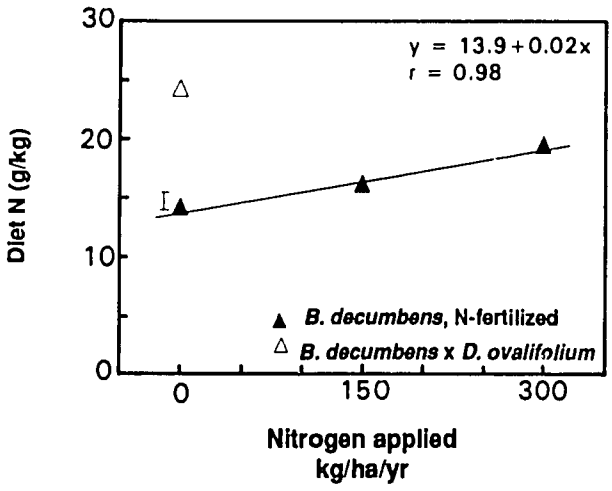

Figure 1. Dietary N concentration as affected by N fertilization and by the inclusion of *D. ovalifolium*. Nitrogen concentration for the mixture was the average of the HGP and LPG treatments. Least significant difference (0.05) for the comparison between *B. decumbens* with no N and the mixtures is shown. Mean of seven grazing cycles.

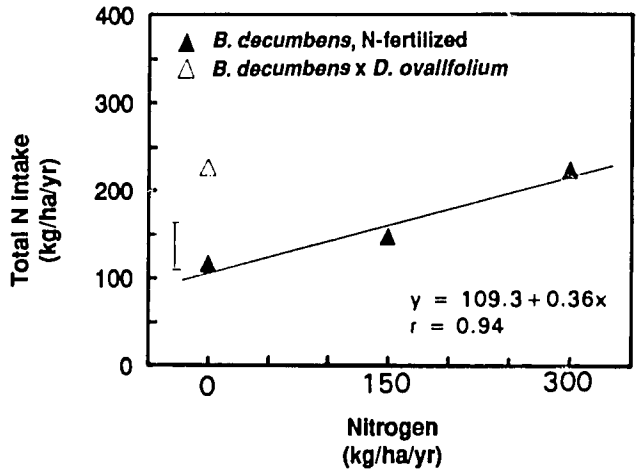

Figure 3. Nitrogen intake as affected by N fertilization and by the inclusion of *D. ovalifolium*. Nitrogen intake for the mixtures is the average of the HGP and LGP treatments. Least significant difference (0.05) bar for the comparions of *B. decumbens* with no N in the mixture is shown.

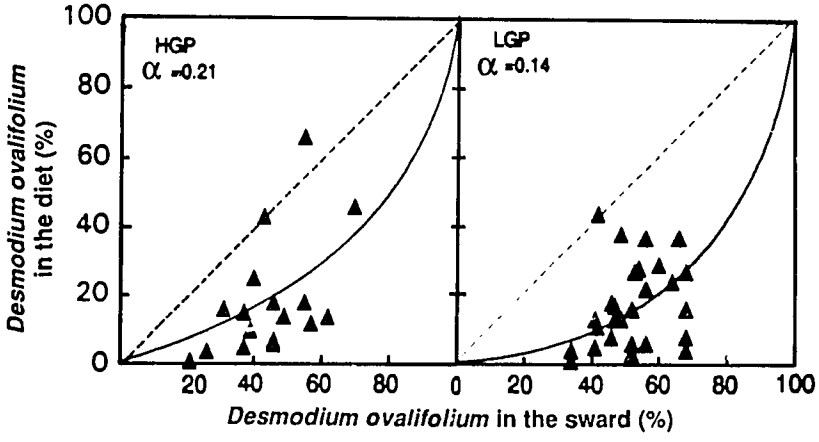

Figure 2. Relationship between the *D. ovalifolium* percentage in the sward and in the diet. The broken line represents the selectivity index; α = 0.5 (no specific preference). The solid lines fitted to the equation Y = 100x/[(100 - x) α] + 2x-100 show selectivity against *D. ovalifolium* mean α values shown on top left-hand corner for high (HGP) and low (LGP) grazing pressure.

practical terms, the impact of this low palatability legume on the animal's consumption was equivalent to a fertilizer application of 330 kg N/ha/yr to the grass pasture. Results suggest that benefits from *D. ovalifolium* in the grass-legume mixture depend more on the increased N concentration of *B. decumbens* than on *D. ovalifolium* consumption. Lack of dependence of dietary N levels and N intake on dietary legume percentage indicates that no benefit would be obtained from practices that increase *D. ovalifolium* utilization.

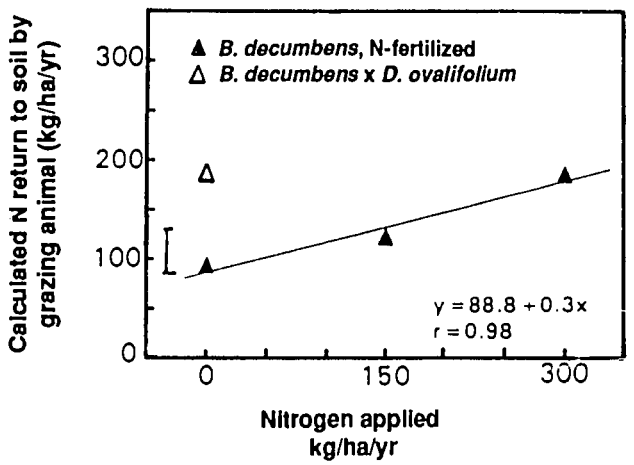

Figure 4. Calculated N return to the soil by the grazing animal. Nitrogen return for the mixtures is the average of HGP and LGP treatments. Least significant difference bar for the comparison of *B. decumbens* with no in the mixture is shown.

Limited Role of Legume Leaf-litter Decomposition as a Nitrogen Contribution Pathway: Y-308C

Miguel A. Ara, N.C. State University
Pedro A. Sanchez, N.C. State University

The decomposition of legume leaf-litter is considered to be one of the main avenues of N contribution from the legume to the growing grass. *Desmodium ovalifolium* leaf-litter biomass accumulated from two grazed *Brachiaria decumbens* x *Desmodium ovalifolium* pastures (described in the preceding sections) was sampled and its N concentration determined five times over a 452-day period. Nitrogen concentration of the leaf-litter was fairly uniform, averaging 15.7 g/kg, which is approximately 68% of the N concentration in the standing biomass (Table 1). Estimated *D. ovalifolium* leaf-litter N pool size was 70 kg N/ha. Annual leaflitter production, calculated from accumulated leaflitter measurements and from a reported decomposition constant, amounted to 6700 kg/ha, and the amount of N returned to the soil via this pathway was 103 kg N/ha/yr (Table 2). Nitrogen released from *D. ovalifolium* leaf-litter and its recovery by *B. decumbens* were estimated by incubation of ^{15}N-tagged *D. ovalifolium* leaf-litter in field microplots during a five-month period (Table 3). Therefore, in spite of a large flux of N via legume leaf-litter accumulation, only a small amount was actually recovered by the plant, perhaps because of the low decomposition rate of *D. ovalifolium* due to its high polyphenolics contents. The remainder is assumed to go directly into the soil organic-matter pools, because all *D. ovalifolium* litter eventually decomposes. It is doubtful

Table 1. Nitrogen concentration of *D. ovalifolium* leaf-litter biomass as compared to the N concentration of *D. ovalifolium* standing biomass.

Sampling date	N concentration of leaf-litter biomass	N concentration of standing biomass	Ratio[§]
	g/kg	g/kg	
20 Oct 1986	16.4	24.2	68
11 Dec 1986	16.2	26.0	62
28 Mar 1987	16.4	21.6	76
5 Oct 1987	14.7	20.3	72
15 Jan 1988	14.9	23.3	64
Mean	15.7	23.1	68
s.d.	0.82	2.22	5.72
CV(%)	5.3	9.6	8

[§] N concentration leaf-litter/N concentration standing biomass x 100

that the *D. ovalifolium* leaf-litter N diverted to the soil organic pool would benefit the grass in the short term. It is likely that the high polyphenolic content of *D. ovalifolium* would form stable organic complexes with proteins and that the N not available in the first flush of mineralization would be released very slowly.

Table 2. *Desmodium ovalifolium* leaf-litter N concentration, calculated leaf-litter production, and N return per year, at different sampling dates.

Sampling date	N concentration	Calculated annual litter production	Calculated N returned with leaf-litter
	g/kg	kg/ha/yr	
20 Oct 1986	16.4		
11 Dec 1986	16.2	1035	16.7
28 Mar 1987	16.4	1382	22.7
5 Oct 1987	14.7	4285	63.0
15 Jan 1988	14.9		
Per year§		6702	102.4
Mean	15.7		
std.	0.82		
CV(%)	5		

§ The total per year is the sum of the values for sampling dates 11 December 1986, and 28 March 1987, and 5 October 1988 (350 days).

Table 3. Labelled N enrichment, total N uptake, N uptake, and percentage of N recovery from *D. ovalifolium* labelled litter by *B. decumbens* grown in three field microplots during a five-month period.

	^{15}N applied to legume	B. decumbens ^{15}N	% of ^{15}N recovered by grass	Labelled D. ovalifolium litter application rate	B. decumbens total N uptake	B. decumbens N from labelled litter	^{15}N recovery by the grass from legume leaflitter
Mean	0.6043	0.0643	9.996	7.97	4.01	3.90	5.73
s.d	0.0538	0.0376	5.77	2.57	0.97	2.42	3.54
CV(%)	9	62	58	4	22	62	62

Estimating the Overall Nitrogen Contribution of the Legume: Y-308D

Miguel A. Ara, N.C. State University
Pedro A. Sanchez, N.C. State University

Few attempts have been made to characterize the components of the N cycle under practical grazing conditions, and no reports of this subject exist for the humid tropics. Modelling the different N fluxes to the grazing animal is a good way to assess the nature of the legume contribution, and it also provides a basis to identify gaps in information and to formulate additional hypotheses. However, definite limitations exist when we try to model these processes using the data given in the preceding sections. First, not all avenues of legume N contribution were studied: root litter and soil organic-matter turnover were not examined. Second, the methods used in the preceding section to quantify the legume contribution may not be the best way to budget N in certain pools and fluxes because these methods rely principally on the net effects of certain pools, and, as a consequence, values for pasture pools and leaf-litter production are not calculated in the conventional manner. It was necessary, therefore, to make indirect calculations and specific assumptions and also to use data from the literature to estimate additional inputs, outputs, fluxes, and compartments. Furthermore, the soil is a complete black box. With these limitations in mind, we analyzed the N contribution of *D. ovalifolium* in terms of N fluxes toward the grazing animal, based on results obtained with a 30-month grazing experiment near Pucallpa, Peru, described in the previous three sections.

Model Description

A flow diagram (Figure 1) depicting the main N compartments and fluxes for our grazed *B. decumbens* x *D.*

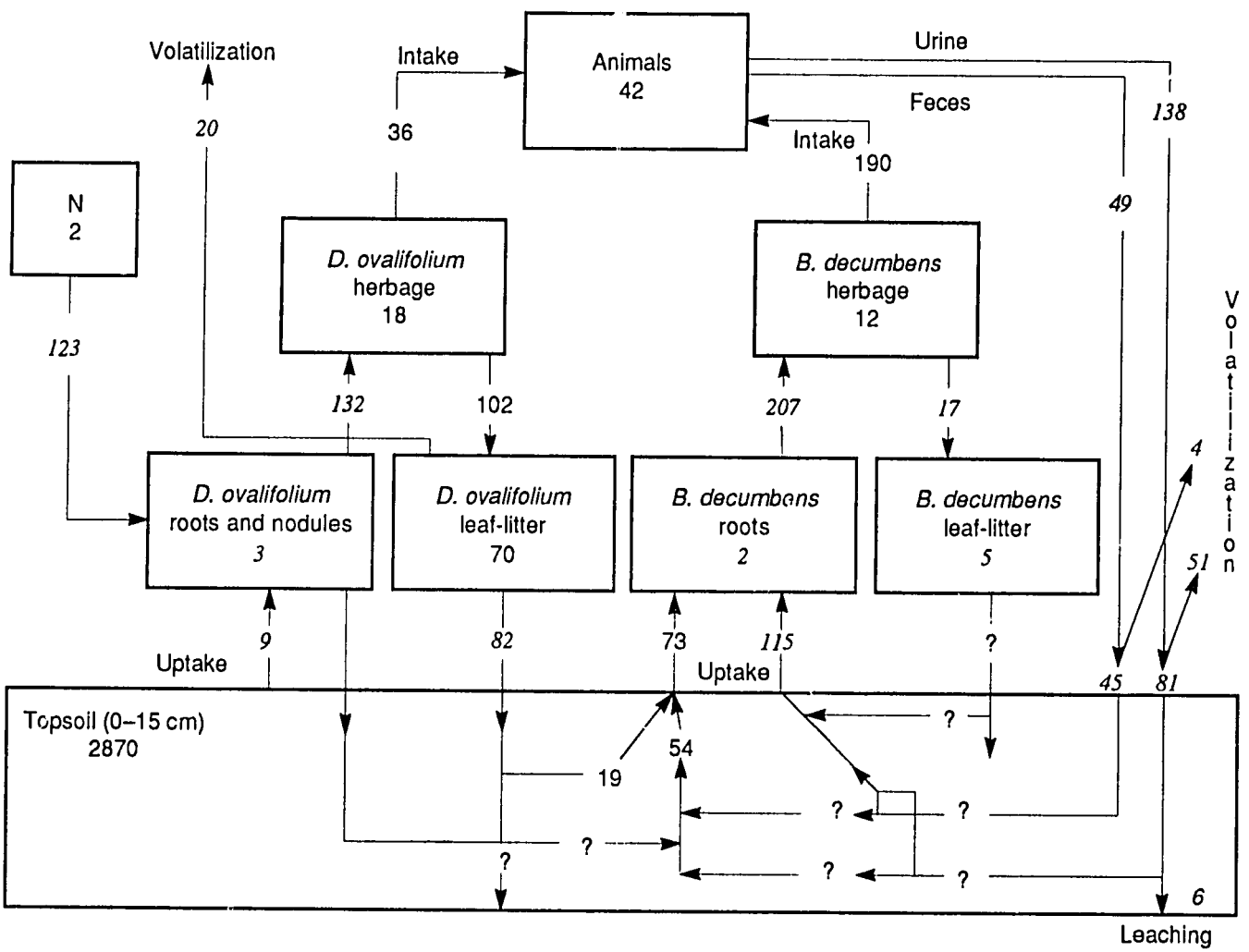

Figure 1. Nitrogen pools and fulxes for a grazed mixture of *Brachiaria decumbens* x *Desmodium ovalifolium*. Numbers in pools are kg N/ha; numbers in fluxes are kg N/ha/yr. Numbers in regular type are either hard data or calculations from them. Numbers in italics are based on assumptions from the literature rather than on actual data.

ovalifolium system was used as a model. The model has two overall assumptions: 1) no N is removed or added to the system by movement of plant, animal, or excreta material and 2) additions of N from nonsymbiotic fixation, ammonia adsorption by the soil, or precipitation are negligible. Numbers in boldface are either hard data or calculations from them, while numbers in script are based on assumptions from the literature. The latter represent at best unsubstantiated estimates that need to be validated by future research.

Four main pools are included in the model (Figure 1). The N in *D. ovalifolium* is considered the primary N input and most of it is assumed to come from symbiotic N fixation. The *B. decumbens* pool includes N contributed from *D. ovalifolium* as well as from the soil. The grass and legume pools are divided into herbage, leaflitter, and root compartments. The animal N pool represents the N incorporated into animal tissue, both from *B. decumbens* and *D. ovalifolium*. The soil pool is the total amount of N to a depth of 15 cm after 30 months of grazing.

Main fluxes include the following: 1) N fixation (calculated), 2) N uptake by grass and legume (calculated), 3) N intake by animals from *B. decumbens* and *D. ovalifolium* (measured), 4) N return through animal excreta (calculated), 5) N return by litterfall (measured), and 6) volatilization and leaching loss of N fluxes from feces and urine (calculated). Also, considered are *D. ovalifolium's* indirect contribution fluxes via *B. decumbens* intake, both through leaf-litter production and root and nodule decomposition (Figure 1).

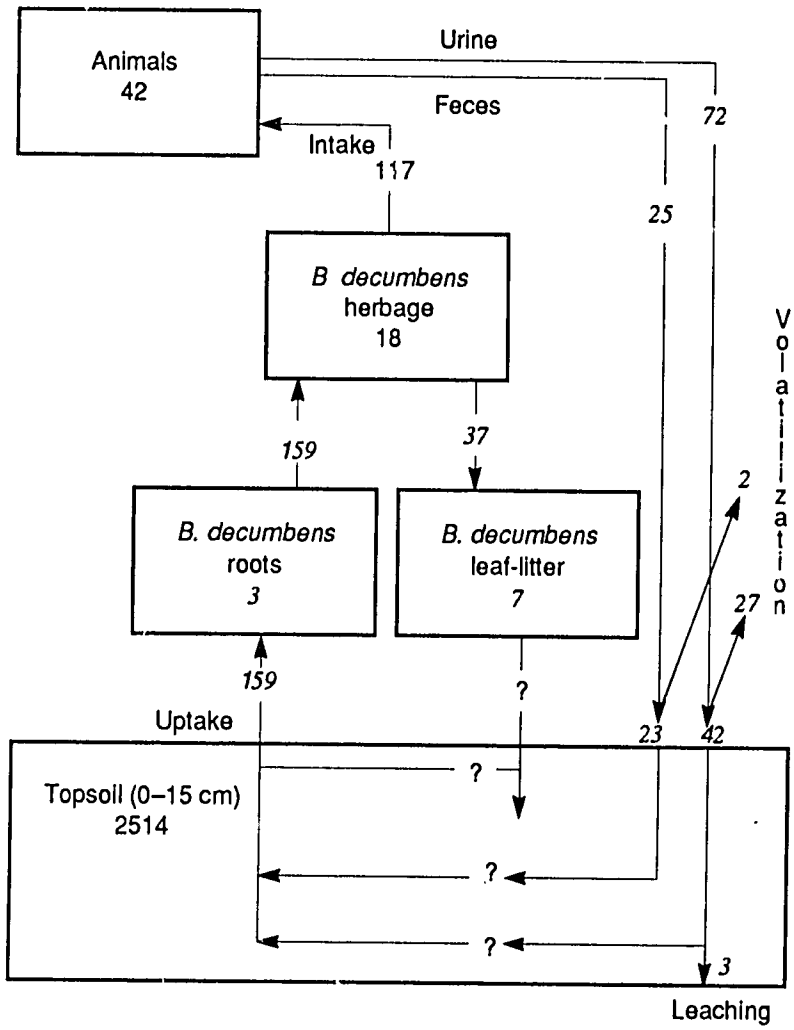

Figure 2. Nitrogen pools and fulxes for a grazed pasture of *Brachiaria decumbens* without N applied. Numbers in pools are kg N/ha; numbers in fluxes are kg N/ha/yr. Numbers in regular type are either hard data or calculations from them. Numbers in italics are based on assumptions from the literature rather than on actual data collected.

Amounts calculated for the different pools and fluxes correspond to the mixtures (Figure 1) and to *B. decumbens* fertilized with 0 (Figure 2) and 300 kg N/ha/yr (Figure 3) (Treatments N0 and N300, respectively). Values for the mixture are based on the average of the high and low grazing pressure treatments, as there were not significant differences between them. Specific details on the assumption are described in Miguel Ara's Ph.D. thesis (1990, North Carolina State University).

Pools

Desmodium ovalifolium

Nitrogen in the herbage compartment of the *D. ovalifolium* pool amounted to 18 kg N/ha (Figure 1). The N in the root and nodules compartment was 3 kg/N/ha. Nitrogen in the leaflitter on the soil amounted to 70 kg/ha.

Brachiaria decumbens

The N in the different compartments of *B. decumbens* totalled 19, 28, and 40 kg N/ha for mixed grass, N0, and N300, respectively (Figures 1, 2, and 3). About 65% of this N occurred in the herbage, 25% in the leaflitter, and only 10% in the root compartments.

Animal Pool

Nitrogen in the animals grazing the mixture and the treatments N0 and N300 amounted to 42, 42, and 46 kg N/ha respectively (Table 1).

Soil Pool

Desmodium ovalifolium inclusion or N fertilization did not have significant effects on the N concentration of the soil at either depth. The average size of this pool at a depth of 0 to 15 cm was 2870 kg/N/ha for the mixtures, and 2514

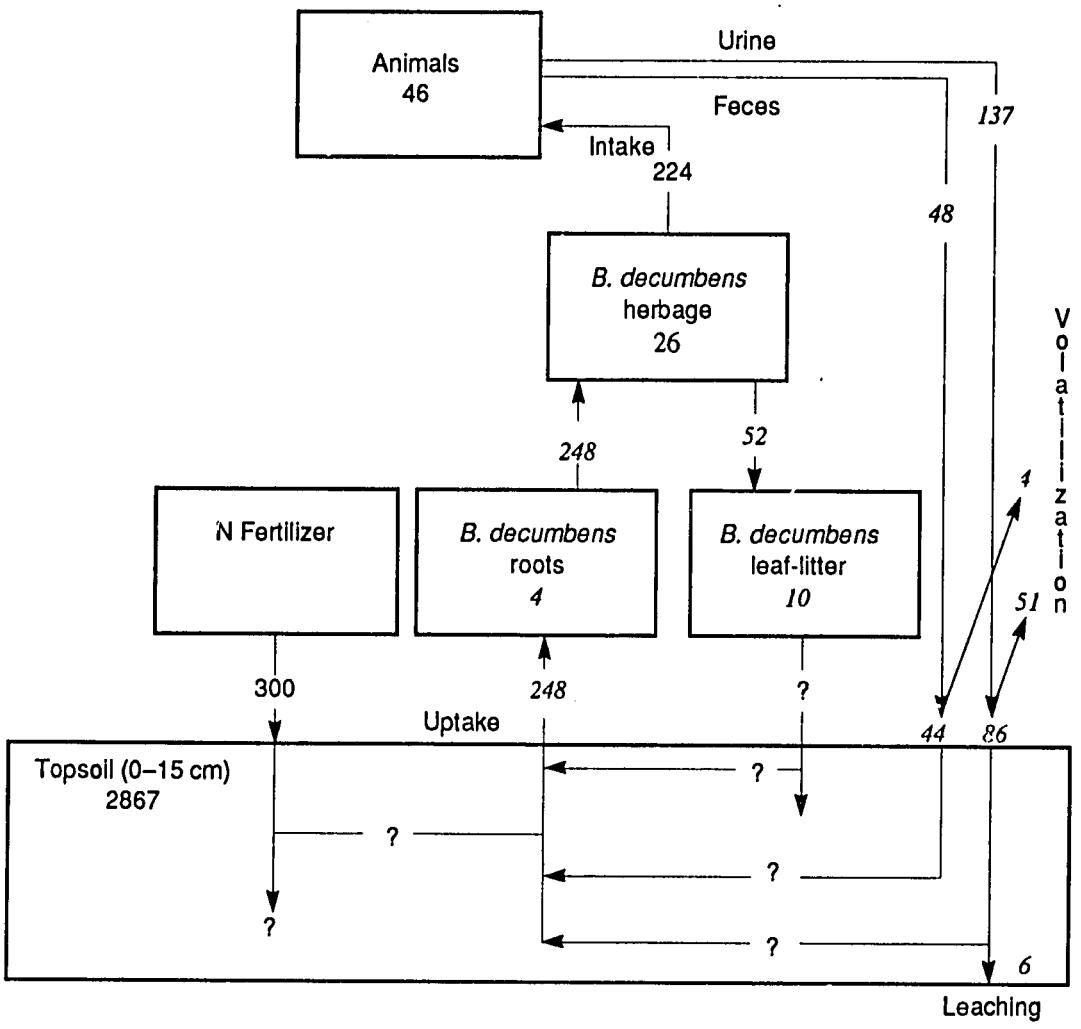

Figure 3. Nitrogen pools and fulxes for a grazed pasture of *Brachiaria decumbens* fertilized with 300 kg N/ha. Numbers in pools are kg N/ha; numbers in fluxes are kg N/ha/yr. Numbers in regular type are either hard data or calculations from them. Numbers in italics are based on assumptions from the literature rather than on actual data collected.

and 2867 kg N/ha for the N0 and N300 treatments (Figures 1, 2, and 3, respectively). The different treatments had no significant effect on N build-up (Table 2). The buildup was consistently positive, but since there was also a buildup in the N0 treatment, these estimates may not be reliable.

One thing is certain: topsoil organic nitrogen contents do not decrease within 30 months of grazing. This observation is consistent with our longer-term experience in Yurimaguas and contrasts sharply with what happens under annual crop production systems.

Fluxes

Animal Intake

Fluxes of N from the mixed swards toward the grazing animal were 190 and 36 kg/ha/yr for *B. decumbens* and *D. ovalifolium* respectively (Figure 1). The flux of N toward

Table 1. Animal pool per grazing cycle for the components of a *Brachiaria decumbens* x *Desmodium ovalifolium* mixture and for *B. decumbens* fertilized with 0 and 300 kg/N/ha/yr.

Grazing cycle	Treatments		
	Mixture	N0	N300
	kg N/ha		
9	37.1	38.7	41.9
10	42.2	39.3	48.4
11	38.0	46.8	40.7
14	46.3	44.0	47.0
15	46.5	40.6	50.0
Mean	42.0	41.9	45.o

the grazing animal from N0 and N300 treatments was 117 and 224 kg N/ha/yr, respectively (Figures 2 and 3).

Animal Excreta

Nitrogen return to the soil via animal excreta was calculated from the total N intake minus 17%, which, according to the literature, is the N retained in the body tissue. This total return in the excreta was partitioned according to the rates established in the literature: 74% of the N is excreted in the urine, and the remaining 26% is excreted in the feces. Flux of urine N into the soil was adjusted by taking into account assumed losses by volatilization, which have been reported to average about 37%. Leaching losses from urine were assumed to be about 4%. Nitrogen flux toward the soil through fecal excreta was adjusted in a way similar to that used for the urine N. N volatilization losses of 8% were used, as established in the literature.

Nitrogen in the excreta from animals grazing the mixtures was calculated to be 187 kg N/ha/yr (Figure 1). From this amount, 138 and 49 kg N/ha/yr were returned as urine and fecal N, respectively. Volatilization losses in urine and feces from this flux were 51 and 4 kg N/ha/yr, respectively. Assumed leaching losses from urine were 6 kg N/ha/yr. The remaining 81 kg N/ha/yr entered the mineral pool N of the soil. No leaching losses from fecal N were assumed. The remaining 45 kg N/ha/yr of fecal return were assumed to enter the labile and stable organic N soil pools in unknown proportion.

Desmodium Ovalifolium Leaf-litter Production

Desmodium ovalifolium leaf-litter production amounted to 102 kg N/ha/yr toward the litter pool of *D. ovalifolium* (Figure 1). An assumed loss of 20 kg N/ha/yr occurred as NH_3 volatilization. The remaining 82 kg N/ha/yr was considered to enter the labile and stable N pools in unknown proportions.

Nitrogen Fixation

The flux of N fixation toward *D. ovalifolium* was assumed to be the result of N accumulated in the herbage plus the root growth in a year minus 7%, which is the average N uptake from the soil of a number of tropical legume species including *Desmodium* spp. The amount of N fixation obtained from preceding calculations was on the order of 123 kg N/ha/yr.

Nitrogen Uptake

Nitrogen uptake for the mixed *D. ovalifolium* and *B. decumbens* amounted to 9 and 115 kg N/ha/yr, respectively (Figure 1). Nitrogen uptake for the N0 and N300 treatments amounted to 159 and 248 kg N/ha/yr (Figures 2 and 3, respectively).

Desmodium ovalifolium N Contribution

Direct N contribution through *D. ovalifolium* intake amounted to 36 kg N/ha and represented 16% of the N consumption from mixtures (Figure 1). On the other hand, the N consumed from mixtures of *B. decumbens* amounted

Table 2. Soil N concentration before (preplanting) and after 30 months of grazing and N buildup for *B. decumbens* with 0, 150, and 300 kg/ha/yr, and for its mixture with *D. ovalifolium*. Mean of three replications.

	Depth	Treatments			
		N0	N150	N300	Mixture
		g/kg			
Before (March 1985)	0–15	0.93	0.70	1.07	0.98
After (July 1988)	0–5	1.46	1.78	1.59	1.51
	5–15	0.93	1.14	1.16	1.22
	0–15	1.14	1.35	1.30	1.30
Buildup§	0–15	0.21	0.65	0.23	0.33
		kg/ha			
Buildup	0–15	463	1433	507	728
Buildup per year	0–15	185	573	203	291

§ Calculated as the difference between the N concentration before and after only for a soil depth of 0 to 15 cm.

to 190 kg N/ha/yr and represented 84% of the total N consumption from mixtures. The N consumed by *B. decumbens* comes from both *D. ovalifolium* transfer and from the soil. The contribution from *D. ovalifolium* was 73 kg N/ha/yr, which represents 38% of the total N flux via *B. decumbens*. The remaining 62% is assumed to come from the soil. The part coming from *D. ovalifolium* leaf-litter amounted to 19 kg N/ha/yr toward the grazing animal (Table 3). Thus, 26% (19:73) of the indirect N contribution can be explained by leaf-litter accumulation.

Desmodium ovalifolium's total N contribution to the grazing animal was 109 kg N/ha/yr (Table 3). Direct legume intake accounted for 33%, and the remaining 67% was indirectly contributed via *B. decumbens* intake and partitioned as follows: 17% came from legume leaflitter decomposition, and 50% came from recycling of animal excreta and legume root decomposition. Low palatability of *D. ovalifolium* limits the direct contribution, but the total contribution was enough to maintain grass N concentrations above the critical levels set to meet cattle requirements.

Discussion

Table 3 indicates that only 48% of the N intake by animals came from the legume source in the mixture. The N intake via mixed *B. decumbens* (117 kg N/ha/yr) came from other sources besides the legume. This is a high proportion of the total N and suggests a good N-supplying ability of the soil or a very effective recycling of the *B. decumbens* litter and the animal excreta. In the humid tropics, grazed pastures of pure *B. decumbens* often look greener than one would expect, even when they receive no nitrogen fertilization. The authors have made this observation in several countries. Although our calculations do not explain such observations, they are thought provoking.

Results from calculated pools and fluxes must be interpreted cautiously until our assumptions can be verified. Some independent calculations, however, seem to agree remarkably well. For example, the N uptake of *B. decumbens* with no N (154 kg N/ha/yr)—calculated from the N intake by grazing animals plus the calculated leaf-litter production is close to 150 kg N/ha/yr. That figure is determined by taking the annual N yield of *B. decumbens* herbage plus the calculated N accumulation in the root growth obtained from reported herbage (root N yield ratio) (Figure 2). However, this agreement does not occur for *B. decumbens* fertilized with 300 kg N/ha/yr (Figure 3).

One of the main information gaps concerns the role of *B. decumbens* leaf-litter in N cycling. Calculations from Australia on accumulation rates for *Digitaria decumbens* leaf-litter show a rather low *B. decumbens* leaf-litter N pool (Figure 1). Results from a grazed *B. humidicola x D. ovalifolium* experiment in Yurimaguas, Peru, show that the grass leaf-litter mass is as high as the legume leaf-litter mass (see potassium dynamics section). Less palatable than *B. decumbens*, *B. humidicola* shows a higher potential for grass leaf-litter accumulation. No matter how much N accumulates in the grass leaf-litter, a higher proportion of this N might have been recovered in a short time by *B. decumbens* because of the low content of

Table 3. Partitioning of animal N intake from different pathways in a *Brachiaria decumbens* x *D. ovalifolium* mixture and in pure *B. decumbens* with N fertilization.

Pathways	Mixture	0 kg/N/ha	300 kg/N/ha
	kg N/ha/yr		
1. Direct legume intake	36	—	—
2. Grass intake (total):	190	117	224
3. From legume leaflitter	19	—	—
4. From legume via excreta and roots	54	—	—
5. From nonlegume sources (2 – 3 – 4)	117	117	224
6. Total intake (1 + 2)	226	117	224
7. Legume contribution (1 + 3 + 4)	109	—	—
8. Percentage due to legume (7/6)	48	—	—
Partition of legume contribution in the mixture:			
		kg N/ha/yr	%
Direct intake		36	33
Leaflitter decomposition		19	17
Recycling of excreta and legume root turnover		54	50
Total		109	100

polyphenolic compounds. This higher recovery rate should account for the apparent sustained production of *B. decumbens* with no N in Pucallpa. We need data concerning the rate of *B. decumbens* leaf-litter production, both from associated and pure grass with no N. Such data will need to be complemented with data about N concentration of the litterfall and estimates of the rate of decomposition.

Most of the indirect N contributed by *D. ovalifolium* (74%) comes from legume root and nodule decomposition and recycling via excreta. But we do not know the proportion of these two pathways. Our guess is that a higher proportion must come from excreta because relatively high stocking rates were used, rotational grazing was employed, and the soil and climate do not seem to favor extensive leaching or gaseous losses. But, again, data concerning the root dynamics of *D. ovalifolium* and the rate and pattern of excreta deposition, as well as leaching and gaseous losses, are necessary to confirm or deny the assumptions made in Figures 1, 2, and 3.

Fortunately, this experiment is being continued by Dr. Ara, who is now with CIAT in Pucallpa. Although TropSoils involvement is discontinued, it is hoped that the gaps indicated will be closed by CIAT and the counterpart's Peruvian institutions in Pucallpa, IVITA, and INIAA.

Nitrogen Uptake Mechanism in Two *Brachiaria* Species: Y-315

Carlos Castilla, N. C. State University
William A. Jackson, N. C. State University

Grass pasture species successfully introduced on acid soils must adapt to high Al contents, produce under low nutrient conditions, and rely on N fixed by the companion legume. Of the several species of the *Brachiaria* genus used extensively in tropical America research at CIAT, *B. humidicola* has proven capable of sustained uptake and growth in the presence of increasing quantities of ammonium. Other *Brachiaria* species, however, showed decreasing uptake and yields with increasing ammonium although they took up nitrate-N in increasing quantities without negative effects. Under field conditions, *B. humidicola* shows low nitrate-N soil contents *(TropSoils Technical Report, 1986-87)*.

Objectives

The purpose of this experiment was to determine if two species of the *Brachiaria* genus differ in their ammonium and nitrate uptake patterns under conditions that simulate grazing.

Procedures

Two *Brachiaria* species were chosen for this experiment: *B. humidicola* (Bh) CIAT 679 and *B. brizantha* (Bb) CIAT 6780 c.v. Marandú. Both species tolerate high aluminum contents in the soil, but Bh is much less demanding in overall nutrient requirements under field conditions. The experiment was carried out in the greenhouse at N.C. State University during March 1988. Plants were germinated from seed in pots containing sandy topsoil. At eight weeks, plants were transferred to an acclimation nutrient solution containing ammonium as the only source of N. The acclimation solution had the following composition: 1.0 mM $(NH_4)SO_4$, 0.25 mM $CaSO_4$, 0.25 mM $MgSO_4$, 0.1 mM KH_2PO_4, 0.9 mM KCl, and 0.02 mM $AlSO_4$. Micronutrient content was 17.0 uM B, 3.0 uM Mn, 0.3 uM Zn, 0.1 uM Cu, 0.04 uM Mo, and 1 mg Fe l^{-1} as Fe-EDTA. Plants were acclimatized in solution for two weeks. Initial solution pH was 4.5, and it was adjusted daily. Acclimation solutions were changed every four days and constantly aerated. Four days prior to the experiment, the acclimation solution was changed daily to prevent N depletion. This solution was also used during the experiment, and only N sources were modified according to treatments. Negative effects due to a continuous low-level supply of NH_4^+ were not observed.

Treatments consisted of the following combination of N sources and cutting regimes:

Treatment	N source	Concentration	Cutting regime
1	NH_4^+	1mM	cut
2	NH_4NO_3	2mM	not cut
3	NH_4NO_3	1mM	cut
4	NO_3^-	1mM	cut

The combined N solution concentration for the intact plants was 2 mM, thus minimizing differential depletion of the ambient solution. Selected plants were cut 10 cm from the base approximately 16 hours before the initiation of the experiment in order to simulate grazing effects.

At the beginning of the experiment, three plants from each treatment (an experimental unit) were placed in two liters of the corresponding solution (pH 4.6) for two hours and then transferred to a fresh treatment solution. Treatment solutions were changed every two hours during 10 hours of total exposure.

At the end of each two-hour period, measurements of solution pH were made. Ammonium-N was determined by the same NaOCl analysis used to determine nitrate-N. Net uptake of each ion was calculated as the difference between the initial and final concentration per unit of root fresh weight (rfwt).

Results

The statistical analysis indicates a strong species x treatment-period effect (Table 1). Although the coefficient of variability was high for all ions studied, r^2 values were also high, indicating that the high CV did not obscure the effects of the individual treatments on the response of each species.

Table 1. Statistical significance for the different treatments on the response variables.

Treatments	Dependent variable		
	NH_4^+ uptake	NO_3^- uptake	pH change
Period (P)	**	**	**
Species (S)	**	**	**
Treatment (T)	**	**	**
S x T	**	**	**
S x P	**	**	**
T x P	**	**	**
S2 x T x P	NS	NS	**
r^2	0.93	0.92	0.99
CV	99.74	8.2	0.85

** Indicates significance at 1%.
NS: not significant.

Acidity Changes

The effect of the N source on the pH of the final solution at the end of each two-hour period is shown in Figure 1. The two species behaved similarly, but differed in the magnitude of their responses. At a given N source, pH decreases were greatest for Bh, but pH increases were greatest for Bb, the difference being greatest at the end of period 2. Whole plants sharply decreased the pH in the treatment solution to around 4.0.

Cut plants of Bh supplied with NH_4NO_3 increased the solution pH to a maximum of 4.9 in the second period, but the pH later declined below initial levels. Cut plants of Bb followed the same pattern, but did not decrease the pH to levels below those of the initial solution. A similar trend was observed with NO_3^-. In the presence of NH_4^+ alone, Bh decreased solution pH to levels lower than initial pH. However, Bb increased the pH during the second period; pH decreased slightly afterwards and levelled off at higher values than those for the initial solution (Figure 1).

Uptake Patterns

For each ion, uptake patterns were similar for the two species, but differed significantly in the magnitude of the

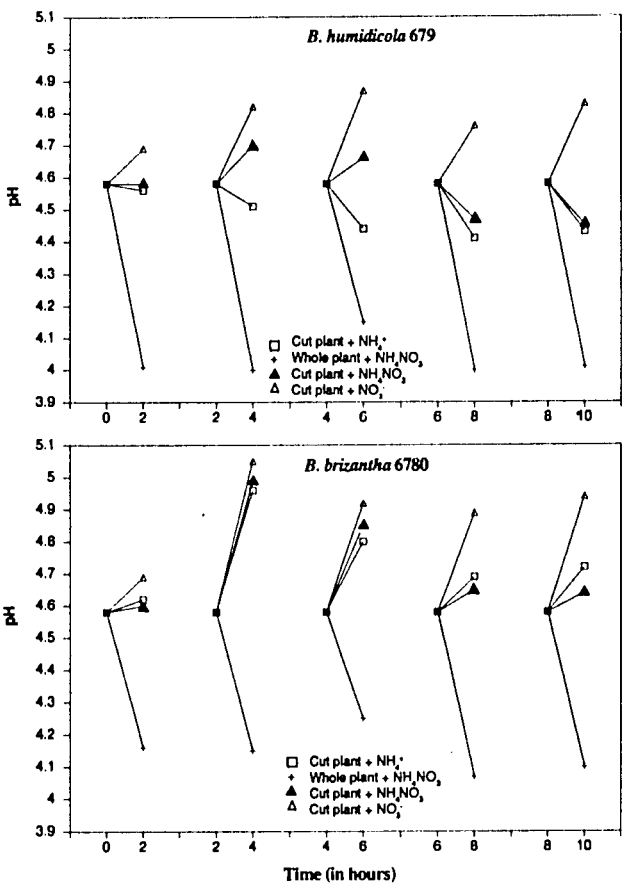

Figure 1. The effect of cutting treatment and N source on the pH of the external solution with two *Brachiaria* species.

response (Table 1). Figure 2 shows the NH_4^+ uptake patterns. Whole plants exhibited a nearly constant continued NH_4^+ uptake, except in period 3. Period 3 corresponds to the hotter part of the day when decreased transpiration may have affected ion uptake. Cut plants of both species supplied with NH_4NO_3 took up NH_4^+ during the first two to four hours, but this uptake was followed by a net efflux. When fed NH_4^+ alone, however, cut Bh plants took 41% as much NH_4^+ as intact plants. In contrast, cut Bb plants exhibited uptake only during the first period, followed by no net uptake in subsequent periods. Cut plants of both species exposed to NO_3^- alone also exhibited a net efflux of NH_4^+ during period 1 (and 2 for Bb) with negligible efflux afterwards (Figure 2).

NO_3^- uptake patterns are shown in Figure 3. On first exposure to NO_3^-, both species showed the same uptake

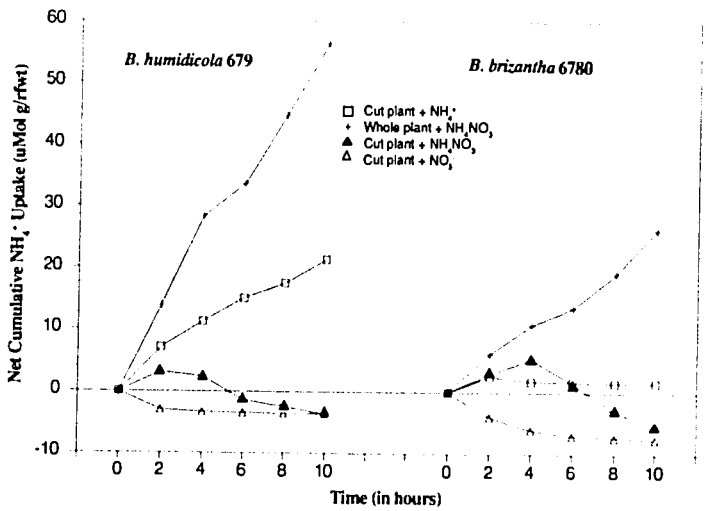

Figure 2. Net cumulative NH_4^+ uptake of two *Brachiaria* sp. as affected by cutting treatment and N source.

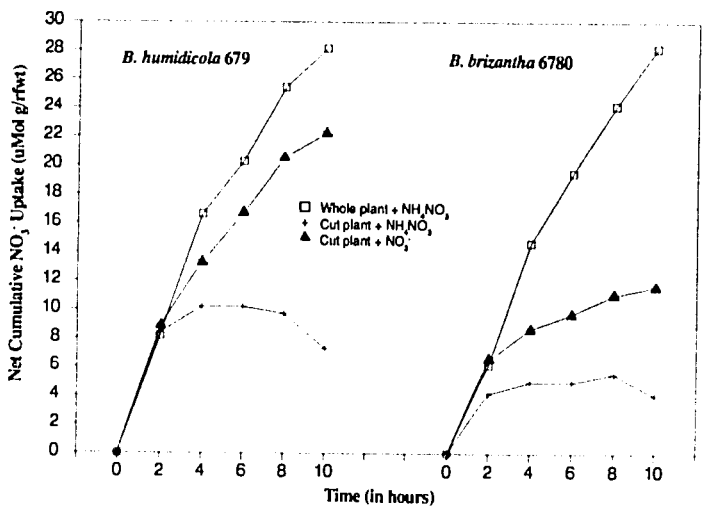

Figure 3. Net cumulative NO_3 uptake of two *Brachiaria* sp as affected by cutting treatment and N source.

tendencies. The rate of NO_3^- taken up by whole plants declined after the first two periods. Cut plants offered NH_4NO_3 behaved similarly, but after period 3, they exhibited efflux, which was higher for Bh. Cut plants offered NO_3^- alone took progressively less NO_3^-, with Bh being more effective than Bb throughout.

Discussion and Implications

When grazed, forage species are subject to cycles of cutting and regrowth. Depending on the grazing pressure, defoliation may lead to drastic reductions in carbohydrate synthesis and supply to the roots, leading to reductions in mineral absorption and respiration. Upon recovery of foliage, plants tend to revert to the original situation. This cycle, called functional equilibrium, suggests that plants attempt to maintain a constant growth pattern rather than a constant size. While there is still much controversy regarding the effects of defoliation on carbohydrate supply and subsequent plant recovery, cutting may contribute to a direct carbohydrate deficiency, effects on growth hormones, or other indirect effects.

Whole Plants

Prior growth in NH_4^+ typically sets up inhibitory and/or repressive mechanisms which lower the NH_4^+ uptake rate in N-replete plants. The state of such repression and/or inhibition is not known for these plants, but may be assumed to have taken place because treatment plants were never purposely N-starved. Therefore, net uptake rates for NH_4^+ may be underestimated relative to the maximum possible rates that the plants could express.

Whole plants exhibited the capacity to take up both NH_4^+ and NO_3^-. Compared to Bb, Bh exhibited a greater total capacity to take up NH_4^+, but the two species did not differ in NO_3^- uptake. These results seem to accord with field observations that Bh is better adapted to poorer environments, possibly NH_4^+ dominated. The similar capacity for NO_3^- uptake implies that plants differ in their NH_4^+ uptake capacity as part of the adaptation mechanism. The sharp pH decrease after 2 hours in the treatment solution indicates greater cation than anion uptake. Lower solution pH with Bh was probably due to Bh's enhanced capacity for NH_4^+ uptake.

Diminished NO_3^- uptake over time indicates an inhibition by NH_4^+. The inhibition of NO_3^- uptake by NH_4^+ has been reported for many grasses and cereals. In contrast to NH_4^+, uptake of NO_3^-, in NO_3^- deprived plants, has been shown to have an induction phase followed by a rapid absorption phase. No

such lag was observed in the species tested (Figure 3). Because uptake was measured during two-hour periods, it is possible that a short induction phase followed by the rapid phase might have been offset by NH_4^+ inhibition and thus not detected. A short lag phase might be an advantage in tropical acid soils because NO_3^- availability may occur as pulses rather than as a continued supply.

Cut Plants

N uptake by cut plants of both species showed a differential uptake due to N source (Figures 2 and 3). Since cutting was performed about 16 hours before the experiment, it is assumed that a carbohydrate limitation or its consequences existed, although a tissue carbohydrate analysis was not conducted.

Because NH_4NO_3 increased NH_4^+ efflux more than did NO_3^- alone, one can infer that, in contrast to whole plants, cut plants preferentially absorbed NO_3^-. As a result, a greater ratio of anion/cation uptake occurred with a resulting pH increase (Figure 1). A pH increase may be beneficial in Al-saturated soils because of decreased Al activity. However, because whole plants show a differential capacity to take up NH_4^+ (with a pH decrease as a result), the mechanism of adaptation must also involve the capacity for continued growth at a low pH.

Cut plants of Bh in NH_4^+ alone continued to take up NH_4^+ at about half the rate of whole plants exposed to NH_4NO_3. In contrast, Bb was only able to take up small quantities of NH_4^+ initially, when NO_3^- was absent, and later showed no further gain (Figure 2). The possibility of a more severely lowered carbohydrate supply in Bb may account for this difference between the two genotypes. This reasoning implies that the more acid-tolerant species has the ability to sustain a higher relative root carbohydrate supply and thus an enhanced capacity to absorb NH_4^+ than does the more demanding Bb species. Since Bh in the presence of NH_4^+ alone was able to lower the pH progressively over time, it is possible that either the effects of carbohydrate limitations were not as severe as in Bb or a faster recovery took place. A very fast regrowth commonly is observed for Bh under field conditions.

When supplied with NO_3^-, cut Bh plants were also able to take up nearly as much NO_3^- as whole plants, indicating that carbohydrate supply for the energy-requiring process of NO_3^- uptake was not severed. At a given level of carbohydrate deficiency, Bh seemed to be able to take advantage of both sources of N, suggesting that the capacity to take advantage of any available N resource may be a part of the mechanism of adaptation to poorer environments.

Simulated Topsoil Carbon Dynamics in a Legume-based Pasture: Y-312

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Pastures can serve as low-input systems suitable for humid tropical conditions. With low amounts of purchased inputs, mainly P and adapted grass and legume species, beef production can be very high. However, millions of hectares have been cleared and planted to poorly adapted pasture species and/or managed without adequate technology, resulting in ecosystem degradation. In the Peruvian Amazon, under semi-commercial conditions, five legume-grass associations have been grazed for nine years, and the data suggest that these pastures can be stable and highly productive (see this report). Little is known, however, about the carbon source-sink relations in humid tropical pastures

Objectives

The purpose of this simulation is 1) to determine if the Century model developed for high-fertility grasslands in the United States can predict the behavior of soil organic-matter (SOM) levels over time in tropical pastures with acid soils and 2) to determine what parameters need to be included and preferentially researched in order to adequately predict C flow in the soil-plant-animal system.

Model Description

The Century model was developed by Parton and collaborators at Colorado State University. It has been modified to predict short-term SOM changes in less than 25 years. The Century model attempts to simulate processes that operate on different time scales. Basically, it consists of two parts (Figure 1): a dynamic C flow where microbial processes decompose organic material in periods ranging from .1 to 25 years, represented by the active and the slow soil-C pools; and a passive pool in which turnover rates are measured on the order of 1000 years. The passivity of this organic fraction has been suggested to be due to its chemical complexity or physical inaccessibility. Because the organic fraction is of little value in short-term studies, it was eliminated from this simulation. This pool is assumed to represent 50% of the total organic C present in the pasture of the Great Plains in the United States.

In the Century model, decomposition rates due to microbial activity vary with temperature and moisture levels. For this simulation, it is assumed that such limitations are not present under tropical conditions, and thus temperate-region parameters are taken at 100% efficiency. This simplification takes into account the lack of strong seasonal fluctuation in udic isohyperthermic regimes and sets up a worst-case scenario for SOM decomposition.

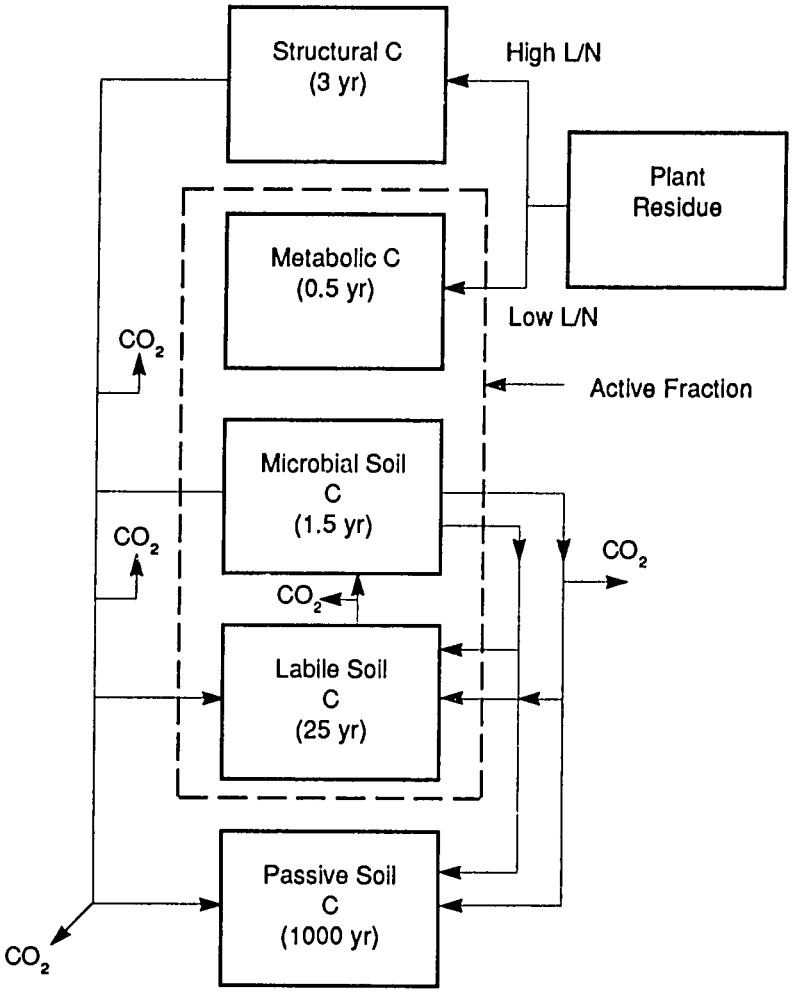


Figure 1. The Century Model (parton et al., 1987, SSAJ 51:1173–1179).

The decomposition rates used for the simulation are calculated with the following equation, which eliminates the temperature and moisture variables, as described by Parton and coworkers:

$$\frac{d\,C_i}{dt} = K_i \cdot C_i$$

where C_i = the carbon in the state variable (kg/ha),
K_i = maximum decomposition rate parameter per day,
t = time, measured in days.

For each state, variable i refers to the following: 1 = metabolic, 2 = nonlignin structural, 3 = lignin structural, 4 = active, and 5 = slow pools. K rates per day are as follows: i = 0.051, 0.0137, 0.0137, 0.0207, and 0.00056, respectively.

The Century model assumes that 55% of the C is lost as CO_2 via microbial respiration from the decomposition of the nonlignin structural, the metabolic, and the slow fraction. Lignin stabilization into the slow SOM is a fairly efficient process with only a 30% respiration loss.

Adaptations for the Humid Tropics

Aboveground C inputs are fecal matter and trampled-on senescent leaf-litter. Carbon inputs from animal intake are based on experiment Y-302, the long-term grazing experiment. Depending on rainfall, three to five animals per hectare gain weight throughout the year at Yurimaguas. Animal intake is not assumed to be limiting and is 2% of the animal body weight. An average animal of 300 kg is considered representative for the simulation and consumes 6 kg/d of dry matter. Diet selection may be of little significance with respect to fecal C since only the animal seems to benefit from a richer diet. This assumption helps researchers avoid the very complex diet-selection process, and it allows them to consider the animal as a substrate homogenizer. Feces still vary in composition, but they are far less variable than the plant component being grazed. It is also assumed that the dry matter is 45% C and that the C returned in the feces is only 30% of the C consumed but is 20% lignin.

The grazing cycle consists of 30 days of grazing and 30 days of rest. There are five cycles per year, and two months are assigned to pasture recuperation. Thus, during grazing, an effective stocking rate of either six or 10 animals per hectare per day is achieved, depending on the species or association being grazed. Stocking rates are fixed during the year.

The input due to trampling is assigned as a constant fraction of the animal intake and estimated at 30% of daily consumption. Carbon inputs from leaf-litter account for half of the aboveground inputs (Table 1). It is assumed that trampling accelerates the fall of dead plants and that the initial litter quality is equivalent to the quality of the standing dead plants. Leaf-litter quantity may be related to the grazing pressure and to the relative proportion of the species in a pasture. In Yurimaguas, legumes make up from 10 to 95% of pasture composition. Initial litter quality is assumed to range from 8% lignin and 2% N in the case of a pure legume pasture to 10% lignin and 1% N for the grasses. This difference provides L/N ratios ranging from 4 to 10. Lignin has a 65% C content (Table 2).

Belowground C inputs are due to roots and root death. The rate of root production and turnover has not been

Table 1. Estimated C inputs in a tropical pasture, depending on root turnover speed and stocking rate.

	Root turnover			
	Slow§		Fast¶	
	Stocking rate		Stocking rate	
Carbon source	3	5	3	5
	t C/ha			
Aboveground	1.4	2.4	1.4	2.4
Belowground	2.9	2.9	9.6	9.6
Total	4.4	5.4	11.0	12.0

§ Root biomass = 6.2 t/ha.
¶ Root biomass = 4.0 t/ha.

studied for humid tropical pastures. The few available estimates of root production vary greatly and depend on the species composition and the grazing pressure. Root production was estimated to range from 6.2 to 4.0 tons/ha, with a slow (4% per month) or fast (20% per month) turnover rate, respectively (Table 1). At these rates, complete root turnover is achieved in either 2 or 0.5 years, respectively. Such rates occur in both temperate and tropical regions.

The Century model assumes that root lignin is a function of annual rainfall. In our case, root-lignin contents were determined from six grazed pastures at Yurimaguas (experiment Y-302 and Y-307). Lignin ranged from 11 to 15% for grass and legume associations. We used a constant value of 13% during the simulation period. With good management, leaf and root biomass production should not be negatively affected over time, and a constant root production and turnover can be achieved and may remain constant.

As in the Century model, the lignin to N ratio (L/N) controls the partitioning of plant residues into the structural and metabolic pools, and all the plants' residual lignin flows into the lignin structural compartment. The lignin fraction controls the decay rate of the structural pools, and it is also incorporated into the slow soil pool. The L/N ratio of the different plant inputs is given in Table 2.

Table 2. Estimated lignin/N ratios of the different C sources.

Carbon source	Lignin: N ratio
Feces	20:0.5
Grass litter	10:1.0
Legume litter	8:2.0
Dead roots	13:1.0
Live roots	13:2.0

As in the Century model, plant residues are divided according to the following equations:

$$F_M = 0.85 - 0.018 \cdot L/N$$
$$F_S = 1 - F_M$$

where F_M = metabolic fraction of the plant material,
F_S = structural fraction of the plant material,
L/N = lignin to Nitrogen ratio.

The equations assume that the inputs to the system are immediately transferred into the metabolic and the structural pools. F_S is divided between lignin and non-lignin structural C pools (L_S and NL_S, respectively). As in the Century model, all of the lignin flows into L_S to be later transferred via microbial decomposition into the slow pool. The decomposition rate of L_S and NL_S depends on what fraction of these materials is lignin and on the maximum decay rate. Therefore (for K_2 and K_3)

$$K_2 = K_2\, e(-3.0^{*} LS).$$

The equation indicates that the ability of microorganisms to decompose SOM decreases as the lignin content increases.

The Century model also includes texture as a factor in the decomposition of the active SOM compartment. The effect of the silt fraction plus the clay fraction on the decay of the active SOM is

$$K_4 = K_4\,(1-.75\,F),$$

where F = silt + clay fraction in the soil.

The effect of texture on the stabilization efficiency of active SOM is considered to be

$$E_s = (.85-.68\,F),$$

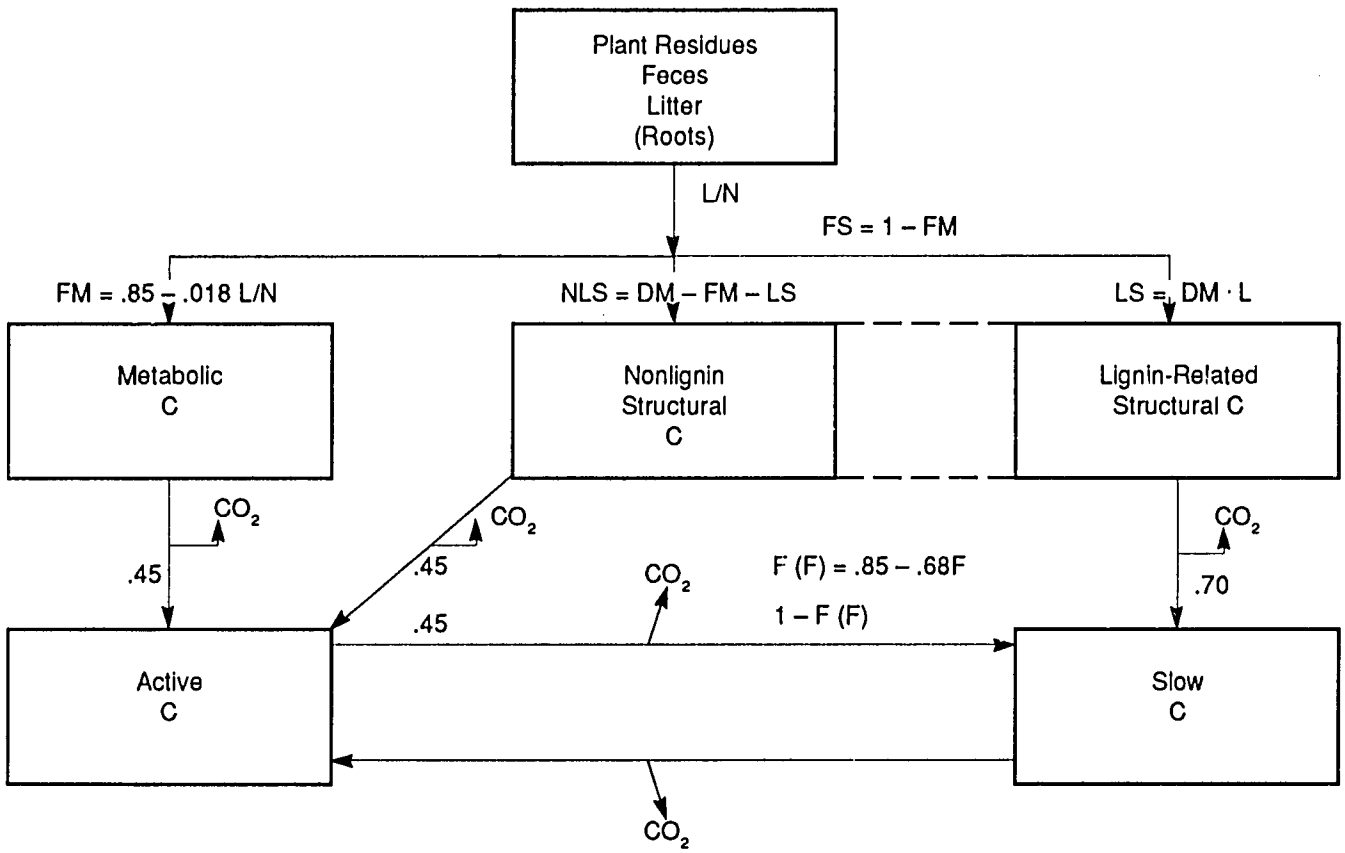
where E_s = efficiency of stabilizing active SOM into slow SOM.

A higher proportion of silt and clay decreases the decay rate of the active component and increases the amount of C stabilized in the slow SOM.

The adapted model for this simulation is shown in Figure 2. The initial values of the state variables were calculated for a representative typic Paleudult, fine loamy, siliceous, isohyperthermic soil containing 50% silt and clay, along with 2% SOM, and having a bulk density of 1.3 g/cm^3 to a depth of 20 cm. We have assumed that 50% of the total C is assigned to the passive pool. These values are as follows.

Active pool: consists of microbial biomass and microbial byproducts: 2000 kg/ha.

Structural pool: shoot and root plant biomass, as described by R. Scholes (1989) for a pasture in Yurimaguas:



L/N = Lignin-to-nitrogen ratio
DM = Dry matter
FM = Metabolic fraction
FS = Structural fraction
LS = Lignin-related structural fraction
NLS = Nonlignin structural fraction
F = Silt + clay content
L = Lignin fraction

Figure 2. Adapted Century Model to predict C flow in a tropical pasture.

6000 kg C/ha equally divided into the nonlignin and the lignin structural pools.

Slow pool: assigned a value to complete 50% of the labile C because 50% corresponds to the passive pool: 6.900 kg C/ha.

Metabolic pool: Assigned an arbitrary value of 100 kg C/ha. This fraction corresponds to sugars, proteins, and amino acids present in the plant and rapidly converted into microbial C. Root exudates may also contribute to the metabolic pool, but their contribution is largely unknown. No data is available, but contents are small compared to other pools.

Results

Simulations imitated daily C inputs for 25 years in an alternate grazing system. The soil depth considered was a 0- to 15-cm layer. By 15 years, all of the variables had obtained steady-state equilibrium. The different L/N ratios of the aboveground and belowground inputs did not appear to make a significant impact on the final C content of the different carbon pools (Figure 3).

Initial values for the C pools are very different from steady-state values (Figures 4 to 7). Over- and underestimations due to a lack of an appreciation of an average value (as in the case of the active pool), or an attempt to correlate measurable soil fractions to one C pool, help identify apparent sources of error, such as live root biomass in the structural pool. The structural pool should be estimated by dead roots only (root litter).

Overall, total plant inputs associated with a fast root turnover provided more C than did those with a slow root turnover. At steady state, the C values of the different pools provide estimates which need to be confirmed in the field: i.e. leaf- and root-litter. Metabolic C approached field values, as described in the previous *TropSoils Technical Report, 1986–1987.*

Animals exert a measurable effect (Figures 7, 8, and 9). The higher the stocking rate a given association can support at adequate grazing pressure, the higher the final C

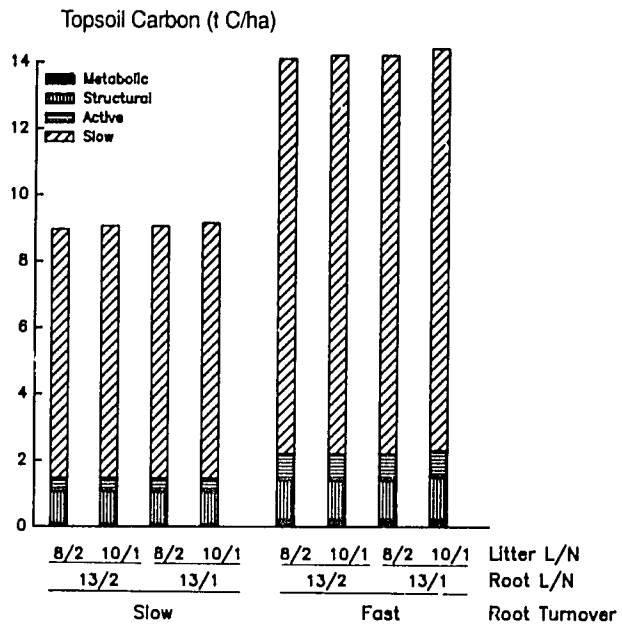


Figure 3. Simulated steady-state C content of the dynamic C pool as affected by inputs of different L/N ratios.

content. Nearly 2 t/ha more C is achieved at the higher stocking rate. This is not an attempt to infer the effects of differential grazing pressures on aboveground and belowground production in one particular association. Different stocking rates on the same association, undoubtedly, will have an effect on the long-term production of leaf and root biomass and their turnover rates.

An estimate of the relative importance of roots and shoots can be obtained if one of these fractions is not included in the simulation (Figure 8). Aboveground inputs alone (no roots) accounted for a maximum of 5 of the 15 tons of the initial C. With slow root turnover, total biomass inputs accounted for a maximum of 9 t C, which is as much C accounted for by roots alone (0 an/ha) if a fast root turnover is considered—that is, 60% of the total initial C. Total plant inputs associated with a fast root turnover account for most of the initial C.

At steady state, predicted total soil SOM contents are given in Figure 9. The passive pool is included and assumed to remain unchanged for the simulation period (50% of the initial soil SOM). Total inputs associated with slow root turnover accounted for a maximum of 80% of the initial SOM, while fast root turnover accounted for 98%. Aboveground inputs alone (no roots) accounted for a maximum of 69% initial SOM, while the contribution from roots alone (0 an/ha) was between 62 to 79% of the total SOM for slow and fast root turnover, respectively. Seven years into the grazing experiment, SOM levels at the Y-302 experiment average 2.16%. Organic carbon has increased with grazing in this experiment

Conclusions

The model, therefore, seems to underestimate SOM content (Figure 9). Decomposition rates in the field may not be at a maximum. The model also indicates that to achieve initial SOM levels, a fast root turnover must occur. The model also estimates that plant inputs are on the order of 10 t C/yr.

The simulation predicts that roots are the major force in maintaining the more dynamic C pools. It also indicates that aboveground inputs alone are not enough to maintain SOM levels. The model emphasizes the importance of roots in the maintenance of SOM and suggests that a

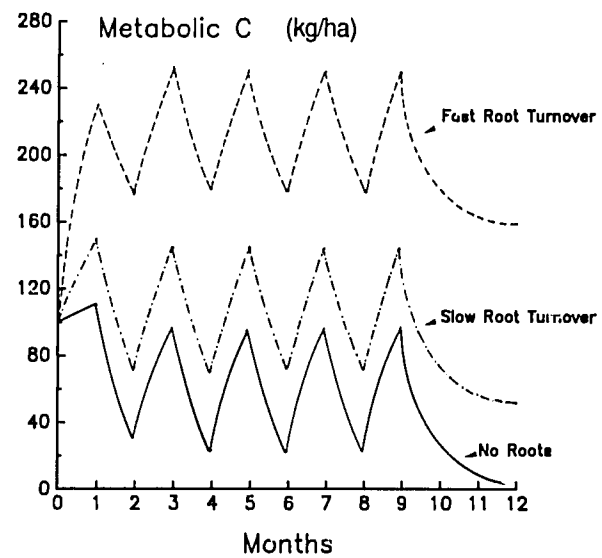


Figure 4. Simulated carbon dynamic of the metabolic pool.

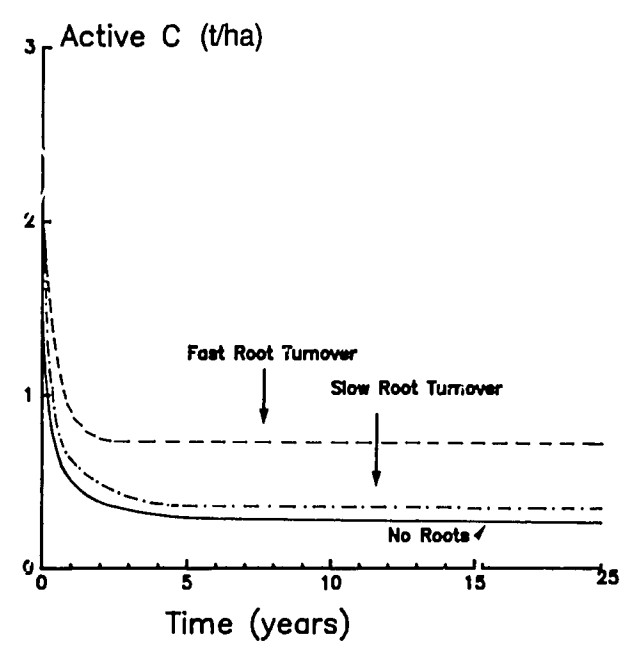


Figure 5. Simulated corn dynamics of the active pool.

rational management of the aboveground biomass should strive to maintain a strong root system. Adapted species are able to tolerate Al toxicities and develop very prolific root systems. But even with adapted species, excessive stocking rates may put undue pressure on the shoot system and eventually decrease overall root production. A better understanding of shoot to root interactions can lead to more stable systems. Root production and interactions should be an active research topic, one which must include the effect of animals.

Overall the Century model seems to work reasonably well for short-term simulations of C under tropical conditions. A further separation of the structural compartments into surface and subsurface compartments may help to keep track of the corresponding litter values. It will also help to validate the overall model performance.

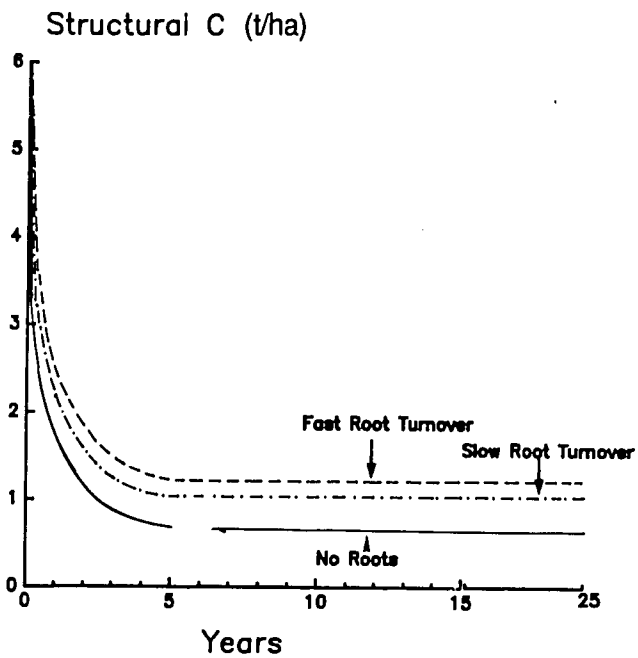


Figure 6. Simulated corn dynamics of the structural pool.

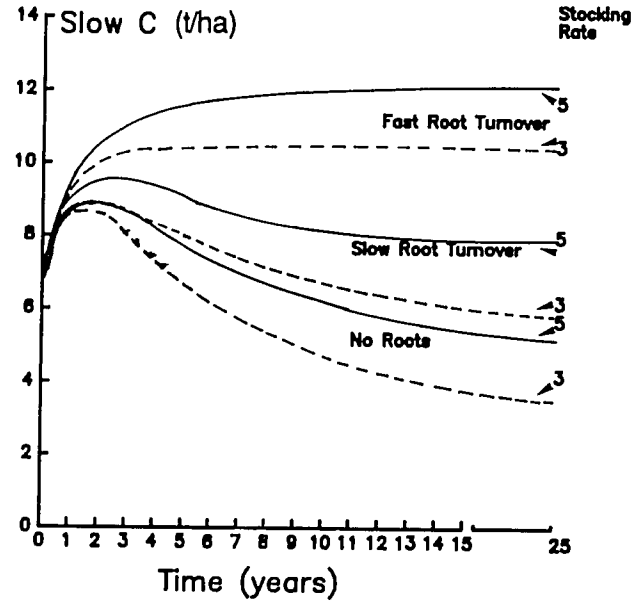


Figure 7. Simulated carbon dynamics of the slow pool.

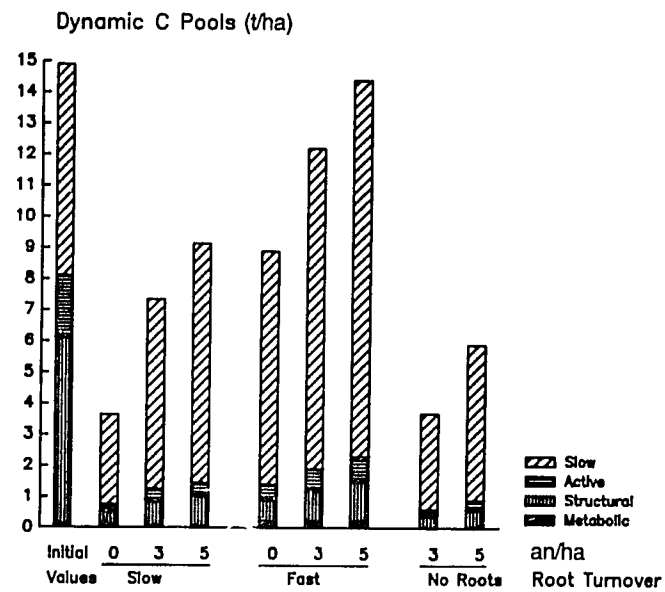


Figure 8. Simulated effect of stocking rate and root turnover on steady-state C content of the dynamic C pools. Passive pool is ignored.

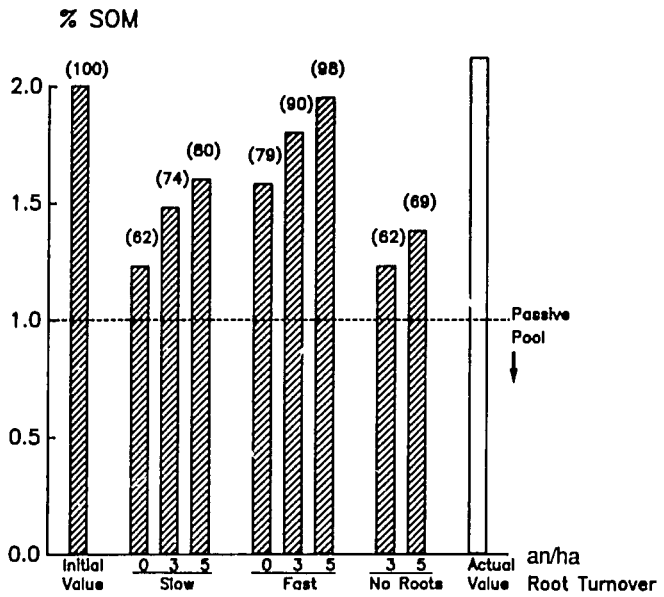


Figure 9. Simulated effect of stocking rate (0.3 and 5 an/ha) and root turnover on SOM levels in comparison with actual value (2.16% OM after seven years of grazing).

Potassium Dynamics in a Legume-based Pasture: Y-307A

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Well-drained acid soils of the humid tropics are, as a rule, highly susceptible to potassium leaching. Potassium deficiency is commonly found, and leaching losses of K applied as fertilizer or as animal excreta are believed to be large. There is, however, little quantitative description of the movement and losses of applied K under field-pasture conditions.

Objective

This study was undertaken to address K dynamics in a *Brachiaria humidicola* x *Desmodium ovalifolium* pasture grown in Yurimaguas.

Procedures

The study consisted of four parts: 1) K retention in the laboratory, 2) K dynamics in bare plots, 3) K dynamics in clipped plots, and 4) K dynamics under grazing.

Laboratory Study

Samples from different horizons of a fine-loamy siliceous Typic Paleudult located in the paddocks used in experiment Y-307 were analyzed for clay mineralogy and K retention. The clay mineralogical composition, which was uniform with depth, is shown in Table 1. Kaolinite is the dominant mineral (65%), but there are significant quantities of micas, interlayered smectite, and vermiculite, which together account for 25% of the clay fraction. This soil has less than 10% weatherable minerals in the sand and silt fractions and therefore is classified as essentially devoid of weatherable minerals in Soil Taxonomy.

Table 1. Estimated mineralogical composition of the clay fraction of a Yurimaguas Ultisol at a depth of 0 to 100 cm. Mean of five soil depths.

Clay mineral	Percentage	Method
Kaolinite	65	TGA
Mica	10	Total K allocation
Fe, Al oxides	10	Citrate dithionite
Interlayered smectite	10	Difference and X-ray pattern
Vermiculite	5	X-ray patterns

Samples taken from five depth intervals were incubated with various rates of K and extracted with buffered 1M solutions of NH_4OAc and $Mg(OAc)_2$ after 24 hours of equilibration. About 98% of the applied K was recovered with NH_4OAc, eliminating the possibility of K fixation (Figure 1).

About 30% of the applied K recovered with NH_4OAc after 24 hours of equilibration was not displaced by $Mg(Ac)_2$, suggesting that specific adsorption of K occurs in wedge zones of partially closed smectites and partially opened micas, where exchangeable Ca, Mg, or Al cannot penetrate. The proportion of specifically absorbed K increased with increasing clay content and decreased with increasing K fertilizer rate. Specific adsorption of K in wedge zones of small quantities of 2:1 minerals present in predominantly kaolinitic soils, therefore, plays a positive role in potassium retention.

Potassium Movement in Bare Soils

Bare plots, kept devoid of vegetation by frequent weeding, were used to 1) describe the rate of disappearance of applied K from the 0- to 5-cm soil layer, 2) monitor its subsequent downward movement, and 3) estimate the net K leaching losses below 100 cm. The experiment was conducted with seven K rates ranging from 0 to 300 kg K/ha, applied once. Changes in the levels of exchangeable K were determined at five soil depth intervals during 15 months. The rate of disappearance of applied K from the 0- to 5-cm topsoil was adequately predicted by a descriptive model as a function of time and cumulative rainfall (Figure 2). Potassium loss from the 0- to 5-cm soil layer coincided with an accumulation of K in the subsoil. After 15 months, most of the K added at a rate below 150 kg K/ha was found at a depth of 5 to 40 cm. Leaching losses below 100 cm occurred only at the rates of 300 kg K/ha (Table 2). Accumulation of K in the subsoil is probably related to the increase in the number of specific adsorption sites for K, as shown in Figure 1.

The results indicate that leaching of applied K can be quantitatively described under field conditions using bare plots. Usually, such studies are conducted using undisturbed soil columns and lysimeters. Although both approaches have advantages over the method used in this study, bare plots are simple to install in the field, and they provide a good estimate of the leaching potential under field conditions. Bare plots can present problems in leaching studies: surface sealing can occur when raindrops hit the exposed surface. In the present work, surface sealing was eliminated by frequent hand-raking.

In the same area, K rates ranging from 0 to 300 kg K/ha were applied to a set of clipped plots with either plant biomass removed or plant biomass returned. Changes in exchangeable K levels in the 0- to 100-cm soil depth were monitored during 15 months on a well-established *B. humidicola* x *D. ovalifolium* mixture. Plants significantly decreased the levels of exchangeable K in the entire soil profile (Table 3). This decrease was attributed to fast K accumulation in the herbage mass due to a large fine-root biomass (7.4 tons of dry matter/ha) and good distribution with depth (Figure 3). After 15 months, plants recovered

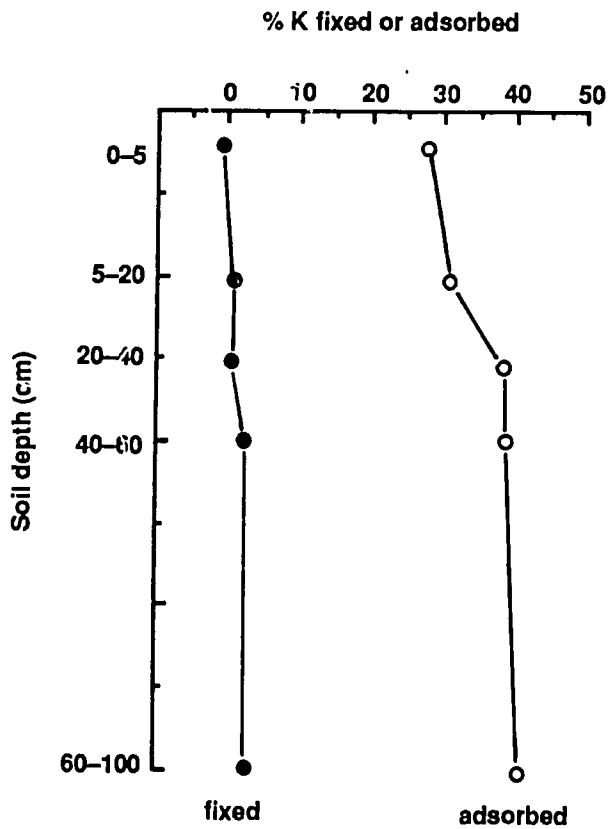

Figure 1. Proportion of applied K fixed or specifically adsorbed as a function of depth in an Ultisol of Yurimaguas. Mean of four rates.

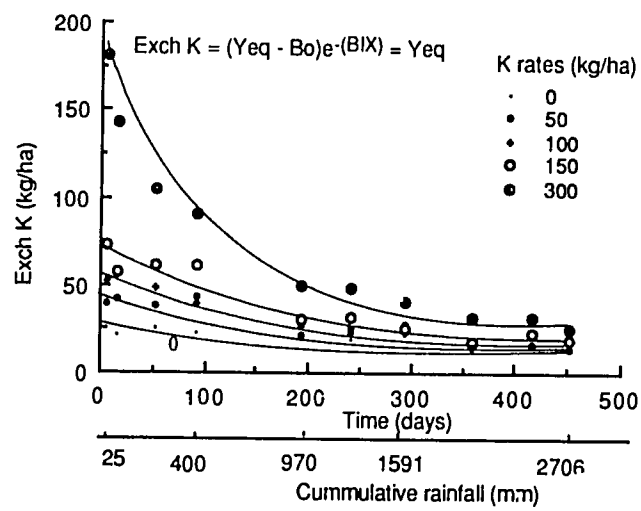

Figure 2. Disappearance of applied K from the 0- to 5-cm layer as explained by a negative exponential model.

Table 2. Potassium gains and losses (–) in the profile of a bare soil one and 60 weeks after fertilizer application and 2700 mm cumulative rainfall.

Depth cm	Time weeks	K rate (kg ha) 0	25	50	75	100	150	300
0–5	1	25.8	33.7	39.2	52.5	52.5	72.9	180.4
	60	12.5	15.6	14.2	20.4	18.0	18.8	25.88
Balance		-13.4	-18.0	-25.0	-32.1	-34.5	-54.1	-154.3
5–20	1	30.0	25.0	25.0	30.0	25.0	27.5	37.55
	60	35.0	32.5	35.0	45.0	40.0	55.0	45.0
Balance		5.0	7.5	10.0	15.0	15.2	25.5	17.5
20–40	1	37.0	30.3	33.3	43.9	30.4	47.3	43.9
	60	40.4	40.4	40.4	43.8	43.8	60.6	52.2
Balance		3.3	10.1	16.8	16.8	10.0	33.7	25.3
40–60	1	40.5	33.3	33.3	43.9	30.4	47.3	43.9
	60	37.1	33.7	37.1	40.5	33.7	47.3	54.0
Balance		-3.3	0.4	3.3	-3.4	3.3	0.0	10.1
60–100	1	87.5	94.8	87.1	87.5	87.5	92.1	116.7
	60	87.0	87.5	72.9	87.5	94.8	109.4	124.7
Balance		0.56	-7.3	-14.1	0.0	7.3	17.2	7.3
0–100 Net balance		-8.90	-7.34	-8.8	-3.6	1.3	22.3	-104.3

100% of the K fertilizer added at rates up to 150 kg K/ha and 76% of the fertilizer added at the rate of 300 kg K/ha (Table 4). Potassium accumulation by the plants is associated with increased dry-matter production and a high K luxury consumption, but near maximum biomass yields were achieved only with 25 kg K/ha (Figure 4). Higher K rates decreased the efficiency of K utilization (Figure 5). Potassium added through plant residues was efficiently recycled within the soil-plant system (Figure

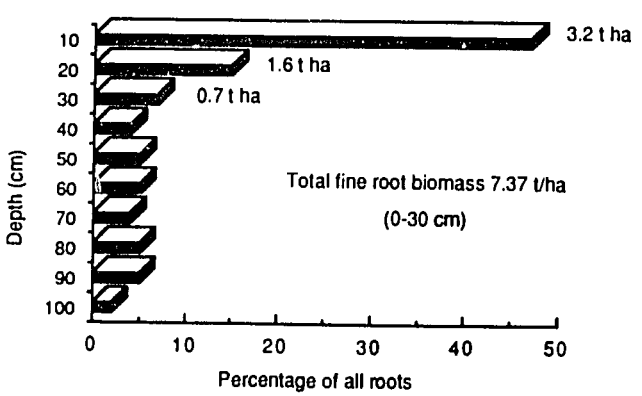

Figure 3. Total root biomass and distribution of a *B. humidicola* and *D. ovalifolium* pasture grown in an Ultisol of Yurimaguas.

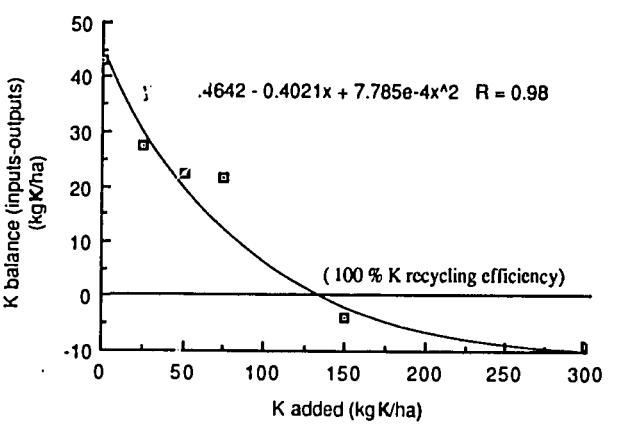

Figure 4. Effect of several K rates on the dry-matter production of *B. humidicola* x *D. ovalifolium* under cutting. Mean of eight cuts.

Table 3. Net potassium losses from the 0- to 100-cm soil depth in three vegetation systems.

Treatment	K applied (kg/ha) 0	25	50	75	100	150	300	Equation	R^2
Bare plot	8.9[a]	2.1[a]	-1.1[a]	4.0[a]	-15.7[a]	9.0[a]	89.3[a]	$Y = 9.31-0.329x + 0.002x^2$	0.98
Biomass removed	24.7[a]	64.0[b]	93.5[b]	107.2[b]	129.6[b]	174.4[b]	241.5[b]	$Y = 49.99 + 0.692x$	0.97
Biomass returned	28.9[a]	27.4[b]	48.4[b]	77.1[b]	78.6[b]	107.2[b]	183.1[c]	$Y = 25.30 + 0.533x$	0.99

Values in columns followed by the same letter are not statistically different according to the LSD test ($P < 0.05$).

Table 4. Potassium balance in the 0- to 100-cm soil under a pasture subjected to clipping and removal of plant biomass during 15 months.

	Potassium added (kg K/ha) 0	25	50	75	100	150	300
	kg K/ha						
Disappearance from soil	24.7	64.0	93.5	107.2	129.6	174.4	241.5
Total plant uptake	96.5	133.4	143.6	191.9	220.0	223.8	324.7
	%						
Efficiency of recovery	—	147.0	94.0	126.0	123.0	84.0	76.0
	kg/ha						
Leaching losses	—	—	2.9	—	—	22.7	71.8

6). Recycling efficiency was higher in the control treatment and decreased with increasing K rate.

In the presence of *B. humidicola* x *D. ovalifolium*, plant uptake is the main process controlling exchangeable K in the soil. At most sampling depths, levels of exchangeable K were consistently lower when plants were present than when they were absent. High K uptake values may be related to the high root biomass and the ability of grasses to absorb K from the soil in large quantities.

Plant uptake appeared to be largely responsible for the disappearance of exchangeable K from the 0- to 100-cm soil depth as suggested by the correlation between these two variables (r = 0.72**). The actual amounts of K absorbed by the plants after 15 months were even higher than those disappearing from the exchangeable K pool. This suggests that plants are able to remove specifically absorbed K from the soil.

Potassium initially accumulated by plants was efficiently recycled within the soil-plant system, as demon-

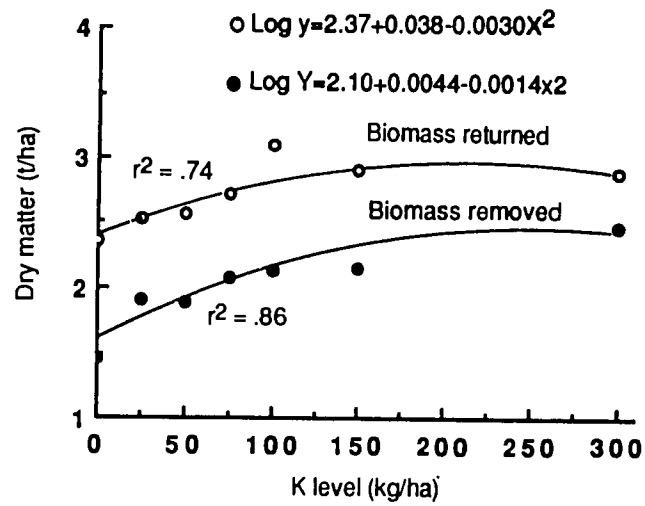

Figure 5. Effect of increasing K rates on the efficiency of K cycling through plant residues in a *B. humidicola* x *D. ovalifolium* pasture under cutting and return of clippings.

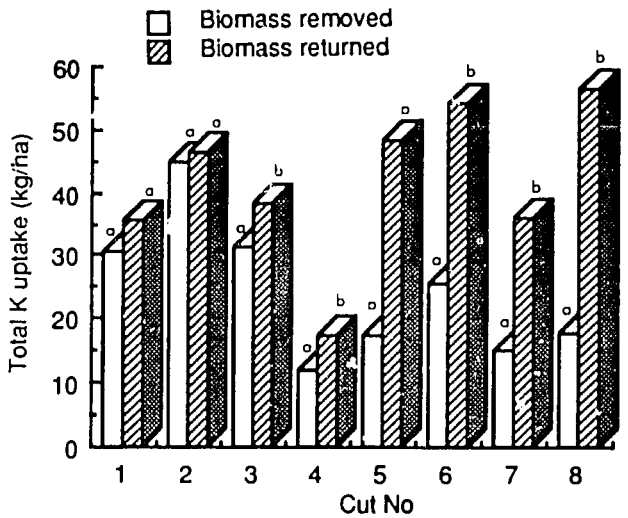

Figure 6. Changes in K uptake influenced by the removal or return of clipped biomass of a *B. humidicola* x *D. ovalifolium* pasture. Mean of 21 observations. Treatments followed by the same letter are not significantly different according to an LSD test at the 0.05 level of probability.

strated from the balance between K additions via residues return and the uptake in subsequent cuttings. The cycling process appears to be fast enough to prevent K accumulation in the soil. This inference is based on the similar levels of exchangeable K observed in the plots where biomass was either removed or returned.

Potassium leaching losses under a cut pasture of *B. humidicola* x *D. ovalifolium* are negligible in an environment with 2700 mm of rain in 452 days. These pasture species absorb large amounts of K, perhaps due to their high root biomass distribution with depth.

Potassium Cycling under Grazing

Cattle play an important role in the nutrient dynamics of pastures because they modify the amounts and composition of litter and return most of the consumed K through urine and feces. In order to test the impact of grazing on K cycling, a grazing experiment was conducted in an area adjacent to the clipping plots. Two stocking rates (3.3 and 6.6 animals/ha) and three K rates (0, 50, and 10 kg K/ha) were arranged in a split-plot design with three replications. A rotational grazing scheme was employed with 12 to 16 days of grazing and 24 to 36 days of resting, with 10 grazing cycles during 15 months. Results are expressed on a per year basis.

Potassium cycling was assumed to consist of two inputs: K in the rain plus dust and K from fertilizer. Potassium outputs were animal harvest and leaching. The pools were measured or estimated as follows: exchangeable K in the soil (0 to 100 cm), specifically adsorbed K in the soil (0 to 100 cm), total pasture biomass, residual standing biomass, aboveground litter, and belowground litter—all of which were measured or estimated as averages per grazing cycle and animal biomass. The fluxes include aboveground and belowground litter decomposition, animal intake, urine, and feces. The reader is referred to Miguel Ayarza's thesis (Ph.D, North Carolina State University, 1988) for a description of the methodologies used.

Biomass Pools and Fluxes

Calculated sizes of the biomass pools are shown in Table 5. Total pasture biomass increased with increasing K rate and stocking rate, averaging 2 tons of dry matter per hectare. This calculation includes the initial available forage prior to grazing and reflects the high levels of pasture biomass present throughout the grazing period. Animal intake of pasture biomass increased somewhat with K rate, but it almost doubled with a doubling of the stocking rate, suggesting an excess availability of forage and a general undergrazing trend in the entire experiment.

Residual standing biomass was calculated as the difference between total pasture biomass and animal intake. Residual standing biomass responded sharply to K fertilization at both stocking rates, averaging 1.1 and 1.2 tons/ha for the low and high stocking rates, respectively. This means that 64% of the available forage in the low stocking rate was not consumed by the animals, and an even lower proportion, 54%, was not consumed at the high stocking rate. Low pasture quality has been considered a limiting factor with this mixture in Yurimaguas.

The standing stocks of aboveground litter did not show a clear trend with K fertilization, but they decreased with increasing stocking rate, averaging 1.3 tons/ha in the low stocking rate and 1.1 in the high stocking rate. Most of the pasture biomass after grazing, therefore, was live standing litter, rather than dead litter.

The live biomass of the belowground litter was only measured in the 0 kg K/ha treatments. The values 4.5 and 3.6 tons/ha in the low and high stocking rates also indicate a decrease in root biomass with increasing stocking rate. Perhaps more importantly, these values show that the majority of litter biomass (75%) consists of roots.

Animal biomass increased with K rates and stocking rates. Animal biomass includes both the initial weight of the animals when introduced to the pasture plus the liveweight gains (Table 6).

Three biomass fluxes are shown in Table 5. Feces production was not affected by K rates but increased from 3.0 to 5.2 t/ha/yr when the stocking rate was doubled. Since feces were calculated as animal intake and dry matter digestibility, these values reflect the trends in animal intake.

Aboveground litter production averaged 3.5 t/ha/yr in the low stocking rate and 3.0 t/ha/yr in the high stocking

rate. These figures reflect a 3.66 turnover rate, indicating that litter decomposed 2.66 times during the year. Belowground litter decay decreased from 5.1 to 4.4 t/ha/yr with increasing stocking rate, based on values determined only at the rate of 0 kg K/ha. Root turnover averaged 1.13 times in the low stocking rate and 1.19 times in the high stocking rate, or less than half the aboveground litter turnover rate.

Potassium Cycling

Calculated K pools, fluxes, inputs, and outputs are shown in Table 7. Total pasture biomass ranged from 17 to 38 kg K/ha in the low and high stocking rates, respectively. This variance appears to be due an the increase in the number of animals, rather than an increase in intake per animal. Residual standing biomass also responded positively to K rate and stocking rate.

Two soil K pools are presented in Table 7, exchangeable K and specifically adsorbed K, both comprising the 0- to 100-cm soil depth, with average values of 160 and 81 kg K/ha, respectively. No trends are observed with K fertilization rate or stocking rate. Because the sum of these pools did not change with a year of grazing, it is reasonable to conclude that the size of the available K pools in the soil is stable.

Table 5. Biomass pools and fluxes in the soil-plant-animal system on an annual basis.

	Stocking rate (an/ha)							
	3.3				6.6			
	K applied (kg/ha)							
Pastures	0	50	100	X	0	50	100	X
Pasture pools: (kg/DM)[¶]								
Total pasture biomass	1577	1747	1756	1693	1841	2452	2575	2290
Residual standing biomass	9853	1141	1142	1087	7944	1375	1567	1246
Aboveground litter biomass	1290	1280	1380	1317	1270	1070	1090	1143
Belowground live root biomass	4510	4510	4510	4510	3650	3650	3650	3650
Animal pool of liveweight: (kg/ha)[§]	481	506	521	503	713	768	641	707
Fluxes (kg DM/ha/yr)								
Animal intake of pasture	5918	6055	6137	6037	10474	10775	10079	10443
Feces output	2959	3027	3068	3018	4237	5387	5039	5221
Aboveground litter production	3431	3411	3678	3507	3384	2851	2904	3046
Belowground litter decay	5130	5130	5130	5130	4370	4370	4370	4370

[§]Animal liveweight. Other figures are dry matter.
[¶]Mean of 10 grazing cycles.

Table 6. Performance of steers grazing a mixture of *B. humidicola* x *D. ovalifolium* receiving three K fertilization rates (grazing period 365 days).

		K rates (kg ha)			
Stocking rate	Animal gains	0	50	100	Mean
an/ha					
3.3	g/an/day	331	347	366	348
	kg/ha/yr	481	506	521	502
6.6	g/an/day	279	274	192	248
	kg/ha/yr	713	768	641	707

Outputs from the system consisted almost exclusively of K removal via the harvested animals since no leaching was detected in the soil samples. Animal export was less than 2 kg K/ha, a figure lower than the estimated input via rain and dust. The other major input was the applied fertilizer.

Potassium fluxes from the plant to the soil consisted of aboveground and belowground litter decay, along with feces and urine inputs (Table 6). Potassium transferred via aboveground litter decay varied somewhat with treatments averaging 41 kg K/ha/yr. Potassium transferred via root decay was lower, 26 kg K/ha/yr in the low stocking rate, decreasing to 22 kg K/ha/yr in the high stocking rate. It was not possible to detect the effect of K fertilization rate was possible to detect because the estimate is based on root analysis only at the level of 0 kg K/ha. It is assumed, therefore, that the percentage of K in the roots did not increase with K fertilizer rate in these calculations.

The contribution of K via feces was not affected by K fertilization rate, but it increased with stocking rate (20 to 34 kg K/ha/yr) reflecting the increase in fecal output with increasing numbers of animals.

Major discrepancies were observed between calculated urine (K in animal intake minus K exported by the animal minus K in feces) and the effective urine (the increase in exchangeable K in the soil affected by urination) (Table 8). An average of only 40% of the calculated urine flux was accounted for by the effective urine. Where did the rest go? After examining the basis for calculations and considering the area affected by each urination (0.12 m^2 or 6283 m^3), one can plausibly assume that the differences were rapidly leached out of the soil at depths below 100

Table 7. Calculated potassium pools, fluxes, inputs, and outputs in the soil-plant-animal system on an annual basis.

	Stocking rate (an/ha)							
	3.3				6.6			
Parameters	0	50	100	X	0	50	100	X
Mean concentration aboveground pasture (% K)	1.05	1.25	1.34	1.21	1.25	1.40	1.49	1.38
Pools (kg K/ha)								
Total pasture biomass	16.56	21.84	23.54	20.49	23.02	34.33	38.38	31.60
Residual standing biomass	0.64	0.64	0.69	0.65	0.63	0.53	0.54	0.57
Belowground litter biomass	22.55	22.55	22.55	22.55	18.25	18.25	18.25	18.25
Exch. K (0–100 cm)	155.30	132.76	158.28	148.78	160.71	156.16	163.53	160.13
Spec. adsorbed K (0–100 cm)	78.65	67.24	80.17	75.35	81.38	79.09	82.67	81.05
Inputs and outputs (kg K/ha/yr)								
Animal export	1.17	1.21	1.23	1.20	1.97	2.05	1.86	1.96
Animal input	0.45	0.45	0.45	0.45	0.90	0.90	0.90	0.90
Rain and dust	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Fertilizers	0.00	50.00	100.00	—	0.00	50.00	100.00	—
Fluxes (kg K/ha/yr)								
Aboveground litter production	36.02	42.64	49.28	41.31	42.30	39.91	43.26	41.82
Belowground litter decay	25.65	25.65	25.65	25.65	21.85	21.85	21.85	21.85
Feces	20.41	18.46	19.94	19.60	36.13	32.86	32.75	33.91
Urine, calculated[§]	40.56	63.51	61.16	55.07	92.82	115.94	23.64	21.94
Leached urine[¶]	30.44	52.54	49.84	44.27	72.58	94.00	91.93	86.17
Animal intake	62.14	75.69	82.23	73.04	130.92	150.85	150.18	144.11
Plant uptake	91.68	121.75	182.05	131.82	126.83	159.94	199.48	162.08

[§] Animal intake minus animal removal minus feces.

[¶] Calculated urine K minus effective urine K in the soil.

cm. If one assumes a K input of 1.35 g K/urination and an impact area of 9-cm radius/urination, the K rate applied to each spot averaged 465 kg K/ha. The effective urine, as previously indicated, averaged 0.57 kg K/ha, or about half the calculated urine amount. Data from bare soils show that K leaches below the 100-cm soil depth when a rate of 300 kg K/ha is applied. It seems reasonable to assume that this has occurred in the urinated areas and that leaching occurred so fast that it was not detected by soil sampling one day after urination. Consequently, the K flux via urine is limited to the effective urine, which ranged from 10 to 23 kg K/ha/yr, while the leached urine ranged from 30 to 94 kg K/ha/yr. This discrepancy represents a major loss of K from the system.

A summary of K leached from urine, shown in Table 8, indicates that leached K increased more with increasing stocking rate than with increasing K fertilization rate. Although there was a measurable increase in leaching from 0 to 50 kg K/ha, doubling the stocking rate almost doubled the leached K estimate (Table 8).

Plant uptake of K—calculated by multiplying the daily biomass growth rate obtained from the clipping experiment by the mean percentage K in the available forage—increased with increasing K rate and stocking rate (Table 7), showing both a clear response to K fertilization and to increased grazing pressure.

Balance

The potassium nutrient cycle for the one of the six treatments is illustrated in Figure 7. Considering the broad assumptions leading to estimates of animal intake, fecal output, and effective urine, the balance between the fluxes of K into the soil and the higher K rates in the pasture is quite close.

The nutrient cycling data indicate that potassium is efficiently recycled in this soil-plant-animal system but not for the reasons assumed in the literature. It had been hypothesized that, under grazing, most of the K recycling takes place via excreta. The data show that this is definitely not the case. The overall contribution of feces and effective urine ranged from 15 to 45% of the recycled K, while that of litter decomposition varied from 28 to 65%. These findings are due to the direct measurement of effective urine on soil exchangeable K, which has not been reported in the literature. In accordance with the literature, this experiment shows that urine and feces distribution is uneven and will eventually result in a significant redistribution of available K in the pasture, with the open areas gradually being depleted and the shaded areas or those near water sources enriched. This work extends this observation to the humid tropics.

Although K cycling seems very efficient, much of the K in urine is lost through leaching. Annual leaching losses in urine spots cause an overall loss of 30 to 94 kg K/ha/yr from the entire pasture. Coupled with the unevenness of excreta deposition, such losses suggest that pastures need maintenance levels of potassium fertilization to counteract leached urine losses.

Table 8. Effect of urine on the levels of exchangeable K in the 0- to 5-cm soil in a pasture of *B. humidicola* x *D. ovalifolium* receiving 0 and 100 kg K/ha. Initial exch. K in soil: 0.09 cmol/L.

K added	Time after urination	Distance from the center (cm) 0	10	20	Mean
kg K/ha		Exch. K (cmol/L)			
0	1 day	.60	.37	.09	.35
	2 weeks	.39	.24	.06	.23
	4 weeks	.39	.28	.18	.32
	8 weeks	.22	.12	.09	.14
	Mean	.43	.25	.10	.26
100	1 day	.82	.40	.10	.44
	2 weeks	.62	.38	.16	.38
	4 weeks	.48	.32	.26	.35
	8 weeks	.30	.20	.15	.34
	Mean	.55	.32	.16	.37

Statistical significance

K level	N.S.
Time	**
K x Time	N.S.
Distance	**
Distance x Time	*
K x Distance	N.S.
CV (%)	57

** Significance effect at the 0.01 level of probability.
N.S. = Not significant at the 0.05 level.

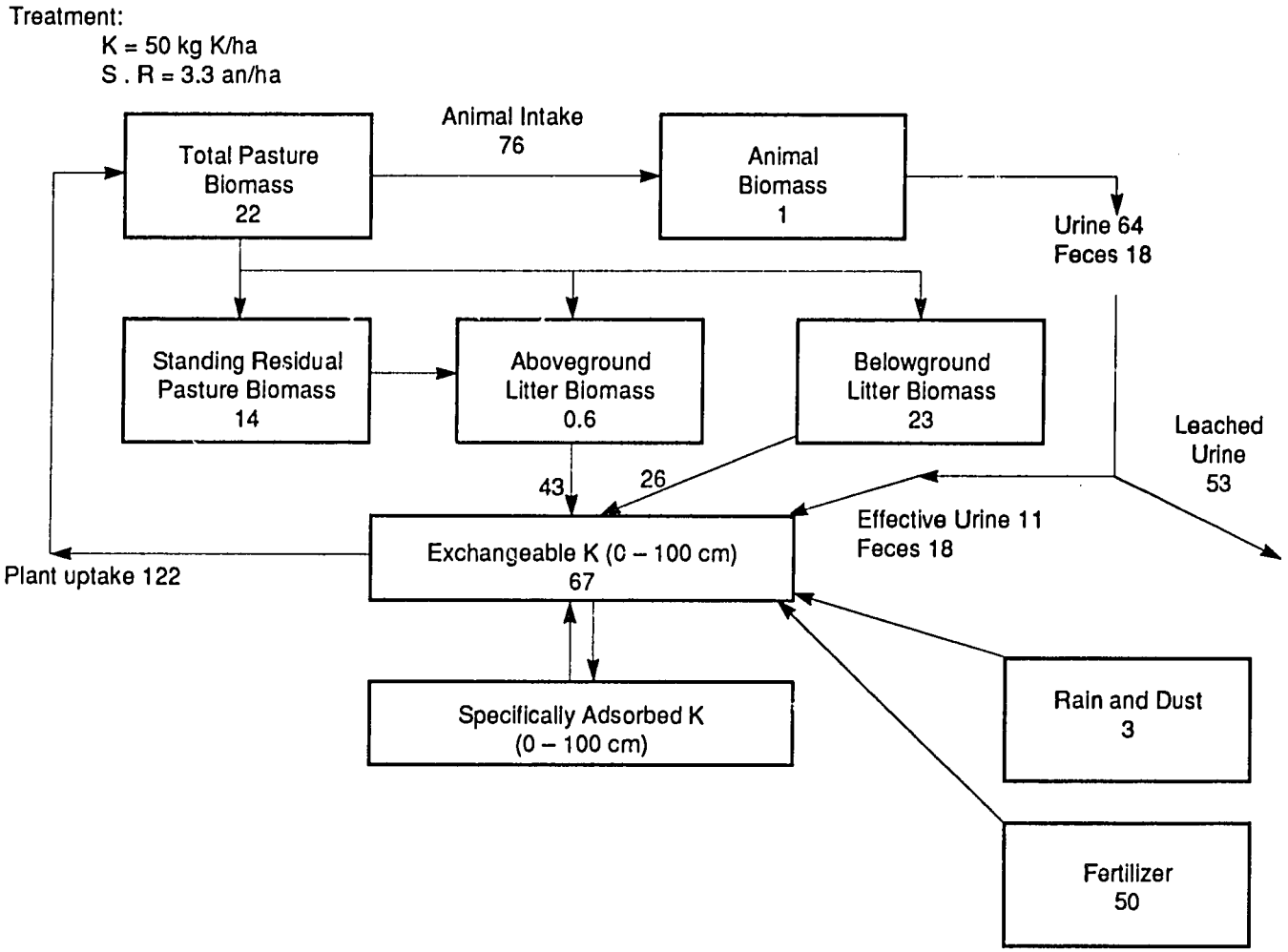

Figure 7. Pottasium cycle in the treatment with 50 kg K/ha and 3.3 an/ha stocking rate. Fluxes are kg k /ha/yr. Fluxes: Plant uptake (122) = AG litter (43) + BG litter (26) + Feces (18) + Effective urine (11) + Rain (3) + Fertilizer (50) – Unaccounted (29).

Grazing Pressure Effects on the Pasture Degradation Process: Y-307B

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Objectives

As a result of the simulation on soil organic matter with the Century model, Experiment Y-307 was modified to evaluate the effect of a differential grazing pressure on aboveground and belowground biomass dynamics—after the termination of the potassium dynamics study.

Procedures

Experiment Y-307 originally consisted of a combination of two grazing pressures (high and low) and 3 K rates (0, 50, and 100 kg/ha) applied once in 1985 with three replications. Of the six available treatments, the four which received K during 1985 were chosen to set up the core experiment with a range of stocking rates: 1) no grazing (NG); 2) low stocking rate (LSR); 3.3 an/ha/year, with a surplus of forage on offer; 3) adequate stocking rate (ASR): 6.6 an/ha/year, with allowances to go down to 5.5 an/ha in periods of low forage availability—ideal management conditions; and 4) overgrazing (OG): 8.3 an/ha/year with lack of available forage. Stocking rates were set to establish widely different aboveground root biomasses. These plots received a blanket application of 50 kg K/ha in 1988 to eliminate differences due to previous treatments.

Two additional plots had never received K fertilization; one continued as such, and the other received 20 kg P/ha as triple superphosphate. These additional treatments will help evaluate the relative response to fertilizer K and P additions.

Even though no P had been applied since 1985, overall available biomass and animal performance were good during 1988, suggesting that P was not limiting pasture biomass production.

Experiment Y-307B began on March 14, 1989. Grazing treatments were set up in a randomized complete-block design with 3 replications. Animals rotated from rep 1 to rep 3 in 42 days. Each rep involved 14 days of grazing followed by 28 days of recuperation. Animals are two-year-old Brown Swiss x Cebu steers initially weighing 180 kg. The pasture was rested three months before beginning the experiment.

Table 1 contains the chronogram of activities which will be performed over a two-year period. Measurements are being made during maximum and minimum precipitation periods.

Soil Fertility

Chemical soil properties at the beginning of the experiment are shown in Table 2. Most of the fertility is concentrated in the 0- to 5-cm soil depth, where conditions for plant growth seem adequate for low-input pastures. Below 5 cm, Al saturation is at least 90%, and it increases with depth.

Rainfall and Soil Moisture

Rather than showing the common monthly averages, Figure 1 shows 10-day cumulative precipitation periods for 1989 to illustrate the good rainfall distribution during the year in a udic moisture regime. Only three times was accumulated rainfall less than 10 mm/10 days, and at no point was rainfall less than 10 mm/20 days. Furthermore, there were no 10-day periods without rainfall.

Soil moisture tension for periods with at least four days between rainfall events is shown in Figures 2 and 3, for 3- and 30-cm soil depths, respectively. These data can be used to describe drying patterns. Each point in the graphs is the median of three locations per plot and 3 reps for each depth; only treatment 1 (without grazing) is depicted, since other treatments show the same tendencies. During rainy periods, soil moisture tension rarely exceeded field capacity even at the 3-cm soil depth.

Table 1. Chronogram of activities to be performed in Y-307B.

Activity	Description
Available biomass	Every 42 days.
Total biomass	Before and after grazing. Began in cycle 3.
Root biomass	Every 42 days.
Root dynamics	During maximum and minimum precipitation periods. Intensive sampling every seven days during a 42-day cycle.
Soil moisture tension	Daily, except weekends.
Decomposition trials	During maximum and minimum precipitation periods. Buried bags sampled at different intervals for six months.
Animal performance	Liveweight gains every grazing cycle (42 days).
Fecal production	Evaluated in lots of animals at 200, 240, and 280 kg of bodyweight.
Bulk density	Every six months.

Table 2. Soil chemical properties of an actively grazed four-year-old *B. humidicola* x *D. ovalifolium* pasture.

Depth	C	P[§]	Al	Ca	Mg	K	Sat Al
cm	g/kg	mg/L	———	cmol(+)/L	———		%
0–5	1.8	10.8	1.7	.51	.26	.13	64
5–20	—	4.4	3.2	.26	.04	.04	90
20–40	—	1.9	3.9	.30	.04	.03	91
40–60	—	1.3	5.0	.25	.05	.03	94
60–100	—	0.4	6.6	.21	.06	.02	96

[§] Olsen P

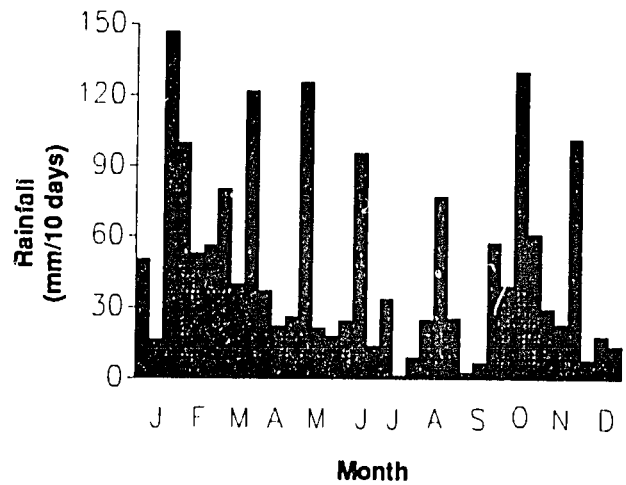

Figure 1. Rainfall distribution during 1989 at Yurimaguas, Peru.

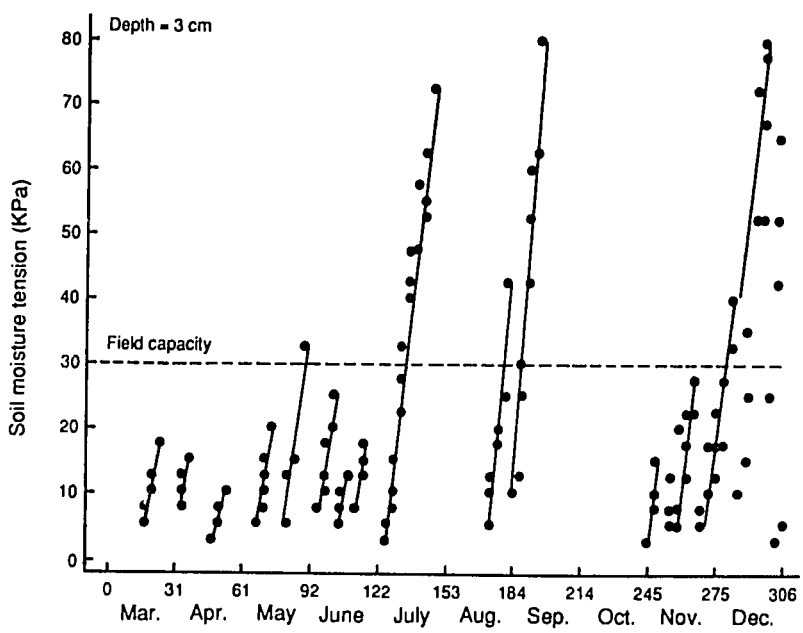

Figure 2. Soil moisture tension at 3 cm during 1989.

Pasture Production

Forage biomasses are shown in Figure 4. Despite low fertility levels, biomass production is high. Because the legume content was less than 5%, biomass consisted mainly of grass. Total aboveground biomass stabilized around 10 t/ha after two grazing cycles. Available biomass estimates the forage that animals may consume and correlates well with stocking-rate treatments. The addition of K did not seem to have an effect on available biomass.

Phosphorus additions also did not increase available biomass, but the legume content in the pasture increased. This effect was dramatic in the number of seeds germinating in the feces. At the same grazing pressure, an average of 14 seedlings germinated per fecal deposition in the P treatment (treatment 6), compared to 2.4 and 1.0 seedlings/deposition in the +K treatment and the control (-K), respectively.

Animal Production

Animal performance due to stocking rate is presented in Figure 5. Liveweight gains at low and adequate stocking rates increased with grazing periods and have not shown drastic fluctuations despite rainfall patterns. Animals in the over-grazed treatment showed large initial gains, but gains declined and losses occurred at the end of 1989. The drier season from July to September accentuated animal weight loss, as available biomass also declined, but even under more favorable rainfall conditions, this loss would be expected, since biomass in the over-grazed treatment decreased rapidly and is expected to reach a steady-state low production in 1990. Despite a very high stocking rate in the over-grazed treatment, *B. humidicola* recovers well after each rotation and has not yet reached

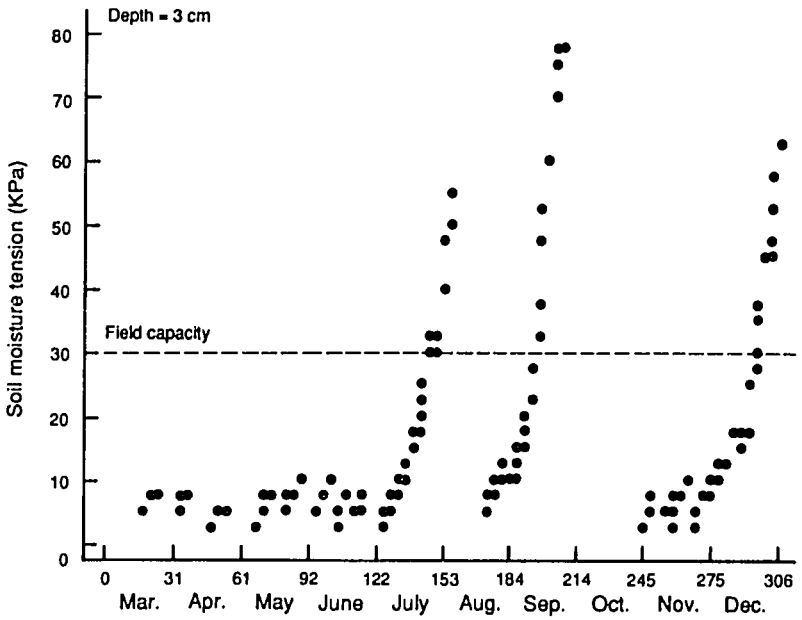

Figure 3. Soil moisture tension at 30 cm during 1989.

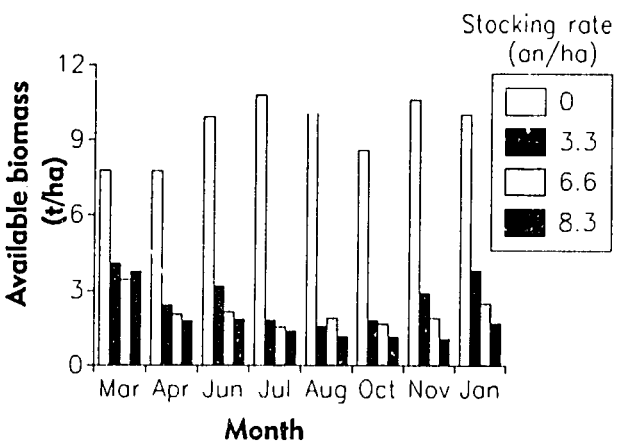

Figure 4. Forage biomass production during 1989.

a completely over-grazed condition after nine months of over-grazing at excessively high stocking rates. Five years after grazing began, findings indicate that *B. humidicola* does not degrade easily, even under poor management conditions.

Root Production

Root biomass was evaluated with a 4.1-cm diameter Giddings probe. Ash-free root biomass distribution is shown in Table 3. Root biomass is the average of 15 samples. At the beginning of the experiment, root biomass averaged 4.7 t/ha to a depth of 50 cm, and 74% of the roots were concentrated in the first 10 cm.

Initially root legume content, as estimated by the proportion of live roots only, was less than 3% in all plots. Coarse and fine roots were those 2 to 1 mm and less than 1 mm in diameter, respectively. Almost no roots had diameters greater than 2 mm. Live roots accounted for the great majority of roots. The proportion of dead roots was around 20%. Coarse roots accounted for an average of 13% of the total root biomass.

Data on root dynamics, total biomass, decomposition rates of roots and leaves, and fecal output are being evaluated and will be completed during 1990.

Soil Compaction

Soil moisture conditions at Yurimaguas are ideal for compaction. The effect of stocking rate on bulk density (BD) is shown in Figure 6. Bulk density was measured three times in a one-year period. Measurements were taken during April 1989 and 1990 at the peak of the rainy period and after the drier period in September 1989 when the soil became saturated with two rainfall events.

The ANOVA of treatment over time indicates a significant interaction. If one starts with an actively managed pasture, the overall effect is for BD to decrease with decreasing stocking rates. One year of rest in the nongrazed plots achieves BD values similar to those reported for virgin or secondary forest, indicating that changes in BD due to cattle grazing are transitory. Also, with the higher stocking rates, no-grazing and low-grazing pressure treatments were significantly different than they were for adequate grazing and over-grazing: the former retained BD values similar to those at the beginning of the experiment.

Because BD is a measure of compaction, soil water relationships were also evaluated one year after the treatments were established (Figure 7). Overall, the contrast between animal trampling and no trampling was not significant, indicating increased root turnover and fecal deposition. The overall effect of trampling is to reduce total porosity linearly ($r^2 = .65$). Because differences are better expressed at low water tensions, the macroporosity is most affected by trampling.

Earthworm Dynamics

Earthworms are an important biological mediator of soil processes in pasture ecosystems, account for most of the macrofauna, and may be affected by grazing treatments. A single sampling one year after the experiment began is presented in Figure 8. Only two kinds of earthworms were used in the experiment: endogeics, soil-feeding worms represented by *Pontoscolex corethrurus*, a polyhumic pantropical earthworm; and epigeics, litter-feeding and

surface-dwelling earthworms. Most of the biomass consists of *P. corethrurus*. With large populations, substantial amounts of soil pass through the gut of the worm and marked effects on soil structure have been observed elsewhere. Grazing pressures do not affect numbers and biomass until over-grazing occurs, at which point *P. corethrurus* is replaced by the surface-dwelling earthworms, possibly indicating a physical effect of trampling.

Earthworm biomass and BD are negatively correlated (Figure 8). Despite a relatively high bulk density, the adequate grazing treatment still has a high earthworm biomass. However, in the over-grazed treatment, the earthworm population crashes with only a small increase in bulk density. This finding suggests that a biological indicator such as earthworms may better indicate damage or degradation than a physical parameter such as bulk density.

Table 3. Root biomass distribution at the beginning of the experiment.

Grazing pressure treatment	Depth	Root biomass Total	Root biomass Live	Dead roots	Distribution of total roots with depth
	cm	t/ha		%	
No grazing	0-10	3.49	2.90	17	72
	10-30	0.87	0.61	30	18
	30-50	0.46	0.32	29	10
Low	0-10	3.33	2.72	18	69
	10-30	0.92	0.68	23	19
	30-50	0.57	0.42	25	12
Adequate	0-10	3.57	2.84	20	77
	10-30	0.67	0.49	31	15
	30-50	0.35	0.27	24	8
Overgrazed	0-10	3.49	2.79	20	76
	10-30	0.77	0.58	26	17
	30-50	0.35	0.26	25	7

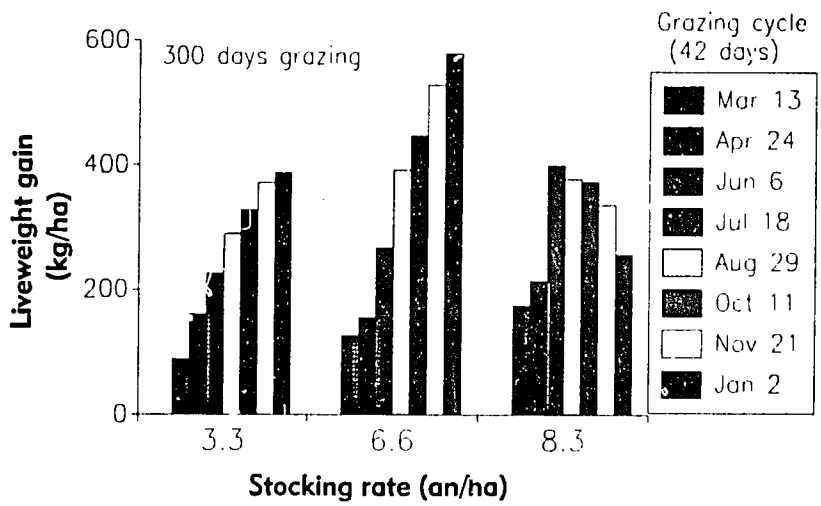

Figure 5. The effect of stocking rate on liveweight gains during 1989.

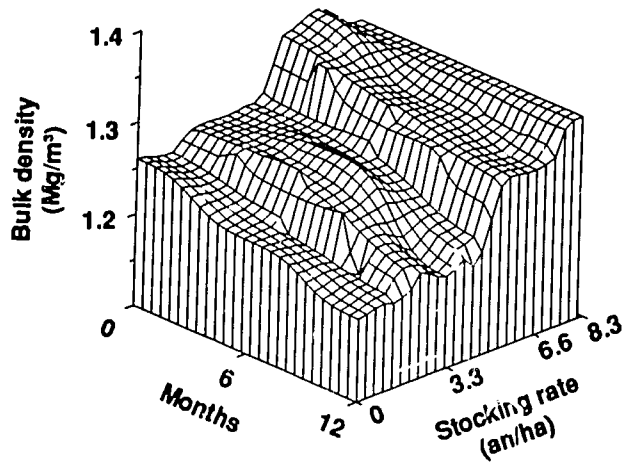

Figure 6. The effect of stocking rate over time on bulk density.

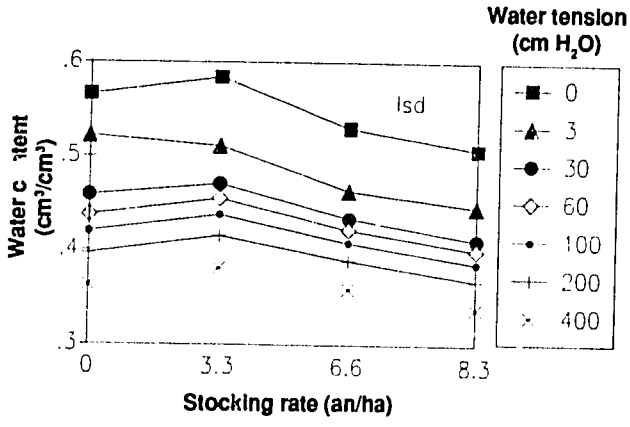

Figure 7. The effect of stocking rate on soil water content.

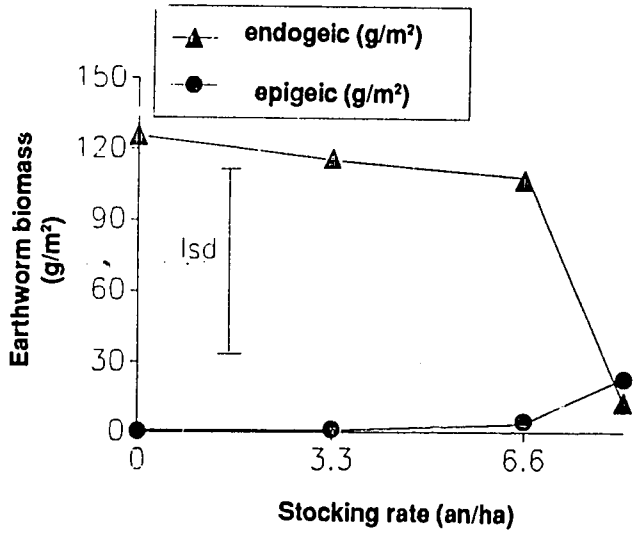

Figure 8. The effect of stocking rate on earthworm biomass at peak populations.

Comparative Soil Dynamics Under Different Management Systems: NC-6

Much of the research at Yurimaguas has been devoted to defining and refining production systems for different soil/landscape positions and socioeconomic conditions found throughout the humid tropics. Although such systems clearly differ in their biological, chemical, physical, and economic characteristics, underlying causes of these differences are not well understood. Moreover, it is often difficult to compare the performance of systems studied at different sites due to the confounding effects of temporal and soil spatial variability. Central experiment Y-412 was begun in September 1985 to compare traditional and promising management practices of the same age on similar soil types. The management systems included the following: 1) shifting agriculture, 2) high-input continuous cropping, 3) low-input cropping, 4) a multistrata agroforestry system, 5) a peach-palm plantation, and 6) an uncut 10-year-old secondary forest. Each was established on a sandy-loam and a loamy-sand phase of a Typic Paleudult. Texture was blocked by replications. The loamy-sand block averaged 7% clay, while the sandy-loam block averaged 17% clay.

The objective was to monitor and compare changes in soil properties and vegetation production after a secondary forest was cleared and the land subjected to the management practices mentioned above. We hypothesized that these practices would have varied effects on the soil's physical, chemical, and biological properties and processes and that these differences could be related to differences in plant production.

Management practices and results from the first year after forest clearing were described in the 1986-87 TropSoils Annual Report. During the first year, there were few significant differences among treatments in soil chemical properties or in total or light-fraction C. Microbial C, however, was significantly higher in the secondary forest than in the other treatments. Moreover, greater quantities of microbial and total C were associated with clayier soil textures. Tree growth and crop production were also generally greater at the sites with finer-textured soils.

This report describes various components of the central experiment denoted by the symbol Y-412, as well as associated observations on other experiments at Yurimaguas. Included are crop-production and tree-growth data, both of which are strongly associated with soil physical properties, soil fertility dynamics, organic inputs, soil organic matter, soil respiration, macrofaunal activity, and mycorrhiza interventions. The report is the first systematic comparison of how various management options affect soil properties. It will also explore the potential productivity of specific systems.

This project is a joint effort supported by various funding sources. In addition to CRSP funds, the Tropical Soil Biology and Fertility Program (TSBF) has been active, with particular support from the European Economic Community to the École Nationale Supérieur of France for macrofauna work, a National Science Foundation grant on tropical soil organic-matter dynamic awarded to Colorado State University and North Carolina State University, and an AID-sponsored strengthening grant awarded jointly to Florida A&M and North Carolina State University. Furthermore, INIAA has allocated considerable resources from their IDRC-Canada project in agroforestry.

Comparative Soil Dynamics Under Different Management Systems: Y-412B

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Summary of Results

After three years, the multistrata system produced much more understory biomass than the other systems (i.e. low-input, shifting cultivation, forest fallow, and peach palm). Nutrient stocks in the understory biomass and above-ground litter compartments on the treatments with a planted legume showed higher nitrogen levels than with shifting cultivation or peach palm. The multistrata system, with a well established *Centrosema macrocarpum* understory, produced the highest or nearly the highest stocks of nitrogen, phosphorus, potassium, calcium, and magnesium, with the low-input system in second place. The first nonfood harvest of the multistrata system was *Inga edulis* firewood at 18 to 20 months after transplanting. Firewood production was high (83 m^3 in sandy-loam blocks).

Examining the soil chemical dynamics over the first three years, one finds that the low-input, peach-palm, and multistrata systems showed significantly higher base status and lower acidity than the forest-fallow check. These findings show the residual effect of the ash. The high-input system produced the most positive changes in soil fertility parameters, including rapid improvement of subsoil base saturation. Significant phosphorus leaching was detected on the loamy sand soil.

Results from the first four years show clearly that crop performance is affected by topsoil texture, which influences the soil's moisture-retention capacity. Both high- and low-input cropping systems showed similar soil respiration values. A litter-bag method was successful in detecting surface-soil erosion losses at levels less than 0.1 t/ha. Soil macrofauna activity was measured in 11 systems. Pastures presented higher microfaunal biomass than even the primary forest. Inoculating earthworms to seedlings in the nursery enhanced growth of achiote (*Bixa orellana*) but not of peach palm. Termite mounds were found to be more fertile than adjacent soil or ant hills. Although not all plants in Yurimaguas are mycorrhizal, one species seems to be particularly associated with peach palm. Three unidentified species were observed and are presently being studied at laboratories in Europe to ascertain whether they are new to science.

Crop Production and Soil Physical Properties: Y-412C

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Crops yields and time of planting for different treatments are shown in Table 1 and the timing and quantity of nutrient inputs in Table 2. The annual precipitation pattern is shown in Figure 1.

Shifting Agriculture

Plots were abandoned after a year of cropping. In October of 1988 and 1989, when secondary vegetation was approximately 24 and 36 months old, respectively, understory biomass production and the diameters of trees (> 1.0 cm/dbh) were measured. Tree biomass will be estimated using regression equations based on dbh.

High-input System

The fourth, fifth, sixth, seventh, eight, and ninth crops (alternately corn and soybeans) were planted with conventional tillage using a bush hog, a disk plow, a five-tine field cultivator, a bed shaper, and a planter. Soybeans were treated with rhizobia before planting. The corn variety used was Marginal 28, and the soybean variety was Jupiter. Herbicide (Dual) was applied to corn and soybeans; weeds in the soybean crop were treated with Poast as well. In the fourth crop, yields were moderate; the fifth and ninth crops (soybean) yielded well, despite the absence of fertilization, indicating that soil fertility had been built up by fertilization during the third and seventh crops. Mean yields for the fourth (corn), fifth (soybean), sixth (corn), seventh (soybean), eighth (corn), and ninth (soybean) were 3.08, 2.03, 3.45, 1.90, 3.09, and 2.55 t/ha, respectively. Total grain yield for the nine crops was 25.5 t/ha (Table 1).

Low-input System

Yields were maintained through five crops and totalled 5.9 t/ha. Mean yields for the fourth (rice) and fifth (cowpea) crops were 1.44 and 0.90 t/ha, respectively. An attempt was made to establish kudzu following the fourth crop. However, a low rate of establishment and a lack of seeds for replanting caused kudzu to be replaced by cowpea in April 1987. Kudzu was again planted following the cowpea harvest, in September 1987. As of January 1988, kudzu ground cover was 25 to 50% on both soil textures, but was higher on the sandy loam than on the loamy sand. Ground cover reached 100% by May 1988. Ground-cover biomass was estimated in September of 1988 and 1989.

Table 1. Crop yields (t/ha) and the time of planting for the different treatments.

	Treatments			
	High-input cropping	Low-input cropping	Multistrata agroforestry	Peach-palm plantation
	t/ha			
4th Crop				
Rice (09/86)		1.44a[§]	0.77b	1.35a
Corn (11/86)	3.08			
5th Crop				
Rice (02/87)				0.52
Cowpea (04/87)		0.90		
Soybean (06/87)	2.03			
6th Crop				
Cowpea (07/87)				0.46
Corn (10/87)	3.45			
7th Crop				
Soybean (05/88)	1.90			
8th Crop				
Corn (09/88)	3.09			
9th Crop				
Soybean (06/89)	2.55			
Total	25.54	5.9	4.4	6.4

[§] Means followed by the same letter for rice are not significantly different at the 5% level using the Waller-Duncan multiple comparison test.

Table 2. Ash, lime, and fertilizer additions (kg/ha) to the different management systems during 28 months, Yurimaguas, Peru.

System	Crop	Planting date	N	P	K	Dolomitic lime
			kg/ha			
All	burn[§]	09/85	nd	25-56	88-375	0
High-input	corn[¶]	10/85	100	43	100	1000
High-input	corn	02/86	100	35	83	1000
High-input	soybean	06/86	40	35	83	0
High-input	corn	11/86	100	35	83	0
High-input	soybean	06/87	0	0	0	0
High-input	corn	10/87	100	35	83	0
High-input	soybean	05/88	0	35	83	2000
High-input	corn	09/88	100	35	83	0
High-input	soybean	06/89	0	0	0	0
Peach palm	rice	11/86	30	0	0	0
Peach palm	rice	02/87	60	0	0	0

[§] Nutrient added in ash. The first number refers to the average additions on the loamy sand, the second to additions on the sandy loam.
[¶] Nitrogen added as urea, P as triple superphosphate, K as KCl.

Multistrata Agroforestry System

The total grain yield for four crops was 4.4 t/ha. The yield (0.77 t/ha) from the fourth and final crop in this system was low compared to that in the low-input or peach-palm plantation systems. Presumably, the low yield was due to shading by the trees with which rice was associated. After the fourth crop, a *Centrosema macrocarpum* ground cover was planted (January 1987), and it covered approximately 100% of the ground within nine months. Ground-cover biomass was estimated in September 1988 and 1989. *Eugenia stipitata* (*arazá*) was replaced by cacao at the end of October 1987 due to poor growth and survival under shade. *Inga edulis* branches were pruned in September 1988, and the biomass of the responding shoots was estimated in October 1989. In September 1988 and 1989, diameters of all trees were measured and will be used to estimate biomass; the biomass of the understory was also estimated via destructive sampling. Shaina (*Collombrina* sp.), a fast-growing tree used in construction, was planted in the last quarter of 1989.

Peach-palm Plantation

The yield of the fourth crop (rice) was similar to that obtained in the low-input system (1.35 t/ha), but the yield of the fifth crop (rice) was much reduced (0.52 t/ha) despite the application of 60 kg N/ha. The yield of the sixth crop (cowpea) was also low (0.46 t/ha). Total grain yield for the six crops was 6.41 t/ha. A *Centrosema macrocarpum* ground cover was planted in September 1987. Ground cover was less than 25% by January 1988, but it had reached 100% by July 1988. Ground-cover biomass was estimated via destructive sampling in September of 1988 and 1989. Palm heights and diameters were also measured periodically.

Secondary Vegetation

The secondary forest was approximately 13 years old in January 1988. During September 1988, individual trees along three 50-m-long by 2-m-wide transects/plot were tagged, and their diameters were measured. This process was repeated in September 1989. Tree biomass will be estimated using regression equations based on dbh. Understory biomass in 1988 and 1989 was estimated via destructive sampling.

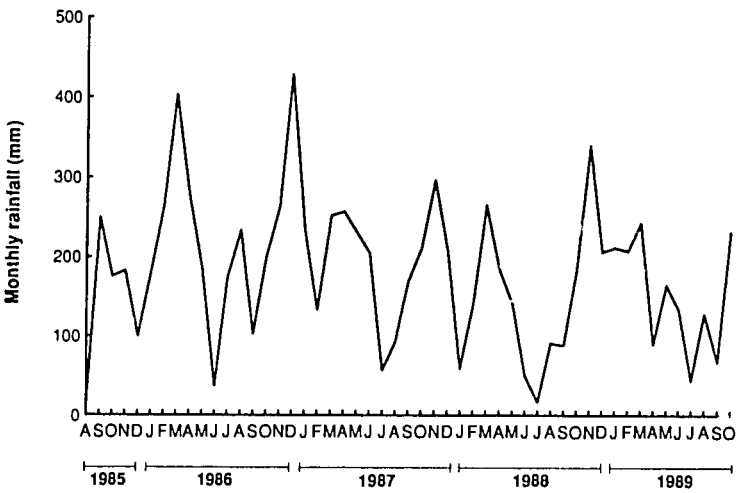

Figure 1. Monthly precipitation during the study (August 1985 through October 1989), Yurimaguas, Peru.

In all three low-input systems, (i.e. low input, multistrata, and peach-palm plantation), crop production was positively correlated with the percentage of clay in the topsoil (Figure 2). The sandy loam soil had greater soil moisture retention (Table 3, Figure 3) and better nutritional properties.

Economic Analysis of the Cropping Phase of the Low-input Systems

The costs of manually clearing secondary forests and the costs associated with a succeeding rotation of rice-rice-cowpea are shown in Table 4. Weeding costs increased with time due to greater weed pressure, while harvesting costs decreased with decreases in the harvested material. Given realistic yields and current prices (Table 5), the net profit from a rice-rice-cowpea rotation was approximately U.S. $380/ha. Using such a rotation in the initial phase of either a multistrata system or a peach-palm plantation would thus help defray the costs of tree establishment, presumably without a detrimental effect on tree production. Similar analyses of the high-input and shifting-agriculture systems are being developed. Such analyses will be extended to cover the effect of management interventions after the first year.

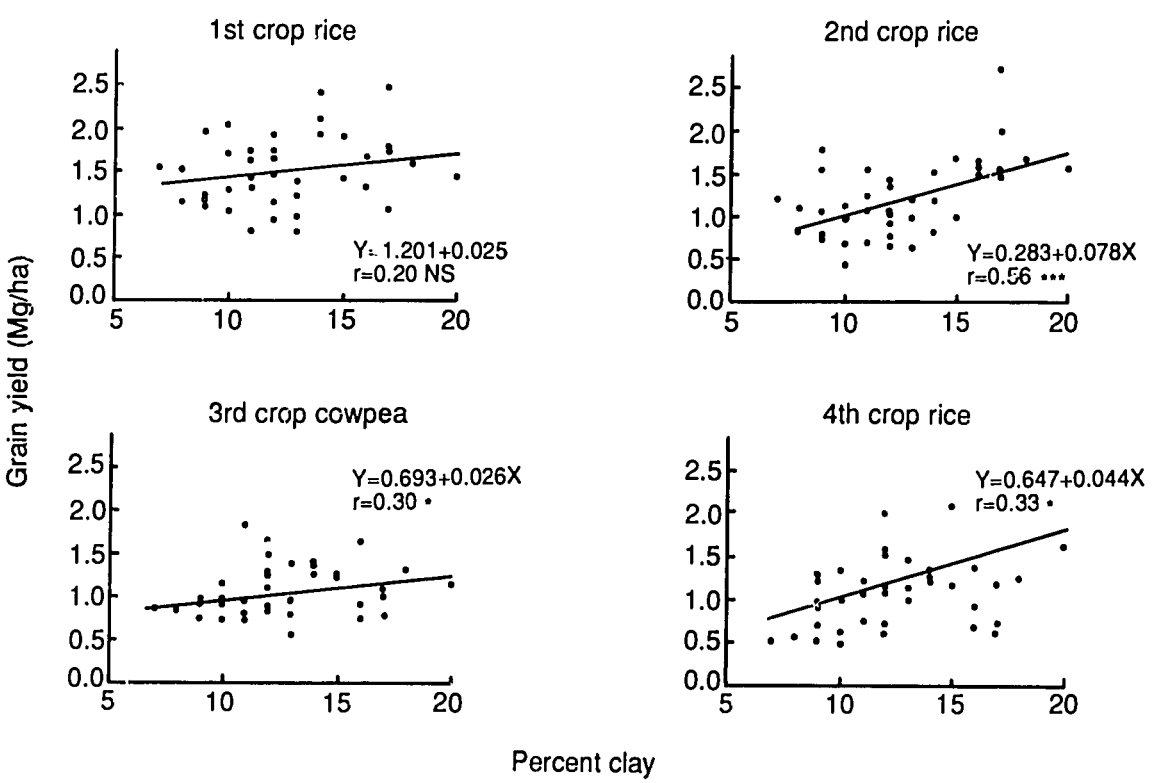

Figure 2. Relationship between grain yields and percent clay in the top 15 cm of soil in the nonfertilized systems, Yurimaguas, Peru.

Table 5. Crop yields, unit prices, and net profit for a rice-rice-cowpea rotation, Yurimaguas, Peru, 1986.

Crop	Yield	Price/kg	Total
	(kg/ha)	U.S.$	
Rice	1605	0.27	428
Rice	1265	0.27	337
Cowpea	1090	0.53	581
Total income			1346
Total direct costs			864
Gross profit			483
Transportation (20%)			103
Net profit			380

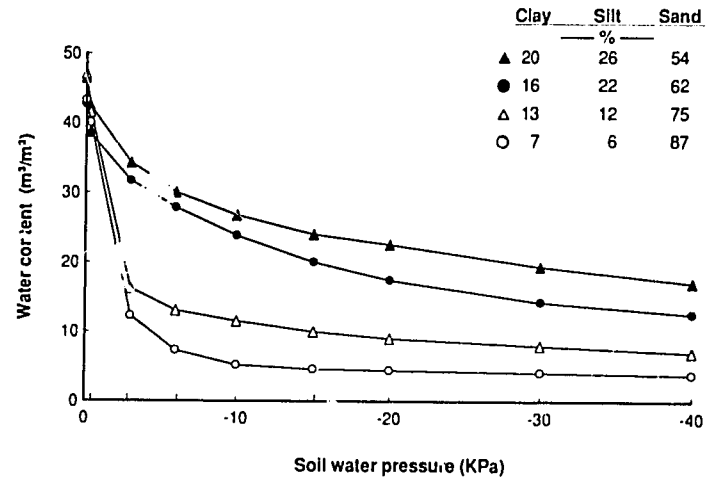

Figure 3. Soil water characteristics for different-textured soils from the various management systems, Yurimaguas, Peru.

Table 3. Available water in different-textured topsoils in the different management systems, Yurimaguas, Peru.

Clay	Silt	Sand	*In situ* field capacity	Wilting point	Available water
%	%	%	cm^3/cm^3		
7	6	87	0.09	0.02	0.07
13	12	76	0.15	0.04	0.11
16	22	62	0.24	0.07	0.17
20	26	54	0.27	0.07	0.20

Table 4. Costs to hand-clear a 10-year-old secondary forest and to plant and harvest three succeeding crops of a rice-rice-cowpea rotation, Yurimaguas, Peru, 1985-86.

Activity	Preplanting	Rice 1	Rice 2	Cowpea 1
	U.S. $/ha (man-days/ha)§			
Clearing brush	30 (15)			
Felling trees	30 (15)			
Burning	4 (2)			
Field prep.			50 (25)	50 (25)
Planting		60 (30)	60 (30)	60 (30)
Weeding & maintenance		90 (45)	100 (50)	100 (50)
Harvest		64 (32)	64 (32)	66 (33)
Threshing		30 (15)	20 (15)	20 (10)
Total	64 (32)	244 (122)	294 (152)	296 (148)

§Man-days/ha are listed in parenthesis.

Tree Growth: Y-412D

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Multistrata Agroforestry System

At least 90% of all tree species were alive 12 months after transplanting. Tree canopy cover 18 months after transplanting was 98% on the sandy-loam and 49% on the loamy-sand blocks (Table 1). The majority of the ground cover was contributed by inga: 88% on the sandy-loam and 45% on the loamy-sand blocks. Peach-palm cover was 6% on the sandy-loam and 2% on the loamy-sand blocks.

Inga edulis began to flower between 18 and 20 months after transplanting, and fruit harvest began at 24 months after transplanting. Fruits were removed from the trees when immature to prevent losses due to unauthorized harvests; the yield was 12,500 units/ha. As a result of branch pruning in September 1988, inga produced 83 m^3 of firewood on the sandy loam and an average of 53 m^3 on the loamy sand. The biomass of resprouting shoots one year after pruning was estimated to be 12.3 t/ha on the loamy sand and 9.6 t/ha on the sandy loam. The following equations were developed to predict the biomass of the resprouting shoots:

Equation	R^2	N
Total biomass/sprout = $-2.377 + 1.391D - 0.075D^2$	0.58	30
Stem biomass = $-1.151 + 0.638D - 0.039D^2$	0.51	30
Leaf biomass = $-0.849 + 0.514D - 0.027D^2$	0.56	30

where D = diameter of the sprout 10 cm above the base.

Tree height and diameter growth in the multistrata system are shown in Table 2. For all tree species, height growth was more rapid on the sandy loam than on the loamy sand. In inga, height growth was nearly exponential during the first two years, but decreased thereafter, and differences in height between the soil types were comparatively small. For the other tree species, differences in height between the different soil types developed during the first two years and remained relatively constant thereafter.

Species showed striking differences in diameter growth. Diameters of inga greatly exceeded those of peach palm which, in turn, were about double those of *Cedrelinga cataeniformis* (Tornillo). Greater heights and diameters of inga compared to the other species indicate its ability to grow well on infertile and acid soils. Within species, differences in tree diameters due to soil types were smaller; diameters were greater on the sandy loam than on the loamy sand.

Peach-palm Plantation

Soil type had similar effects on height and diameter growth of palms in the peach-palm plantation (Table 2). At 36 and 48 months, the heights and diameters of the palms in the plantation exceeded those in the multistrata treatment. This difference may be due to lesser nutrient immobilization in litter (and hence greater nutrient availability) in the palm plantation as compared to the multistrata system. Greater competition with other trees in the MS system may also be responsible for reduced heights and diameters. Racime production in the plantation during the 36- to 48-month period was greater on the sandy loam than on the loamy sand (2.8 versus 3.3 racimes/tree for the trees which produced racimes or 1.45 versus 2.74 racimes/tree when averaged over all trees).

Table 1. Changes in canopy area and percentage cover provided by three species on topsoils of different textures in the multi-strata agroforestry system.

Species	Clay %	Months after transplanting 6		12		18	
		m^2/plot	%	m^2/plot	%	m^2/plot	%
Peach palm	7	5.8	0.5	13.9	0.7	37.3	2.0
	17	16.2	0.9	9.0	2.1	112.7	6.0
Tornillo	7	6.7	0.4	13.4	0.7	32.4	2.0
	17	16.6	0.9	26.8	1.4	70.3	4.0
Inga	7	61.1	3.3	341.2	19.3	852.0	45.0
	17	198.9	10.6	607.5	32.4	1645.0	88.0

Young Secondary Forest

The secondary fallow forest that grew in the shifting agriculture treatment was dynamic with regard to tree density and numbers of species (Table 3). At abandonment, the density of woody individuals with diameters (dbh) greater than 1 cm was 11556/ha, but by two and three years after abandonment, tree density had decreased by 17% and 45%, respectively. Between abandonment and the third year, average annual mortality increased with time, and the average annual recruitment rate decreased.

Table 2. Average heights and diameters of trees in the multistrata (MS) and peach-palm plantation (PP) treatments in relation to topsoil (0 to 15 cm) clay content, Yurimaguas, Peru.

			Months after transplanting							
		Clay	3	6	12	24	36	48	36	48
Systems	Species	%	Height (m)						Diameter (cm)	
MS	Tornillo	7	0.36	0.45	0.89	1.63	3.63	6.49	3.7	8.3
		17	0.40	0.58	1.27	3.53	3.98	8.31	4.2	8.8
MS	Inga	7	0.15	0.63	2.09	5.18	7.45	§	47.6	
		17	0.22	1.05	3.13	6.28	7.89	§	50.6	
MS	Peach	7	0.12	0.26	0.74	1.58	3.73	6.40	9.0	15.3
	palm	17	0.13	0.42	1.33	3.53	4.74	7.48	12.4	15.6
PP	Peach	7	0.09	0.23	0.73		5.06	8.02	15.7	19.4
	palm	17	0.09	0.33	0.97		6.01	9.04	17.1	18.7

§ Pruned after 36-month evaluation.

Table 3. Temporal changes in the population of trees with diameters > 1.0 cm in an abandonment shifting-cultivation system.

	Years after abandonment		
Parameter	0	2	3
Tree density (#/ha)	11556	9645	6356
Mortality (#/ha)	4622	5022	
Recruitment (#/ha)	2711	1733	
Net change (#/ha)	-1911	-3289	
Avg. Height (m)	3.08	4.03	4.66
Avg. Diameter (m)	2.1	3.2	3.9
# of tree categories (#/225 m²)	21	20	31
Avg. # of tree categories per rep (75 m²)	12	15	16

During the first three years following abandonment, the total number of tree categories found in all replications increased from 21 to 31, although the average number of categories per repetition changed little (from 12 to 16). Ocuera and yanavara were found in all repetitions, and together accounted for 56, 49, and 34% of the trees present at abandonment and at two and three years afterwards, respectively. During this period, the percentage of the population composed of yanavara remained relatively constant (between 26 and 31%), but ocuera's presence in the population decreased from 27% initially to 18 and 6% in the second and third year after abandonment. Other species of importance were cetico (*Cecropia* sp.), cetico colorado, bellacocaspi (*Hymanthus platanofolia*), and acerocaspi (*Inga* sp.). They each composed 2 to 10% each of the tree population.

Average tree height increased approximately 0.5 m/y after abandonment. Average diameter increased 1.1 cm during the first two years and 0.7 cm in the third year.

Old Secondary Forest Fallow

The characteristics of the tree population in the secondary forest changed little between the 13th and 14th year (Table 4). The number of species and individuals with diameters greater than 1.0 cm decreased by 4 and 33/ha, respectively, but average diameter increased slightly (0.4 cm). Six species accounted for approximately 50% of the individuals at year 13 and 14. Five of these were common to both years: cetico, shimbillo (*Inga* sp.), huamansamana (*Jacaranda* copaia), yurac (*Croton*, sp.), ciprana, and moena (*Lauraceae*). In year 13, cedro caspi was an important species, but it was replaced by cordoncillo (*Piper* sp.) in year 14. Equations will be developed for the various species to predict biomass based on diameter.

Table 4. Changes in the population of trees with greater than 1-cm diameter in the 13- to 14-year-old secondary forest treatment, Yurimaguas, Peru.

Parameter	October 1988	⟶	October 1989
Avg. density (#/ha)	2433		2400
Mortality (#/ha)		250	
Recruitment (#/ha)		217	
Net change (#/ha)		-33	
# of species	37		33
Avg. dbh (cm)	10.6		11.0

Understory Biomass and Nutrient Stocks: Y-412E

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Accumulation of mass and nutrients in the understory or cover crops and the litter in the five nonfertilized systems was estimated in September 1988 and 1989. Data from 1988 are presented in Table 1. Understory or cover-crop biomass excludes trees with dbh > 2.5 cm. Litter includes recognizable litter plus a fragmented, partially decomposed fraction that had been floated in water and collected on screens to remove adhering soil particles.

Understory Biomass

The total accumulation of aboveground understory biomass was greatest in the multistrata treatment and least in the peach-palm treatment (Table 1). Differences among treatments were chiefly due to differences in litter accumulation since most treatments except the low-input contained 2.5 to 3.5 t/ha of living biomass. Litter accounted for around 50% of this biomass in the peach-palm and low-input treatments and for more than 80% in the others. The reason for the large litter accumulation in the multistrata treatment is unclear since the same ground cover (*Centrosema*) was planted at the same time in both the peach-palm and multistrata treatments. Higher rates of *Centrosema* turnover, additions of slowly decomposing inga litter, and lower temperatures due to greater shading may be causes of greater litter accumulation in the multistrata treatment.

Over 95% of living aboveground biomass accumulation in the low-input, multistrata, and peach-palm treatments

Table 1. Living biomass and litter (t/ha) in the nonfertilized treatments 36 months after burning, Yurimaguas, Peru.

	Understory		
Treatment	Live biomass	Litter	Total
	t/ha		
Shifting cultivation	2.63	10.45	13.08
Low-input	5.59	5.85	11.44
Multistrata	3.35	15.65	19.00
Peach palm	3.59	4.70	8.28
Forest fallow	2.44	14.00	16.45

came from the legume cover crop. In the forest-fallow treatment, lianas made up about 50% and of the total understory biomass, tree seedlings about 30%.

Understory Nutrient Stocks

Treatment-related patterns in N accumulation were generally similar to patterns of biomass accumulation (Table 2). With the exception of the low-input treatment, more than 50% of the N was found in the litter. In the low-input treatment, living biomass (primarily *Pueraria*) contributed more than 50% of aboveground N. Litter in the low-input was also N-enriched compared to the other treatments.

With the exception of the low-input treatment, litter also stored the majority of P. In the low-input treatment, however, living biomass accounted for approximately 65% of P stocks. Litter in this treatment also had comparatively high P concentrations. In the forest-fallow treatment, litter was comparatively P-depleted.

Total K stocks were greatest in the low-input and least in the forest-fallow treatments, mainly due to differences in K storage in the living biomass. In the low-input, multistrata, and peach-palm treatments, the majority of K was found in living biomass; in the shifting cultivation and forest-fallow treatments, the majority of K was in litter. Litter from the forest-fallow treatment, especially, was K-depleted.

Treatment-related patterns of total Ca and Mg accumulation were similar to patterns in understory biomass. The majority of Ca and Mg in all treatments was found in the litter, and concentrations of both elements in litter were similar among treatments.

These data refer only to a portion of the ecosystem's biomass and nutrient stocks; trees whose dbh exceeded 2.5 cm were excluded, as were belowground biomass and soils.

Table 2. Quantities (kg/ha) of nutrients contained in understory or ground-cover biomass (B) and litter (L) for the nonfertilized treatments in September 1988, three years after burning. Biomass estimates exclude trees in which dbh exceeds 2.5 cm.

Understory biomass and litter	System				
	Shifting cultivation	Low-input	Multi-strata	Peach palm	Forest fallow
	kg/ha				
Nitrogen					
Biomass	37	140	66	83	41
Litter	155	119	372	82	260
Total	192	259	438	165	301
Phosphorus					
Biomass	5.1	11.3	7.0	7.9	2.8
Litter	14.8	7.3	15.3	5.7	11.0
Total	19.9	17.6	22.3	13.6	13.7
Potassium					
Biomass	44	117	70	78	37
Litter	77	31	58	22	47
Total	121	148	128	100	84
Calcium					
Biomass	19	44	40	39	23
Litter	181	94	305	85	266
Total	200	137	345	124	289
Magnesium					
Biomass	4.2	13.8	8.3	7.7	4.4
Litter	34.0	14.1	39.0	9.4	43.3
Total	38.2	27.9	47.3	17.1	47.7

Organic Inputs: Y-412F

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Aboveground organic inputs, as litterfall and crop residues, have been measured in the various treatments according to the methodologies of the Tropical Soil Biology and Fertility Program. Litterfall is collected biweekly from seven litterfall traps (0.5 x 0.5m) in each of the forest-fallow, shifting-cultivation, and multistrata plots. Litter is dried and separated into leaves, branches, flowers, and small fragmented material. The components are analyzed for nutrients from composites made every three months. Crop residues are measured and analyzed for nutrient content at each harvest.

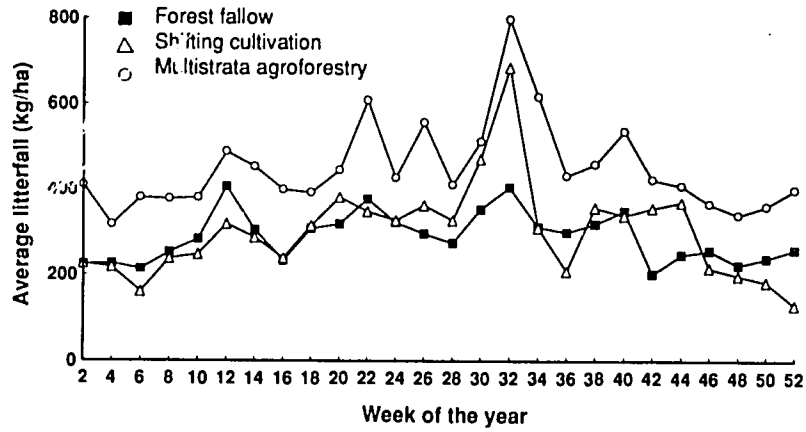

Figure 1. Litterfall pattern in three land-use systems, Yurimahuas, Peru. Values represent three-year averages.

Annual litterfall averages 7.5 t/ha for both the shifting-cultivation treatment (which is now a four-year-old forest fallow) and the multistrata treatment. This amount is significantly less than the 11.7 t/ha/yr in the forest-fallow control treatment (Table 1). Leaves account for 90% of the litterfall for the three treatments. The litterfall pattern is similar for all the treatments, showing a slight peak during the dry season (Figure 1).

Table 1. Aboveground inputs as litterfall or crop residues for the various management options.

	Litter or Residue	N
	t/ha/yr	kg/ha/yr
Shifting cultivation	7.4	120
High-input cropping	7.4	60
Low-input cropping§	4.8	60
Multistrata agroforestry§	7.4	184
Fallow control	11.7	211

§ Numbers do not include litterfall from cover crops.

The N concentration of the leaflitter in the multistrata system averages 2.45%, compared to 1.62%, and 1.87% for the shifting-cultivation and forest-fallow treatments, respectively (Table 2). These values correspond to 184, 211, and 120 kg N/ha/yr for the multistrata, forest-fallow, and shifting-cultivation treatments, respectively. Phosphorus concentrations were similar for the multistrata and shifting-cultivation system, but lower for the forest fallow. Concentrations of the basic cations were higher for the shifting cultivation system compared to the multistrata and forest-fallow treatments.

Aboveground inputs as crop residues in the high-input cultivation were similar to input via litterfall in the

Table 2. Nutrient concentration of aboveground inputs for different treatments.

	N	P	K	Ca	Mg
	%				
Shifting cultivation (leaves)	1.62	.14	.94	2.03	.31
High-input					
corn stalks	.91	.19	1.54	.21	.14
soybean residues	.51	.39	0.70	1.04	.22
Low-input					
rice straw	1.10	.18	2.08	.35	.22
cowpea residues	1.90	.26	1.91	1.28	.18
Multistrata agroforestry	2.42	.15	.70	1.67	.21
Forest fallow (leaves)	1.87	.10	.50	1.62	.21

multistrata treatments, whereas residues in the low-input treatment were significantly lower. Nitrogen inputs in residues were much lower than that added via litterfall because of the low N concentrations of the plant material. Calcium inputs with residues would also be lower than with litterfall.

Soil Fertility Dynamics: Y-412G

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High-input System

The high-input system is treated separately from the other systems because periodic lime and fertilizer applications cause clear differences in its soil chemical properties. Furthermore, the analysis of the high-input system concentrates on the downward movement of nutrients, since subsoil chemical constraints often limit root growth in Ultisols. The downward movement of nutrients to the subsoil would improve the rooting environment of this layer and would permit greater root proliferation. This, in turn, would increase the amounts of water and nutrients available to crop plants.

To detect changes in the extractable nutrient pool at the four depths (0 to 15, 15 to 30, 30 to 50, and 50 to 100 cm), we selected the soil nutrient levels three days after burning as reference points against which to compare measurements at 3, 6, 12, 18, and 24 months after burning. The differences between succeeding observations and the reference points are called delta values. Reference values are presented in Table 1.

Potassium Movement

Table 2 presents the delta K values for the two soil textures. For the loamy sand and for the sandy loam, the post-burn topsoil K level was 0.23 cmol/L (Table 1). Table 2 indicates that this surface K level could not be maintained by applications of K fertilizers to the loamy sand; delta K values at the surface after burning were negative. On the other hand, the surface K level of the sandy-loam surface horizon was increased by subsequent K fertilizer applications. The ability of the sandy-loam surface horizon to maintain its K levels for longer periods after K additions was related to its higher CEC and clay content, and hence its higher K-buffering capacity. This finding indicates that those managing K fertilizers in high-input systems must consider the way in which texture controls the residual effect of K additions.

As indicated in Table 2, K applications resulted in net positive and statistically significant increases in subsoil K levels for the two soils. This finding suggests that K moves downward. That pattern was much more pronounced for the loamy sand, which, as indicated above, exhibited a short residual effect from K additions in the surface horizon. Therefore, the short residual effect of K applications in Ultisols of loamy-sand surface texture was associated with very rapid leaching of the applied K.

Twenty-four months after the rotation was established, the residual effect of previous K additions had virtually

disappeared from both soils. The delta K values indicate that the 252 kg/ha of K applied during 24 months (Table 2) could not be detected. However, since the crop was close to physiological maturity, a significant portion of the applied K may have been contained in the crop biomass at a fairly high yield level (Table 1) and therefore could not be detected by soil analysis.

Calcium Movement

The effect of Ca additions, in the form of ash and as 2000 kg/ha of dolomitic lime, on subsoil Ca levels is presented in Table 3. Although some Ca leaching took place in the loamy sand, downward Ca movement was of a lesser magnitude than in the case of K. As with K, the accumulation of Ca at lower depths was of greater importance in the loamy sand. For the sandy loam, significant increases in Ca contents between 15 and 30 cm were detected only at 24 months after burning.

Magnesium Movement

Mg movement exceeded that of Ca for the two textures (Tables 3 and 4). Magnesium levels for the loamy sand increased significantly down to 100 cm at 12 months after burning, but in the sandy loam, Mg levels between 30 and 50 cm were increased only 18 months after burning. This difference suggests that texture also has an important effect on the leaching rate of this cation.

Table 1. Nutrient levels to 1-m depth for the two different-textured soils in the high-input system three days after burning, Yurimaguas, Peru. These values served as reference points against which values from later dates were compared.

	Loamy sand					Sandy loam				
Depth	P	K	Ca	Mg	Al	P	K	Ca	Mg	Al
cm	mg/L	cmol/L				mg/L	cmol/L			
0–15	10.4	.23	.84	.14	1.0	12.5	.23	.61	.22	3.8
15–30	3.5	.06	.54	.06	2.1	3.1	.06	.41	.08	4.9
30–50	4.5	.04	.48	.07	2.5	1.9	.04	.45	.09	5.6
50–100	6.0	.06	.24	.05	2.3	1.8	.06	.22	.07	6.4

Table 2. Delta K values for the two soils 100-cm depth during the first 24 months of the high-input rotation, Yurimaguas, Peru. Delta K is the difference between the actual value and original value (see Table 1).

	Delta K (cmol/L)					
	Months after burning					
	-0.25	3	6	12	18	24
Depth (cm)			Loamy sand			
0–15	-0.14	-0.03	-0.05	-0.09	-0.08	-0.10
15–30	-0.02	0.13*	0.13*	0.04*	0.02*	0.00
30–50	0.00	0.08*	0.09*	0.04*	0.04*	0.01
50–100	0.00	0.00	0.02	0.02*	0.02	0.00
			Sandy loam			
0–15	-0.14	0.18*	0.10*	0.03	-0.05	-0.02
15–30	-0.02	0.16*	0.09*	0.12	0.07	0.03
30–50	-0.01	0.08	0.06	0.07	0.05	0.03
50–100	0.00	0.00	0.00	0.00	0.04*	0.01

* = Statistically significant $P < 0.05$ charge.

Changes in Soil Exchangeable Acidity

Accumulation of Ca and Mg at lower depths should result from the movement of those cations with their respective anions. Thus, accumulation of Ca and Mg carbonates at lower depths should decrease exchangeable acidity. Table 5 indicates that exchangeable acidity significantly decreased at lower depths for the two soil textures. This change was consistent throughout the loamy-sand profile; significant decreases of exchangeable acidity took place down to 50 cm from the sixth to the 24th month. In the loamy sand, the pattern was more erratic; exchangeable acidity decreased significantly down to 100 cm only at 12 months after establishment.

Table 3. Delta Ca values for the two soils to 100-cm depth during the first 24 months of the high-input rotation, Yurimaguas, Peru.

	Delta Ca (cmol/L)					
	Months after burning					
	-0.25	3	6	12	18	24
Depth (cm)			Loamy sand			
0–15	0.01	-0.08	0.76*	0.63*	0.72*	0.90*
15–30	-0.02	-0.21	0.18	0.25	0.33*	0.45*
30–50	-0.08	-0.17	-0.06	-0.15	0.20	-0.04
50–100	0.00	0.00	0.01	0.02	0.20*	-0.09
			Sandy loam			
0–15	-0.13	0.52*	0.80*	1.45*	1.50*	1.62*
15–30	-0.08	0.04	-0.08	0.22	0.62	0.18*
30–50	-0.24	-0.16	-0.21	-0.16	-0.05	-0.28
50–100	0.00	0.00	-0.07	-0.02	0.09	-0.13

* = Statistically significant $p < 0.05$ charge.

Table 4. Delta Mg values for the two soils to 100-cm depth during the first 24 months of the high-input rotation, Yurimaguas, Peru.

	Delta Mg (cmol/L)					
	Months after burning					
	-0.25	3	6	12	18	24
Depth (cm)			Loamy sand			
0–15	-0.01	0.06	0.33*	0.37*	0.35*	0.83*
15–30	-0.01	0.03*	0.14*	0.21*	0.47*	0.32*
30–50	-0.03	0.02	0.02	0.03	0.20*	0.11*
50–100	0.00	0.00	-0.01	0.03*	0.11*	0.01
			Sandy loam			
0–15	-0.70	0.31*	0.34*	0.62*	0.64*	1.23*
15–30	-0.02	0.10	0.03	0.20*	0.43	0.23*
30–50	-0.04	-0.03	-0.01	0.03	0.09*	0.01
50–100	0.00	0.00	-0.01	0.00	0.05	-0.02

* = Statistically significant $p < 0.05$ charge.

Table 5. Delta Ac changes in KCl-extractable acidity values for the two soils down to 100 cm during the first 24 months of the high-input rotation, Yurimaguas, Peru.

	Delta Ac (cmol/L)					
	Months after burning					
	-0.25	3	6	12	18	24
Depth (cm)			Loamy sand			
0–15	0.34	0.32	-0.82*	-0.40	-0.86*	-0.94*
15–30	-0.01	-0.06	-0.83*	-1.24*	-1.73*	-1.05*
30–50	-0.20	1.34	-0.59*	-0.83*	-1.00*	-0.71*
50–100	0.00	0.00	-0.20	-0.59*	-0.32	0.07
			Sandy loam			
0–15	0.54	-0.92*	-1.32*	-2.68*	-2.64*	-3.14*
15–30	-0.12	0.52	-0.32	-2.08*	-1.24*	0.03
30–50	0.04	-3.78*	-0.74	-2.12*	-0.70	0.02
50–100	0.00	0.00	0.26	-1.62*	-1.00	-0.02

* = Statistically significant $p < 0.05$ charge.

In order to better quantify the relationship between changes in soil acidity and changes in Ca and Mg contents at each depth, we developed a series of linear equations. The regressions indicate that increases in Ca contents at lower depths and decreases in subsoil exchangeable acidity were significantly related, but that increases in Mg could not explain the observed decreases in exchangeable acidity. The relationships for the loamy sand are as follows:

Depth cm	Regression equation	R2	Sig
0–15	Delta Ac = 0.193–1.193 Delta Ca	0.602	0.01
15–30	Delta Ac = 0.422–0.152 Delta Ca	0.595	0.01
30–50	Delta Ac = 0.442–2.171 Delta Ca	0 280	0.01
50–100	No variables in the model are significant.		

For the sandy loam, there was no significant relationship between subsoil exchangeable acidity and Ca or Mg levels, perhaps because Ca and Mg leaching on this soil was reduced. However, a relationship was found between Delta Ca and Delta Ac at the surface:

$$\text{Delta Ac} = 0.14 - 1.46 \text{ Delta Ca} \quad r^2 = 0.913 \quad (a = 0.001)$$

Phosphorus Movement

Phosphorus leaching in acid soils has usually been considered to have only academic interest. However, the data in Table 6 indicate that P leaching in sandy acid soils may be of practical importance.

Statistically significant increases in soil P levels down to 100 cm were observed for the loamy sand after 12 months and after a total P application (ash plus fertilizers) of approximately 138 kg/ha. Phosphorus leaching in the sandy loam, however, was less. The fact that P leaching appears less in the soil with higher clay content suggests that fixation sites must be saturated before downward movement of P becomes important. Downward movement of P in organic forms not susceptible to fixation may also be a possibility. These soils, although acid, have a low P-fixation capacity and low P-buffering power, both of which make the size of the labile pool sensitive to P additions.

Low-input and Agroforestry Systems

Levels of exchangeable Al, K, Ca, Mg, and available (Olsen) P in the 0- to 15-cm and 15- to 30-cm horizons were compared among systems receiving little or no fertilizers (i.e. the high-input system was not included in these comparisons). At each date, Duncan-Waller LSD's were used to compare treatment means for each soil texture. Furthermore, orthogonal contrasts were used to test the following hypotheses: 1) the soil under the old forest fallows would be impoverished compared to the other treatments because of greater nutrient extraction and immobilization in the forest biomass; 2) the soil nutrient levels would be lower and exchangeable Al levels would be higher in the low-input cropping systems than in the other three systems (shifting agriculture, multistrata, and peach-palm plantation) due to greater nutrient removal in crop harvests; 3) the soil nutrient levels would be higher in the shifting-agriculture system, compared to the multistrata and peach-palm systems, because fewer nutrients are removed in crop harvests; and 4) relatively minor differences in soil nutrient levels would exist between the

Table 6. Delta P values for the two soils down to 100 cm during the first 24 months of the high-input rotation, Yurimaguas, Peru.

	Delta P (cmol/L)					
	Months after burning					
	-0.25	3	6	12	18	24
Depth (cm)			Loamy sand			
0–15	-0.23	2.53	0.84	11.16*	11.92*	15.84*
15–30	1.52	2.69*	3.74*	7.00*	10.36*	0.34*
30–50	1.66	2.55	-1.78	2.50*	5.17*	3.38*
50–100	0.00	0.00	-0.20	3.67*	2.76*	4.71*
			Sandy loam			
0–15	-4.90	-0.02	-1.80	5.06	8.52	9.84*
15–30	0.96	0.26	-1.28	1.08	4.54*	1.72*
30–50	-1.32	0.40	-0.96	1.86	3.38*	1.32
50–100	0.00	0.00	1.20	1.34*	1.80*	2.40

* = Statistically significant p <0.05 charge

multistrata system and the peach-palm plantation because of similar rates of nutrient removal in crop and tree production.

The contrasts are shown in Table 7. The topsoil under the 13-year-old forest fallow is less fertile than under any of the other systems in terms of lower base contents and higher Al content. This difference probably shows the effect of ash in increasing soil fertility, an effect which was still significant after 36 months in the topsoil. There were no consistently significant differences in the contrasts between the low-input, shifting-agriculture, peach-palm, or multistrata systems—a similarity which suggests similar soil chemical dynamics.

Overall Trends

At most dates, available P in the soil's upper 15 cm was approximately 25 to 50% greater in the loamy sand than in the sandy loam; K, Mg, and Al levels were approximately 30 to 50% greater; and Ca levels were only slightly greater. Nevertheless, absolute changes in the level of each nutrient over time in the different soils were similar.

In the 15- to 30-cm horizon, nutrient cations and available P levels were less than 50% of those measured in the top 15 cm, and exchangeable Al in the lower horizon was more than double that in the upper layer. As in the upper layer, available P was greater in the loamy sand than in the sandy loam, while the reverse was observed for K, Mg, Ca, and Al.

Greater soil moisture retention and nutrient levels were probably responsible for the greater crop yields and tree growth on the sandy loam than on the loamy sand. Reductions in crop yields after 12 months in the multistrata system and after 18 months in the peach-palm plantation were probably due to K limitation and the shade produced by the associated trees.

Potassium

In the soil's upper 15 cm, K approximately doubled within three months after burning, decreased to near preburn levels by 12 months, and was maintained around these levels to 36 months (Table 8). In the forest-fallow treatment, K levels fluctuated with time. They were lower than in the other treatments up to 12 months after burning, but intermediate thereafter. At 24 and 36 months, K levels differed among treatments, but there were no clear patterns in these differences.

In the 15- to 30-cm horizon, K levels more than tripled as a result of the burn, but declined to preburn levels by 24 months (Table 9). Potassium levels in the forest-fallow treatment fluctuated with time and were significantly lower than in the other treatments at three and six months; after six months, there were few differences among treatments.

Calcium and Magnesium

In the soil's upper 15 cm, patterns of change in Ca and Mg over time were qualitatively similar (Table 8). Levels of both elements peaked within three to six months after burning and declined to near preburn levels within 24 to 36 months. Ca and Mg levels in the forest-fallow treatment tended to decline with time and were lower than in the other treatments. In the shifting-cultivation, low-input, and multistrata treatments, both Ca and Mg increased between 12 and 18 months. We are unable to determine

Table 7. Pairwise contrasts of soil nutrient levels at two depths among management systems, Yurimaguas, Peru. The < or > signs refer to the comparison of the first treatment of the pair with the other. The numbers following the signs are the months after burning in which a significant difference (p < .05) was present.

	Contrast[§]			
Nutrient	SF vs LI,SA,MS,PP	LI vs SA,MS,PP	SA vs MS,PP	MS vs PP
	0- to 15-cm soil depth			
Al	>3,6,18,24,36	>3		
K	<3,6,12,36		<3, >36	<6,24
Ca	<6,12,18,24,36			
Mg	<3,6,12,18,24,36			
	15- to 30-cm soil depth			
Al	>3,36	>3,18		
K	<3,6,24			
Ca	<3,18,36			
Mg	<3,18,36			>3

[§] SF= old secondary forest; LI= low-input cropping; SA= shifting agriculture; MS= multistrata agroforestry; PP= peach-palm plantation.

the cause of this peak, but we have seen it before. One possibility is the release of bases from tree stumps and large roots.

In the 15- to 30-cm horizon, the peak due to burning was observed immediately for Ca and three months afterwards for Mg (Table 9). Values of both elements declined between three and 12 months, increased between 12 to 18 months, decreased between 18 and 24 months, and increased between 24 and 36 months. In the forest-fallow treatment, Ca levels tended to decrease during the first 25 months, but Mg levels were approximately constant over time. With the exception of the 36-month sampling, there were few significant differences among treatments in Ca or Mg levels at any date. At 36 months, Ca and Mg levels tended to be higher in the shifting-cultivar and peach-palm treatments and lowest in the forest-fallow treatment.

Phosphorus

In the soil's upper 15 cm, levels of modified Olsen available P fluctuated between 8 and 11 mg/L at most sampling dates (Table 8). At 18 months, however, P levels tended to be higher than at other sampling dates, but at 36 months, levels were lower. There were no significant differences among treatments at any date.

Available P levels in the 15- to 30-cm horizon tended to fluctuate between 3 and 6 mg/L (Table 9). Once again, the highest levels of P (6 to 8 mg/L) were observed at 18 months. There were no significant differences among treatments at any sampling date.

Exchangeable Acidity

In the soil's upper 15 cm, exchangeable acidity declined within 12 to 18 months following burning, and except for the multistrata and forest-fallow treatments, acidity levels at 36 months were still well under preburn levels (Table 8). In the multistrata treatment, acidity at 36 months was similar to the preburn level; in the forest-fallow treatment, acidity levels generally tended to increase with time. At the majority of sampling dates, treatments differed significantly in acidity levels: acidity was significantly greater in the forest-fallow treatment than in the others.

In the 15- to 30-cm horizon, temporal patterns in exchangeable acidity levels were similar to those in the upper soil layer with the exception that acidity levels approached or exceeded preburn levels at 24 months before dropping to below preburn levels once again at 36 months (Table 9). There were few treatment-related differences at any sampling date: only at 3 and 36 months were acidity levels significantly greater in the forest-fallow treatment than in the others.

Conclusions

The following conclusions are clear:

1) More treatment-related differences were observed in the soil's upper 15 cm than at 15 to 30 cm, probably due to greater nutrient fluxes (plant nutrient uptake, leaching, mineralization) in the upper layer.

2) Apart from the forest-fallow treatment, which had lower soil nutrient and higher acidity levels than the other treatments at most sampling dates (Tables 7 to 9), there were few differences among the other treatments. This

Table 8. Changes* in soil (0 to 15 cm) chemical properties with time in the nonfertilized management systems.

Months after burning	System					
	Shifting cultiv.	Low input	Multi-strata	Peach palm	Forest fallow	
			Exch. Al (cmol/L)			
-1	1.57 b	2.47 a	1.16 b	1.36 b	1.87 ab	
0	1.56	1.84	1.45	1.39	—	ns
3	1.09 b	1.79 ab	0.94 b	0.89 b	2.25 a	
6	0.76 b	1.35 ab	0.75 b	0.68 b	2.07 a	
12	1.11	1.11	0.61	0.45	0.69	ns
18	0.55 b	1.35 ab	0.53 b	0.69 ab	1.97 a	
24	0.92 b	1.61 ab	0.97 b	0.97 b	2.19 a	
36	0.64 b	1.45 ab	1.15 ab	0.94 ab	2.33 a	
			Exch. K (cmol/L)			
-1	0.11	0.09	0.10	0.10	0.09	ns
0	0.20	0.19	0.17	0.16	—	ns
3	0.23 a	0.29 a	0.21 ab	0.26 a	0.11 b	
6	0.18 b	0.19 ab	0.17 b	0.21 a	0.11 c	
12	0.07 b	0.09 a	0.08 ab	0.11 a	0.07 b	
18	0 10	0.10	0.10	0.12	0.10	ns
24	0.09 ab	0.09 ab	0.07 b	0.10 a	0.08 ab	
36	0.12 a	0.08 b	0.08 b	0.08 b	0.11 ab	
			Exch. Ca (cmol/L)			
-1	1.01	0.86	0.92	0.93	1.01	ns
0	0.77	1.12	0.87	0.83	—	ns
3	0.77	0.92	1.23	1.09	0.63	ns
6	1.19 ab	1.10 ab	1.09 ab	1.27 a	0.72 b	
12	1.14 ab	1.01 ab	0.97 ab	1.35 a	0.66 b	
18	1.37 a	1.10 ab	1.32 a	1.20 a	0.68 b	
24	1.11 a	0.88 ab	0.95 a	1.08 a	0.50 b	
36	0.89 a	0.92 a	0.68 a	1.02 a	0.38 b	
			Exch. Mg (cmol/L)			
-1	0.18	0.17	0.17	0.15	0.17	ns
0	0.15	0.22	0.18	0.16	—	ns
3	0.32 ab	0.30 ab	0.34 a	0.31 ab	0.15 b	
6	0.28 a	0.27 a	0.26 a	0.25 a	0.14 b	
12	0.25 a	0.22 ab	0.21 ab	0.23 a	0.15 b	ns
18	0.30 a	0.25 ab	0.28 a	0.24 ab	0.20 b	
24	0.21	0.20	0.21	0.20	0.12	ns
36	0.23 a	0.20 ab	0.19 a	0.19 a	0.13 b	
			Olsen P (mg/L)			
-1	9.6	9.0	9.9	10.7	10.7	ns
0	10.5	10.9	8.9	9.9	—	ns
3	12.1	8.6	11.0	11.6	6.5	ns
6	8.1	7.3	7.4	8.8	5.3	ns
12	10.5	8.1	9.1	10.7	7.0	ns
18	10.7	13.1	11.0	13.4	14.1	ns
24	8.4	9.1	7.5	9.0	7.8	ns
36	6.6	6.3	5.1	7.3	8.4	ns

* For a given date, treatments followed by the same letter are not significantly different (p = 0.05), based on the Duncan-Waller test.
SF = secondary forest.

Table 9. Changes* in soil (15 to 30 cm) chemical properties with time in the nonfertilized management systems.

Months after burning	System: Shifting cultiv.	Low input	Multi-strata	Peach palm	Forest fallow	
			Exch. Al (cmol/L)			
-1	2.64 bc	3.73 a	2.37 c	2.73 bc	3.31 ab	ns
0	2.62	3.31	2.66	2.65	—	ns
3	2.49 ab	3.30 ab	2.11 b	2.18 b	3.56 a	
6	2.35	3.00	2.17	2.21	3.19	ns
12	1.75	2.19	1.68	1.61	2.23	ns
18	2.68 ab	3.39 a	1.90 b	2.73 ab	2.85 ab	
24	3.04	3.67	2.65	2.83	4.11	ns
36	2.21	3.11	2.30	2.09	3.68	ns
			Exch. K (cmol/L)			
-1	0.04	0.04	0.04	0.04	0.05	ns
0	0.04	0.06	0.05	0.06	—	ns
3	0.16 a	0.14 a	0.14 ab	0.17 a	0.06 b	
6	0.11 a	0.12 a	0.11 a	0.14 a	0.05 b	
12	0.08	0.08	0.12	0.09	0.04	ns
18	0.08	0.08	0.07	0.07	0.10	ns
24	0.04 ab	0.05 ab	0.05 ab	0.06 a	0.03 b	
36	0.06	0.07	0.07	0.07	0.07	ns
			Exch. Ca (cmol/L)			
-1	0.50	0.48	0.54	0.51	0.54	ns
0	0.52	0.55	0.60	0.60	—	ns
3	0.41 ab	0.37 ab	0.51 a	0.47 a	0.27 b	
6	0.35	0.35	0.36	0.37	0.36	ns
12	0.29	0.31	0.33	0.44	0.31	ns
18	0.48	0.50	0.50	0.37	0.31	ns
24	0.24	0.24	0.21	0.24	0.20	ns
36	0.40 a	0.38 a	0.33 ab	0.43 a	0.20 b	
			Exch. Mg (cmol/L)			
-1	0.06	0.07	0.08	0.06	0.07	ns
0	0.06	0.09	0.07	0.07	—	ns
3	0.10 ab	0.10 ab	0.14 a	0.10 ab	0.07 b	
6	0.06	0.06	0.06	0.05	0.04	ns
12	0.07	0.08	0.08	0.07	0.07	ns
18	0.14 a	0.14 a	0.15 a	0.11 ab	0.07 b	
24	0.07	0.07	0.07	0.08	0.05	ns
36	0.10 a	0.08 ab	0.09 ab	0.10 a	0.05 b	
			Avail. P (mg/L)			
-1	6.4	5.0	5.5	6.2	5.0	ns
0	2.8	3.3	4.2	4.2	—	ns
3	5.8	4.6	5.8	6.4	3.7	ns
6	3.3	3.0	4.0	4.0	3.5	ns
12	4.5	4.2	5.4	5.7	4.0	ns
18	6.1	7.4	8.4	7.6	8.4	ns
24	4.7	4.2	4.2	5.8	4.5	ns
36	5.0	5.0	5.1	6.7	4.9	ns

* For a given date, treatments followed by the same letter are not significantly different (P = 0.05), based on the Duncan-Waller test.

uniformity was probably due to similar amounts of nutrient removal in harvested products, biomass immobilization in the treatments, and the relatively short period in which the soil had been exposed to these effects. In the forest-fallow treatment, lower soil nutrient levels were likely the result of greater nutrient immobilization in vegetation. These treatment differences were more accentuated on the loamy sand than on the sandy loam since the greater CEC and higher clay content of the sandy loam tended to buffer soil nutrient levels.

3) Available P and K appeared to be well-buffered since P levels changed little after burning and since there was little change in K levels after 12 months.

4) The effect of the burn was delayed. Peaks in nutrient levels or low acidity levels were usually observed three to six months after burning; furthermore, the residual effect appeared to last approximately 24 months. In the 15- to 30-cm soil layer, the effect of the burn was less pronounced, and the residual effect appeared to be shorter.

5) Peaks in nutrients and acidity in both soil depths at 18 months (in the midst of the wet season) and the observation of higher peaks on the loamy sand may have been caused by rapid nutrient release from organic material; alternatively, the peaks may be the result of our analytical method.

Soil Carbon and Nitrogen Dynamics: Y-412H

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Total soil C and N, microbial N, and mineralizable N are monitored yearly. The determinations are made on three subsamples from each plot at two depths: 0 to 15 cm and 15 to 30 cm. Total C is determined by the Nelson-and-Sommer method and total N by the micro-Kjeldahl methods. Mineralizable N is determined from a 10-day laboratory incubation. Subsamples are analyzed for K_2SO_4 extractable ammonium and nitrate (inorganic nitrogen) at time zero. Soils are incubated at room temperature (26° C) for 10 days and then extracted for exchangeable ammo-

Table 1. Total soil carbon and nitrogen in the topsoil (0 to 15 cm) three years after the treatment was established.

	Block		
System	1 Loamy sand	2 Sandy loam	3 Loamy sand
	% C		
Shifting cultivation	1.16	0.95	.66
High-input cropping	.96	1.12	.73
Low-input cropping	1.04	1.24	1.12
Multistrata agroforestry	1.17	1.09	0.71
Peach-palm plantation	1.21	0.82	1.13
Forest fallow	1.06	1.18	0.86
	% N		
Shifting cultivation	.07	.08	.06
High-input cropping	.06	.09	.07
Low-input cropping	.07	.09	.07
Multistrata agroforestry	.08	.10	.07
Peach-palm plantation	.08	.07	.08
Forest fallow	.08	.10	.07

nium and nitrate. The difference in exchangeable inorganic nitrogen during the 10-day period is considered net N mineralization. The laboratory incubation is performed on soils at the moisture content at which they were collected. Microbial N is determined by the fumigation direct-extraction method, and the K_2SO_4 extract is analyzed for ninhydrin-reactive N at time zero and after a five-day fumigation.

Three years after the treatments were established, there were no significant differences in total soil C or N among treatments, including the forest-fallow control treatment (Table 1). This implies that there was no significant change in soil C or N with time in any of the treatments, a finding confirmed by the lack of significant difference in soil C and N between any of the sampling dates (data not shown). There were differences in C and N contents among blocks. The differences in topsoil C were not related to soil texture, but N was highest in the block with the highest clay content. The similarity in soil C with the different management options is surprising given the different amounts of aboveground and belowground organic inputs, fertility treatments, and tillage treatments. Other studies in the humid tropics have shown large differences between forest and managed sites after only a few months. In this experiment, we are comparing treatments to a secondary forest, which could explain the lack of response to management.

Nitrogen mineralization was consistently highest in the forest-fallow control treatment compared to the other treatments (Table 2). There were no further trends among treatments from year to year, none being consistently high or low. Measurements of nitrogen mineralization are time-consuming and often give extremely variable results, especially in the humid tropics. Modelling mineralization according to temperature and soil-moisture trends may provide an alternative method for predicting nitrogen availability throughout the year.

Soil microbial N, expressed as extractable ninhydrin-reactive N, also was generally higher in the forest-fallow treatment and tended to be lowest in the high-input cropping system (Table 3). Microbial N was higher in the treatment with a sandy-loam texture as compared to the treatments with loamy-sand texture. There was no correlation between N mineralization and microbial N for any of the three years. This lack of correlation was unexpected and brings into question what the measurements represent in terms of soil microbial biomass. A measurement for microbial turnover rates would perhaps be more meaningful for nitrogen availability.

Table 2. Mineralizable nitrogen* in the topsoil (0 to 15 cm) for three years after the treatment was established.

System	1987*	1988	1989
	——— g N/g soil/10 days ———		
Shifting cultivation	1.26	—	5.32 bc
High-input cropping	3.90 a	4.99 a	3.34 d
Low-input cropping	4.01 a	4.15 ab	5.60 bc
Multistrata agroforestry	3.71 a	4.14 ab	4.93 c
Peach-palm plantation	2.66 ab	2.59 b	5.94 b
Forest fallow	4.10 a	6.08 a	7.05 a

* Values within a column followed by the same letter are not significantly different

Table 3. Microbial N in the topsoil (10 to 15 cm) expressed as extractable ninhydrin-reactive N in the different treatments.

System	1987	1988	1989
	——— g N/g soil ———		
Shifting cultivation	22.5 b	4.4 bc	9.1 a
High-input cropping	15.6 d	2.9 d	9.2 a
Low-input cropping	19.2 c	5.2 b	8.0 a
Multistrata agroforestry	20.0 bc	4.6 bc	17.4 a
Peach-palm plantation	16.2 d	4.0 d	11.1 a
Forest fallow	33.6 a	6.4 a	10.7 a

* Values within a column followed by the same letter are not significantly different.

Agroforestry: NC-4

Shifting cultivation is no longer a sustainable farming system in many areas of the humid tropics because increased population pressure and land-tenure systems have decreased fallow periods. Often an insufficient infrastructure or inaccessible markets preclude continuous cultivation as an economically viable alternative. Under the traditional system, land is in production one year for every five years in unproductive fallow. The low-input system provides two to three years of profitable cropping, but then productivity declines due to decreasing fertility and increasing weed problems. At this point, the system has to be abandoned. Agroforestry offers a variety of land-use options ranging in degrees of management and inputs.

Agroforestry research in Yurimaguas started in 1983 and has focused on three areas of research: food-tree systems, alley-cropping, and improved fallows. Current problems in agroforestry research relate to the sustainability of these systems.

Food-tree systems include combinations of trees or woody perennials that produce edible fruit in combination with ground-cover plants. Relatively unknown native food trees with market potential have been collected and screened for acid tolerance in Yurimaguas and Manaus. The principal species include peach palm (*Bactris gasepaes*), guaraná (*Paulina cupana*), arazá (*Eugenia stipitata*), carambola (*Averrhoa carambola*), and achiote (*Bixa orellana*). Various aspects of nursery management and fertilization have been investigated, as has the management of peach palm in acid soils. A technological package is being developed for extrapolation.

Tree-crop systems need research on the role of mycorrhizae in nursery management and transplanting survival, the selection of appropriate cover crops, and the importance of fertilization during the establishment and production phase of food-tree crops. Work is just beginning on species other than peach palm and guaraná. The research design for that work will be the same one used for investigating the establishment and management of the peach palm.

In the subhumid tropics, alley-cropping is a successful agroforestry system for soils with a high base status. Thus far, we have had limited success with alley-cropping in sandy Ultisols. We need to investigate nutrient budgets and related biological processes (decomposition and mineralization as related to mulch quality, N-fixation, mycorrhizal associations, root dynamics, and tree-crop competition) in order to understand the nutrient dynamics and related crop yields.

Several alley-cropping studies monitor mulch quality, nutrient cycling, root dynamics, weed biomass, and physical properties of the soils. In addition, tree selections and management trials continue to look for trees appropriate to the alley-cropping systems used in the region's various soils. Selection trials for leguminous trees that tolerate acid soils have thus far concentrated on the genera *Inga* and *Gliricidia*.

Research on improved fallows is important because the fallow period has become shortened in many areas of the tropics, often reaching a point at which there is insufficient time for the site to regenerate. This regeneration appears to involve soil fertility and weed control. Efforts must be made to manage and improve the fallows. These efforts should seek to reduce the size and vigor of the weeds' seed pool and to enrich the soil with nitrogen by including nitrogen-fixing species in the fallow vegetation.

Farmers must see some tangible reason for adopting new technologies. If species used in the improved fallows provide some economic product during or at the end of the fallow phase, farmers may be more inclined to plant managed fallows.

Summary of Results: Y-400B

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Peach-palm Research

Fertilization and liming trials have been conducted for the vegetative stage of peach-palm fruit production. These trials indicate the need for N and P fertilization during the establishment phase. Using cover crops during this phase may help supply the necessary N. An experiment was established in 1987 for testing various cover crops (mucuna, centrosema, desmodium, and inga) and establishment practices (low-input cropping and fertilization). Early results indicate that a year of low-input intercropping was not harmful to the establishment of the palm, but immediate establishment of the cover crop retarded palm growth. Mucuna was a particularly competitive cover crop. Mucuna and centrosema planted following a year of cropping appear to be the best choices. The rest of this experiment will focus on managing various types of cover crops. In some treatments, the cover crop will be cut periodically, while in others, a continuous cover will be kept. Nitrogen availability patterns will be monitored in all treatments.

A 10-year-old plantation is being used to test the effects of K fertilization on fruit production. The response to K has varied: 80 kg/ha was an optimum rate one year, but there was little response the other two years.

Validation trials for peach-palm fruit and heart-of-palm production have been established on six farms.

Alley-cropping Research

Selection trials for leguminous trees tolerant to acid soils are concentrating on the genera *Inga*, *Cassia*, and *Gliricidia*. The inga project began in 1988 with a search and collection of local species. To date, 303 trees from 14 provenances have been sampled. The samples have been sent off to several international herbaria for identification. In late 1990 and 1991, field trials will begin to test 10 to 15 of these inga species for biomass production, tree architecture, mulch characteristics, and tree-management practices. *Gliricidia sepium* provenance trials began in 1988. Of 15 original varieties, only two or three have been shown to grow well in the Yurimaguas region. Provenance 14/84 from Guatemala produced significantly more biomass the first year. This trial will continue in order to determine sustainability in biomass production. In addition, provenance 14/84 will be tested at other sites via the RISTROP network.

An alley-cropping trial on alluvial soils, begun in 1985, has been successful for corn and cowpea production. Rice, however, did not perform well in the alley-cropped plots.

Several farmers indicated interest in alley-cropping because of the effective weed control provided by inga mulch. A field day and subsequent farmer selection is planned to begin on-farm trials of alley-cropping with *Inga edulis* on alluvial soils.

Alley-cropping has been tested unsuccessfully in upland acid soils, where nutrient deficiencies showed up after the first crop. In 1987, two new alley-cropping trials were established and are giving contradictory results.

One of the trials on a sandy loam soil has shown continued high yields of rice and cowpea—even after eight crops. There is no difference in yields for the various mulch treatments (*Inga edulis*, *Gliricidia sepium*, and *Cassia reticulata*) or P fertilization. The other study on a loamy sand with *Inga edulis* as the hedgerow species shows low and declining yields without fertilization. Yields are maintained with fertilization, but competition with the hedgerows reduces yields close to the trees. Pruning hedgerow roots increases rice yields. The differences obtained in the two studies may be related to soil texture, the sandy loam soil having a higher nutrient-storing and buffering capacity than the loamy sand.

Managed Fallows

Planted leguminous fallows that included a tree component stored more nutrients than the herbaceous fallows and in some cases even more nutrients than the natural fallow after 4.5 years. Rice yields following clearing and burning of the natural and managed fallows were higher in the managed *Desmodium ovalifolium* and *Inga edulis* treatments compared to the others. Nitrogen mineralization was initially higher in plots with trees but did not correlate to crop yields overall. Weeds were controlled better and faster by the herbaceous, ground-cover types of managed fallows.

After three rice crops, the plots have been planted to fallow again. For the second fallow phase, a combination of tree (*Inga edulis*) and cover crops (*Centrosema macrocarpum* or *Desmodium ovalifolium*) has been planted. The fallows will be allowed to grow for two or three more years, at which time they will be cut, burned, and cropped to upland rice. Rice yields and the number of crops will be compared for the two managed fallow treatments and a traditional shifting-cultivation system.

The search for economically valuable tree species that can be used in managed fallows has just begun. Several local species—including *Inga edulis*, *Colubrina glandulosa*, and *Calicophyllum sprucianum*—have been identified for their rapid growth, their resistance to weeds, and their usefulness as fuel wood. Demonstration plots and management trails using these and other local species are planned for 1991–1992.

Allometric Relationship to Predict Heart-of-Palm Yields: Y-439

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Objectives

Basic information is needed regarding biomass partitioning in both adult and juvenile peach-palm plants. With juvenile plants used for heart-of-palm, such information can be used to develop more efficient harvesting and processing procedures. The objectives of this study were to describe biomass allocation in juvenile palms and to relate this allocation to easily measurable plant parameters.

Procedures

In the first study, 40 small palms less than 6.3 m tall were harvested at ground level in order to establish relationships between heart-of-palm fresh weight (HPFW) and length (HPL) and external morphological characteristics. Diameters were measured at 0.10, 0.65, and 1.30 m above the soil surface and at the origin of the oldest leaf. The aboveground height of the oldest and youngest leaves (excluding the spikelet) were also measured, and the leaves were counted.

The middle section of the plant containing the heart-of-palm was cut out, and overlying layers of tissue were removed. The length and fresh weight of the heart-of-palm were measured, as were the diameters at the base and tip.

In the second study, 30 small palms were harvested to establish relationships between heart-of-palm quantity and various parameters of agro-industrial importance such as transport weight. Diameters were measured at the points where the three newest leaves originated and at the top of the arch of the newest unfolded leaf, and the leaves were counted. The section of the plant containing the heart-of-palm was cut out, leaving three leaf layers on the outside for protection during transport.

At a heart-of-palm factory in Iquitos, the palm segments were weighed, their lengths measured, and the three outer leaf layers removed and weighed. Other unmerchantable parts (the ends, which have a harder or more fibrous texture) were also removed, measured, and weighed, as a result of which the heart-of-palm was ready for canning. The diameters at the butt and tip were measured, and the heart-of-palm was cut to fit the can. The resulting heart-of-palm pieces were counted and weighed.

Relationships among variables were examined. Correlation procedures and regression models were used to describe these relationships.

Results

In the first study, mean heart-of-palm fresh weight (HPFW) was 242 g (maximum 474 g, minimum 77 g), and mean heart-of-palm length (HPL) was 48.3 cm (maximum 62 cm, minimum 36 cm) (Table 1). Variation in HPFW was large (cv = 48%), but there was less variation in HPL (cv = 15%). HPFW and HPL were significantly correlated with a number of external characteristics of the tree (Table 2).

Table 1. Descriptive statistics for the peach palms harvested for heart-of-palm at Yurimaguas, Peru.

	Study a	Study b
Variable	Mean	Mean
Heart-of-palm fresh weight (HPFW) (g)	242.0	184.1
Heart-of-palm length (HPL)	48.33	5.5
Height to origin of the 3 newest leaves (H3) (m)	2.63	1.66
Stem diameter at origin of 3 newest leaves (D3) (cm)	4.1	3.9
Stem diameter at the origin of the 2 oldest leaves (D2) (cm)	13.2	
Stem diameter at the neck (DC) (cm)	13.8	5.1
Distance between H3 and the neck (DHN) (cm)	1.99	
Number of live leaves (L)	7.7	6.3

Table 2. Correlations and (significance level) between heart-of-palm fresh weight (HPFW) or length (HPL) and various peach-palm morphological characteristics at Yurimaguas, Peru.

Morphological variable	HPFW	HPL
D3	0.75 (.0001)	0.55 (.0002)
D2	0.32 (.0466)	0.35 (.0269)
DN	0.56 (.0002)	0.45 (.0033)
$D3^2$	0.73 (.0001)	0.53 (.0005)
$D2^2$	0.33 (.0363)	0.36 (.0210)
DN^2	0.55 (.0002)	0.43 (.0051)
H3	0.64 (.0001)	0.64 (.0001)
DHC	0.63 (.0001)	0.68 (.0001)
L	0.77 (.0001)	0.72 (.0001)

The best field predictor of HPFW was the number of leaves (NL). The best two-variable regression model contained NL and diameter at the origin of the three youngest leaves (D3). The regression equations are shown in Table 3.

The single best predictor of HPL was also NL (Table 3). The best two-variable model contained NL and the ratio of NL to the distance between the origin of the three youngest leaves and the neck.

Further work is needed to clarify the relationship of the heart-of-palm segment to an external characteristic, such as the second leaf. Clarifying such relationships will produce more efficient harvests and lower transport costs.

In the second study, the bulk of the material transported to the factory was waste (approximately 88%). Approximately 65% of the transport weight was due to the three outer protective layers of leaves and the fibrous tip. A hard base, similar to water chestnuts and having market potential, comprised 25% of the transport weight. The usable length of the segment transported to the factory represented approximately 50% of the total length.

Clearly, the traditional criteria used for deciding where the palm should be cut can be improved. A key issue is to establish the optimal number of outer leaf layers needed to provide protection during transport while keeping excess weight to a minimum.

In the factory, the volume of the heart-of-palm, based on its length and the average of the radii at both ends, was a good predictor of HPFW (equation 5, Table 3). This finding suggests that the density of heart-of-palm tissue (approximately 0.86 g/cm^3, based on the regression equation) was relatively constant under the conditions of the study.

There was a weak relationship between the basal diameter of the heart-of-palm and the diameter of the neck measured in the field and also between the heart-of-palm apical diameter and D3 (equations 6 and 7, Table 3). Predictors of heart-of-palm diameter (especially smaller diameters) are needed in order to ensure compliance with minimum or maximum critical diameters specified by the market.

Table 3. Regression equations for predicting heart-of-palm fresh weight (HPFW) and length (HPL).

	Equation	R^2	P
1	HPFW (g) = -2.53 + 31.954N	0.59	0.0001
2	HPFW (g) = -142.07 + 56.303*d3 + 20.0*N	0.70	0.0001
3	HPL (cm) = 34.54 + 1.787N	0.49	0.0001
4	HPL (cm) = 39.18 + 2.242N -2.087LHR	0.58	0.0001
5	HPFW (g) = 17.72 + 0.895 (*HPL*R^2)	0.90	0.0003
6	HPAD (cm)= 1.96 + 0.292*D3	0.27	0.0036
7	HPBD (cm)= 2.92 + 0.0356 dn	0.24	0.0064

Key HPW = heart-of-palm fresh weight
HPL = heart-of-palm length
HPAD = heart-of-palm apical diameter
HPBD = heart-of-palm basal diameter
N = number of leaves
D3 = diameter of the stem at the origin of the three youngest leaves
LHR = N/DHN
R = average radius of the heart-of-palm basal and apical radii
DN = diameter of the neck

International Provenance Trail of *Gliricidia Sepium:* Y-407B

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Fast-growing tree species are major components of agroforestry technologies. With the exception of *Leucaena leucocephala*, most species currently used have not been tested for their biological potential and adaptability to site conditions and management.

Gliricidia sepium (Jacq.) Walp. is a leguminous tree native to Mexico and Central America. It has been introduced to many tropical countries, is easy to establish via seeds or cuttings, and is used by farmers for a variety of purposes—such as fuel wood, fodder, live fences, and green manure.

International collaboration with centrally coordinated exploration and collection efforts organized by the Oxford Forestry Institute (OFI), University of Oxford, England, has resulted in rangewide seed collections sampled from over 2400 individuals from 30 provenances (sources of origin) in eight countries. These collections represent a broad genetic base and will allow flexibility in future selection and improvement.

The trial at Yurimaguas represents the only site on very acid soils (pH 4.2 to 4.5, Al saturation 70 to 92%) in the International Network of the gliricidia provenance trial. This network aims to study genotype-environment interactions and promote the exchange of information and genetic material on an international scale.

Objectives

The objectives of this study were 1) to evaluate growth and biomass productivity of selected OFI accessions of *Gliricidia sepium* on an Ultisol in the Peruvian Amazon and 2) to select provenances with tolerance to acid soil conditions for further testing at different locations.

Procedures

The experimental protocol for the provenance trial provided by the OFI served as the major reference for experimental design and methods.

Seeds of 15 provenances from five countries in Central America were obtained from OFI. All seeds were inoculated with a gliricidia-specific strain of Rhizobium supplied by NifTAL and sown in nursery beds containing a soil similar to the experimental site. This soil contained an abundance of fine *Pueraria phaseoloides* (kudzu) roots, which served as a source of vesicular-arbuscular mycorrhizae (VAM) fungi. Three weeks after germination, the seedlings were planted in polyethylene pots. At about four months, seedlings were planted in the field.

The experimental design is a randomized complete block with six replications and 12 tree-line plots. The basic layout consisted of single rows of trees at 0.5-m spaces within rows and 4-m spaces between rows. Three rows of annual crops were planted between rows of trees. Provenances were randomized within replications.

Results

Plant heights six months after planting show significant differences among provenances (Figure 1). Provenance 14/84 from Guatemala was significantly better than all the others: these plants were 40% taller than those in the second-ranked provenance. Interestingly, provenances 14/84, 11/86, 31/84, and 10/86—all of which had high germination percentages—were among the provenances with the tallest plants at six months.

Cumulative leaf, wood, and total biomass production after three cuttings (20 months after planting in the field) differed significantly among provenances (Figure 2). Once again, provenance 14/84 was significantly more productive and yielded 41% more leaves, 98% more wood, and 70% more total biomass than the second ranked provenance. Provenance 14/84 may have broad adaptability to a variety of site and environmental conditions, but further tests over a range of soil types and environmental conditions are needed to confirm this inference.

Given the scarcity of fast-growing tree species suitable for agroforestry technologies on acid soils, identifying provenances of *G. sepium* tolerant to soil acidity would provide a potentially important multipurpose species for farmers. Provenance 14/84 shows good leaf- and wood-production potential for acid soils. In addition, it does not appear to be attacked by leaf-cutter ants and is relatively easy to establish via cuttings. *G. sepium* could become an

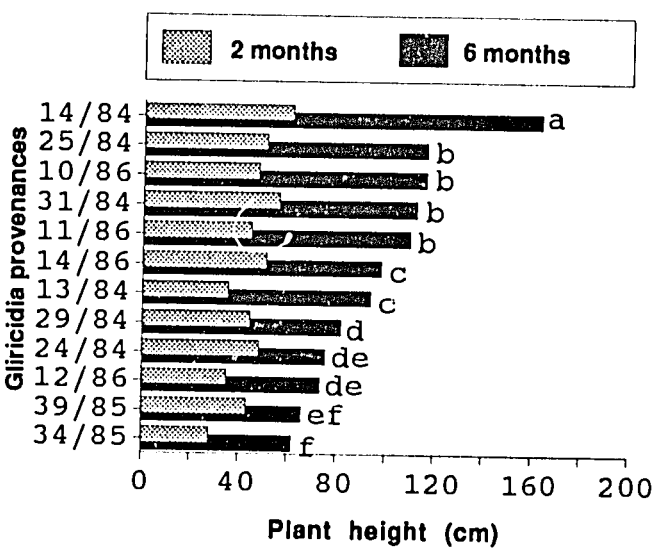
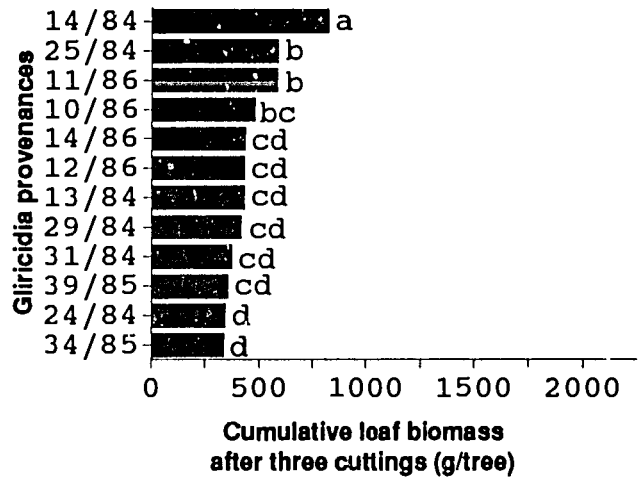
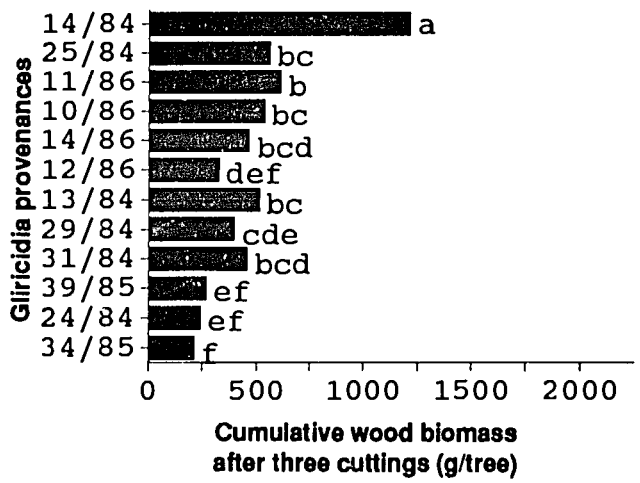


Figure 1. Plant heights at two and six months in the field. Heights at six months with the same letter are not significantly different at k = 100 (Waller Duncan).





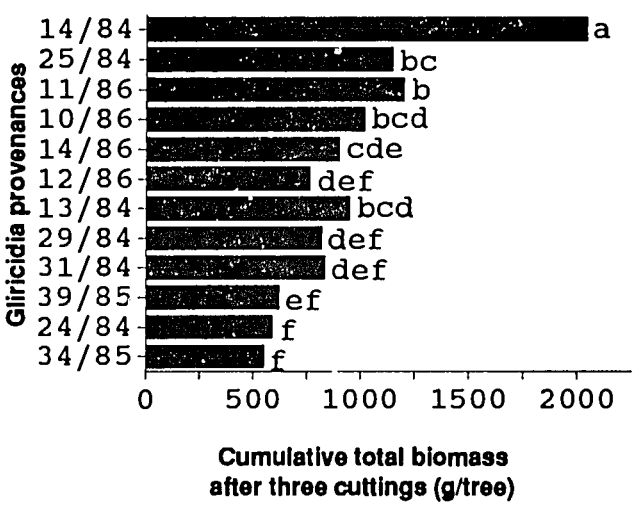


Figure 2. Cumulative leaf, wood, and total biomass after three cuttings. Columns with the same letter are not significantly different at k = 100 (Waller Duncan).

important component of alley-cropping on slopes. It could also be useful as shade/browse trees in grass pastures and live fences for agro-silvo-pastoral systems.

The large differences in growth rates and productivity of the *G. sepium* provenances emphasize the importance of identifying the right seed source, especially when exotic or nonadapted species are being tested. It is likely that many potentially promising species are discarded on the basis of trials involving only a single seed source.

Leguminous Mulch Quality and Its Effects on Soil C and N Dynamics and Crop Yields: Y-405B

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As agriculture is expanding onto marginal lands—where the use of fertilizers and tillage equipment is often uneconomical—attention has again focused on the importance of soil organic matter and organic inputs to crop production. Particular emphasis has been placed on leguminous mulches because of the N they supply. However, nitrogen utilization efficiencies from leguminous mulch are low as compared to inorganic N sources. A possible reason for the inefficiency is asynchronous release of N compared to crop demand. Efficiency of N utilization might be improved if release of N from the mulches were synchronized to crop demand. This synchrony will depend on the timing of application and the N-release patterns or on the quality of the mulch relative to crop uptake patterns.

The quality of mulches can also be important in the maintenance of soil organic matter. Materials high in lignin or polyphenolic content and those with high C/N ratios will help form and maintain stable forms of soil organic matter. Organic materials of higher quality (lower in lignins, polyphenolics, or C/N ratio), on the other hand, may provide a short-term increase in more labile forms of C and N, but they do little to maintain soil organic-matter content.

In order to maintain crop production through the additions of organic inputs, we need a better understanding of how input quality affects soil nitrogen dynamics and crop yields.

Objectives

The objectives of this study were 1) to investigate nitrogen-release patterns from a range of tropical legumes and determine the chemical constituents that influence quality; 2) to investigate how the quality of leguminous mulches affects soil organic-matter fractions and nitrogen dynamics; and 3) to observe the effects of mulch quality and soil organic matter on crop yields.

Procedures

A laboratory study was designed to address the first objective. Leaves of 10 tropical leguminous trees and shrubs and rice straw were analyzed for nitrogen, lignin, and polyphenolic concentrations. Nitrogen-release patterns were related to the N, lignin, and polyphenolic concentrations of the leaves. Ground leaf material was incubated in an acid soil, pH 4.5, and the soil was analyzed for extractable NH_4-N and NO_3-N at 0, 1, 2, 3, 4, and 8 weeks. Three patterns of net N mineralization emerged over the eight-week period. One of the patterns exhibited by the control soil, rice straw, and leaves of the two *Inga* species was a low, positive net mineralization. Another pattern exhibited by *Erythrina* sp, *Gliricidia sepium*, and *Samanea saman* was a much higher and more rapid mineralization rate than that of the control soil. The third pattern exhibited by *Cajanus cajan* and the *Desmodium* species was an initial immobilization followed by low but positive mineralization rates. The amount of nitrogen mineralized as compared to the control soil ranged from +46 to –2% of the nitrogen added in plant material (Table 1). Mineraliza-

Table 1. Characteristics of organic additions, eight-week cumulative mineralization, and percentage of nitrogen mineralized.

Treatment	N	Lignin	Phenolic	Eight-week cumulative mineralization	% of aded N mineralized
Gliricidia sepium	3.74	7.8	1.02	54.00 a*	45
Erythrina sp.	3.52	9.7	1.04	48.25 a*	39
Samanea samam	3.20	6.3	1.48	40.68 c*	29
Inga edulis	3.18	16.3	3.43	21.62 ef	-4
Oryza sativa	1.13	6.2	0.69	23.32 de	-3
Inga sp.	2.97	17.9	1.61	22.21 e	-3
Leucaena leucocephala	3.94	5.2	2.94	25.19 d	1
Cassia reticulata	2.50	10.8	2.20	23.52 de	-1
Cajanus cajan	3.48	10.2	3.34	18.74 fg*	-8
Desmodium gyroides	2.99	11.7	1.91	17.53 g*	-12
Desmodium ovalifolium	2.37	9.1	3.61	15.91 g*	-19

* Values within each column followed by * are significantly different from the control, Dunnet's LSD, p = 0.05.
Values followed by the same letter are not different, LSD p = 0.05.

tion was not correlated to % N or % lignin in the leaf material, but it was found to be negatively correlated to the polyphenolic concentration.

The two other objectives were investigated in a modified alley-cropping trial (details of the experimental design are described in *TropSoils Technical Report, 1986-1987*).

Prunings from three leguminous trees—*Inga edulis, Cajanus cajan*, and *Erythrina* sp.—were used as a mulch at rates of 0 (mulch level 1), 3.3 (mulch level 2), and 6.7 (mulch level 3) t/ha/crop for four consecutive crops of upland rice. The leaves of the three species differed in quality: erythrina leaves had low lignin and low soluble polyphenolic concentrations, and they decomposed and released nitrogen faster than leaves of inga and cajanus, which decomposed at similar rates. Leaves of inga were high in both lignin and polyphenolics whereas cajanus had high polyphenolics but low lignin. The following effects were measured: rate and quality of prunings on soil N mineralization, soil C and N, light fraction C and N, soil microbial N, and corresponding crop yields.

Soil N and C

Soil N mineralization rates were highest in erythrina plots immediately after applying mulch. The differences in mineralization rates lasted only two to three weeks, after which they were similar in all treatments. Total soil C and N did not differ significantly among the species and mulch rates 20 months after the initiation of the experiment (Table 2), despite additions totaling 27 t/ha to some of the plots and 0 to others. Light-fraction C and N comprised only 2 to 3% of the total soil C and N. These fractions were highly variable and did not differ among treatments. Microbial biomass N, however, did differ significantly among species and mulch rates. In general, microbial N values in erythrina plots were higher or equal to those in inga plots. Microbial N values in cajanus plots were significantly lower and more similar to those of plots without mulch. Microbial biomass N increased with increasing mulch rates.

Crop Yields

Rice grain yields for the first four crops in the central experiment are shown in Figure 1.

The analyses of variance by crop, in general, showed no significant differences in rice grain yields among species of mulch but significant differences among rates of mulch applications: Mulch Level 3> Mulch Level 2> Mulch Level 1 (Figure 1). By the fourth crop, yields declined to 29% of the first crop's yield in plots with no mulch. Plots with the higher rate of erythrina pruning were still maintaining 70% of initial yields.

A simple N budget was calculated for each treatment during the 20-month period covering the four consecutive rice crops. Nitrogen uptake and N recovery were low for all treatments, N recovery averaging only 16% (Table 3). The N-utilization efficiency of inga was about half that of erythrina and cajanus, but erythrina had larger losses or more unaccounted for N. Cajanus had the lowest losses of N. For increasing mulch level, the N utilization efficiency of erythrina remained the same, but it decreased for inga. N losses more than doubled for both species. The N-P-K-fertilized treatment showed a somewhat higher utilization efficiency of 23%, but % N recovery in the grain (8.0%) was low compared to the other treatments. Nitrogen losses were high, similar to those for the highest mulch rate. The highest N utilization efficiency and lowest N losses were obtained for the treatment in which inga prunings were incorporated.

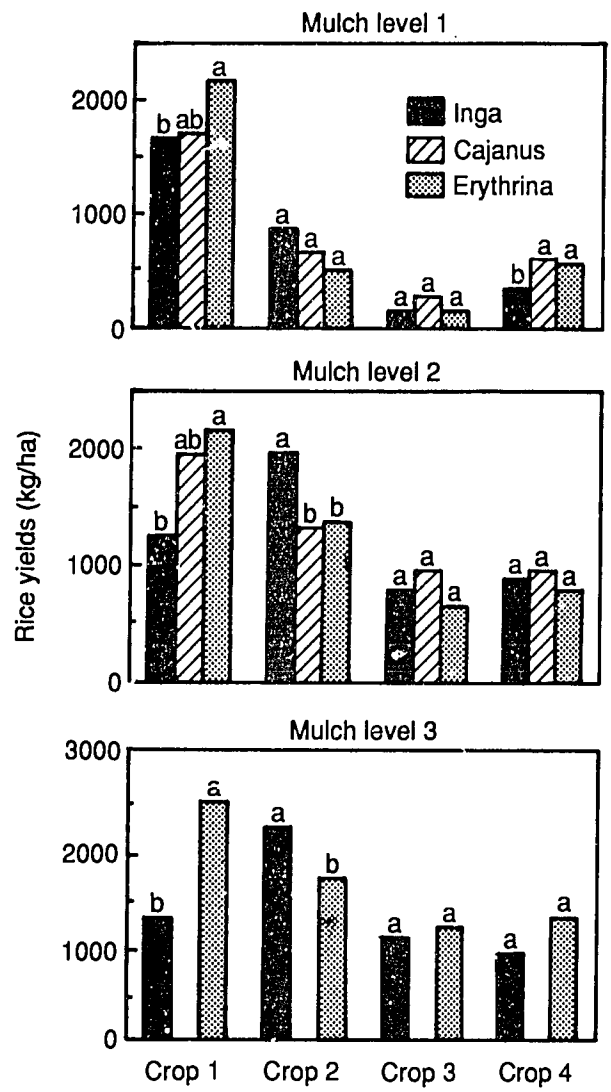

Figure 1. Rice grain yields for the different types and rates of mulch application. Yield values with the same letter are not significantly different from others within the same mulch level and crop.

Several influences may contribute to the low apparent N utilization efficiencies. For inga and cajanus, part of the inefficiency occurs because 30% of the N added in the pruning is still tied up in the undecomposed mulch. Another reason for the inefficiency could be volatilization of NH_3, since the mulch was applied to the surface. A third reason for the generally low efficiencies could be a synchrony of N availability and crop demand.

Conclusions

The nitrogen-release patterns observed from the leaves of a variety of tropical legumes and the possible role of polyphenolics have several management implications. When legumes with low polyphenolic contents are used as green manures or mulches, they may release N rapidly and provide sufficient N for plant growth, but the nitrogen may be readily lost by leaching if it is not released when the plants need it. Legumes with a high polyphenolic content immobilize nitrogen. Plants with a high polyphenolic content may not provide enough nitrogen for plant growth in the short term, but they may contribute to the build-up of organic nitrogen in the soil and provide a low but continual supply of nitrogen in the long-term. A combination of the two types of legumes may provide the best agroecosystem management.

Table 2. Total soil C and N, light-fraction C and N, and microbial N at 20 months in the top 10 cm of soil.

Treatments	Total C	Light-fraction C	Total N	Light-fraction N	Microbial N		
	t/ha	kg/ha	t/ha	kg/ha	ug g/kg	g/ha	%
No mulch	25.01	384.7	1.82	21.5	57.5	85.9	4.7
Inga–2	24.48	315.6	1.60	20.1	68.6	107.6	6.7
Inga–3	24.85	295.2	1.71	18.5	76.1	117.5	6.9
Cajanus–2	25.59	464.8	1.76	28.5	59.8	89.6	5.1
Erythrina–2	25.96	286.6	1.94	15.8	69.8	106.3	5.5
Erythrina–3	28.50	454.2	2.12	25.6	86.7	131.1	6.2
lsd p = 0.05	3.12	340.2	0.27	20.2	3.81	18.4	

§ Number following treatment indicates mulch rate, 2 = 3.3 t/ ha, 3 = 6.7 t/ ha crop.

Table 3. Nitrogen budgets and nitrogen utilization efficiencies for the various types of mulch, rates of mulch application, mulch management strategies, and N fertilization rates for four rice crops.

Treatment	N added	N removed: grain + straw	N utilization efficiency: grain + straw	N remaining in mulch	Unaccounted for N	
No Mulch	kg/ha		%	kg/ha		%
3.3 t/ha Mulch						
Inga	284	125	11.9	91	68	24
Cajanus	235	137	19.7	64	34	14
Erythrina	216	135	20.6	13	68	32
6.7 t/ha Mulch						
Inga	567	137	8.1	183	248	44
Erythrina	431	171	19.8	25	235	54
Inga/ Erythrina *a*	250	126	14.3	52	71	28
Inga/ incorporated *b*	284	157	23.5	91	35	12
N-P-K Fertilizer *c*	400	182	23.0	NA	217	54

Assumes same rate of decomposition of surface-applied mulch.
a,b,c: Three additional treatments were also compared: a = an equal split of Inga and Erythrina prunings applied at a combined rate of 3.3 t/ha/crop; b = 3.3 t/ha of Inga prunings incorporated with rototiller; and c = fertilizer applied at 100 kg/ha N (urea), 100 kg/ha K (KCl), and 25 kg/ha (P_2O_5).

Root and Leaf Decomposition in Agroecosystems: Y-433D

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Objectives

Little is known about rates of decomposition and nutrient release from crop residues and green manure in humid tropical agroecosystems. The objectives of this study were as follows: 1) to measure these rates for a range of agriculturally important organic residues incubated in a cropped field; 2) to determine how these rates vary seasonally, especially with soil moisture; and 3) to compare these rates with those of similar materials incubated in pastures.

Procedures

The following fresh materials were gathered: leaves, fine roots (< 2 mm diameter, unlignified), coarse roots (2- to 3-mm diameter, lignified) of *Inga edulis, Mucuna cochinchinensis*, rice (near harvest), and *Centrosema macrocarpum*. It was thought that these materials, besides having agricultural importance as crops, mulches, and cover crops, also represented a large range in organic-matter quality.

The materials were allowed to dry for a few hours before being weighed and placed in bags. Prior to weighing, roots were chopped into pieces 2- to 3-cm long. Approximately 1.5 g of root material was evenly distributed within 5- by 10-cm mesh bags (mesh size 9 by 9 mm). Also, 7.5 g of inga and rice leaves, 8.0 g of centrosema leaves, and 11.0 g of mucuna leaves were placed (trying to avoid compacting the sample) in bags (10 by 20 cm) of two differing mesh sizes (10 mm and 52 mm). Subsamples of all plant materials were taken for determinations of dry weight, ash content, and nutrient concentrations.

In August 1989, bags were placed in the crop-interrows midway between the hedges of an alley-cropping experiment (Y-433). Root bags were placed in vertical slits made in the soil to a depth of 5 cm; leaf bags were placed on the soil surface. Two block replications were installed on a flat area and two on an approximately 20% slope. Each block contained 14 bags of a given root material (two bags x seven sampling dates) and seven bags of a given leaf material. The position of the bags within each replication and the date on which a given bag was harvested were randomized. Centrosema roots and leaves were also included in a comparison experiment in pastures (see Y-307).

A subset consisting of eight bags for a given type of root and four bags for leaves was harvested at 4, 7, 14, 30, 60, 90, and 180 days after installation. All plant material was cleaned of adhering soil, dried, and then weighed. Half the repetitions of each leaf and root type were ashed in order to determine ash content; the samples in the other repetitions were ground, and their nutrient content was then analyzed. All weights and calculations are expressed on an ash-free basis.

Two or three ceramic cup tensiometers were installed at a 3-cm depth in each block and were read every other day.

Results

Leaves

Temporal patterns of mass loss for leaves of centrosema, mucuna, and rice were similar but faster than the rate of mass loss of inga leaves (Figure 1). For leaves of the former species, mass loss during the first two weeks was around 30% in the large mesh bags and 15 to 25% in the small mesh bags. In contrast, inga leaves lost approximately 15% of their mass during the same period, regardless of mesh size. For both types of bags, rates of mass loss either remained relatively constant or tended to decrease with time after the initial two weeks. The percentage of material remaining in the 52-mm mesh bags after four months was 67%, 31%, 22%, and 13%, for inga, centrosema, rice, and mucuna, respectively. In the 9-mm mesh bags, the percentage of leaf material remaining was 67%, 38%, 22%, and 36% for the same species. Hence, mesh size had little effect on rates of mass loss of inga and rice leaves during four months, but for mucuna and centrosema, rates of mass loss were slower in the bags with smaller mesh size.

Roots

Temporal patterns of mass loss of both fine and coarse roots were similar (Figure 2). An initial period (ranging from four to 15 days), during which losses were rapid, was followed by a period in which rates of mass loss were slower. After one month, rates of mass loss were very slow for fine and coarse roots of centrosema and fine roots of mucuna.

Although temporal trends were similar for different species and root diameters, at most dates there were large differences in mass loss among species. After two weeks of incubation, mass loss ranged between 21% (inga) and 45% (mucuna) for fine and coarse roots. After two months, mass loss of fine roots was 26%, 43%, 59%, and 78% for inga, rice, centrosema, and mucuna, respectively; for coarse roots of the same species, mass loss was 34%, 46%, 54%, and 76%. Presumably, differences in disappearance rates of leaves and roots among the various species were due to differences in lignin, polyphenol, or nutrient concentrations. These hypotheses will be examined upon completion of plant tissue analyses.

With the exception of mucuna, the disappearance rates of leaves and fine and coarse roots for a given species

during two months differed by 12% or less. Mucuna roots in both diameter classes disappeared much more rapidly than leaves because they were transported from the bags by termites.

Differences related to mesh size in the disappearance rate of leaves probably result from the greater accessibility to macrofauna and the comminution of material in the bags with larger mesh. That mesh size did not affect the

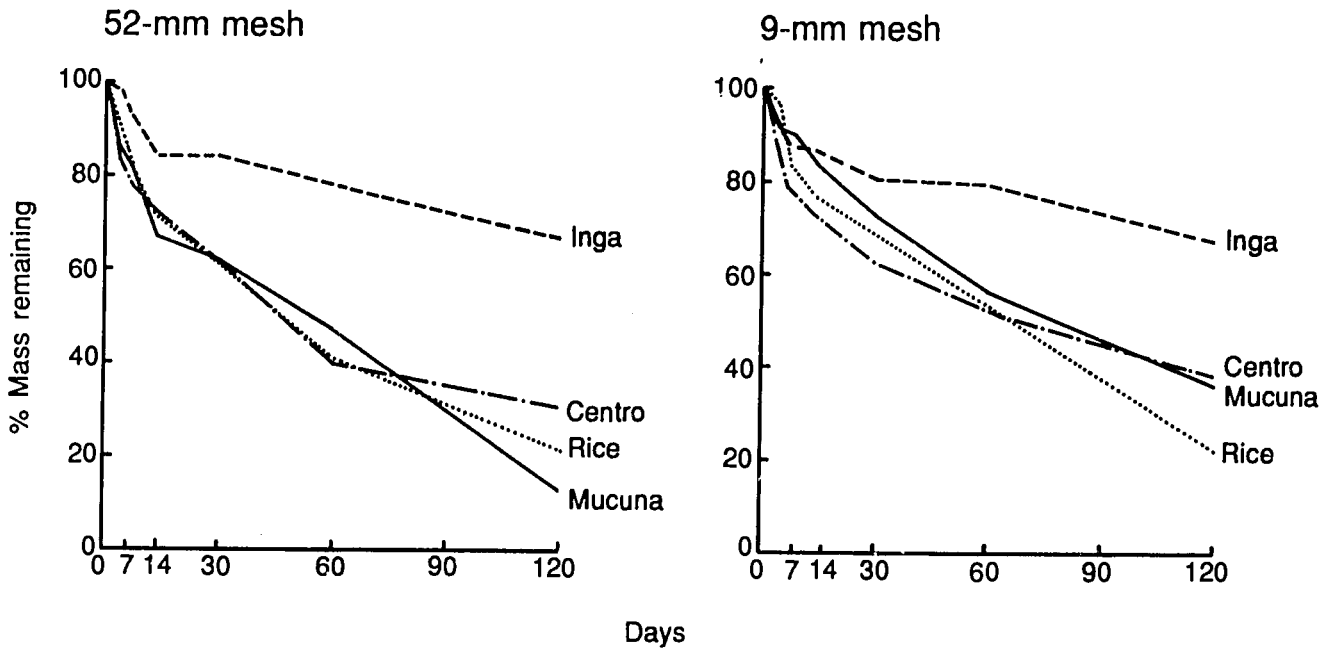

Figure 1. Rates of mass loss from air-dried leaves of four plant species incubated in 9-mm and 52-mm mesh bags placed on the soil surface in a cropped field, Yurimaguas, Peru.

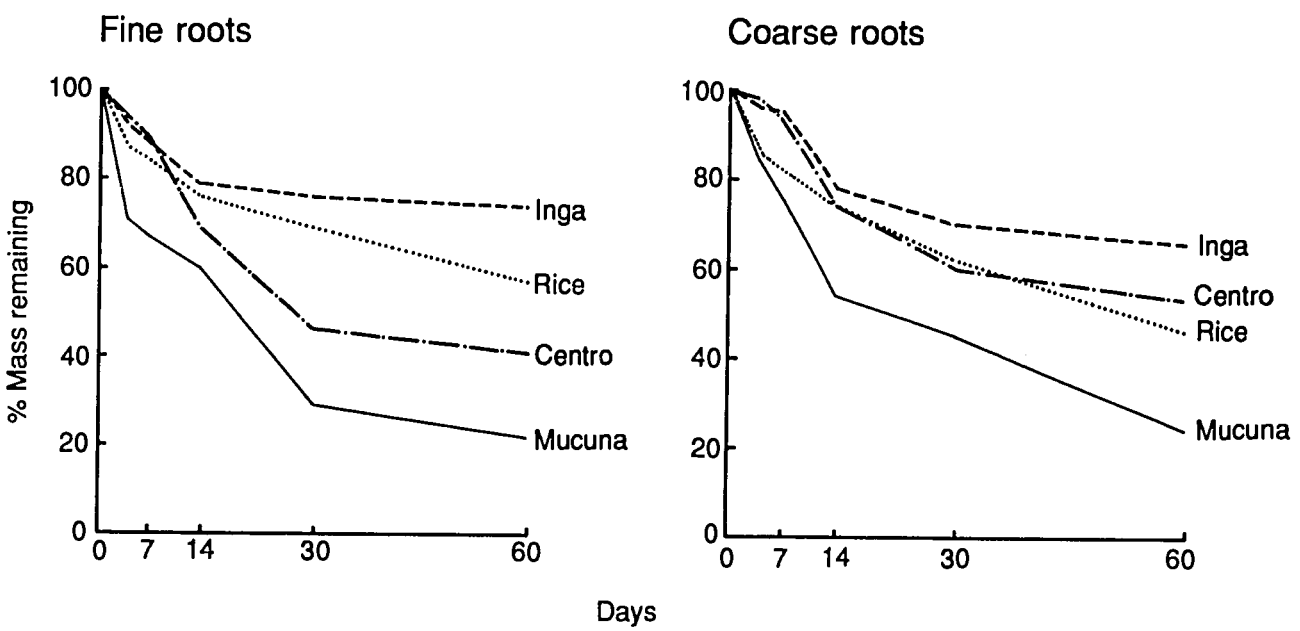

Figure 2. Rates of mass loss from fine (< 2 mm diameter), unlignified roots and coarse (2- to 3-mm diameter), lignified roots of four plant species incubated in 9-mm mesh bags placed at the 0- to 5-cm soil depth in a cropped field, Yurimaguas, Peru.

loss of inga and rice leaves (species which, however, differ greatly in the percentage of material lost after four months) suggests that large soil macrofauna play a reduced role in the disappearance of these materials. The slightly greater disappearance rates of coarse, as compared to fine, roots may be due to the presence of higher concentrations of allelopathic compounds in fine, unlignified roots.

This study was installed during the dry season when soil moisture in the top 3 to 5 cm of soil was often scarce. Rates of disappearance from the dry season will be compared with those obtained, using the same materials and techniques, during the wet season, when the topsoil is often near saturation. Results obtained with centrosema leaves and roots in this study will also be compared with results for the same materials incubated in a pasture.

Conclusions

1) Leaves of *Centrosema macrocarpum*, *Mucuna cochinchinensis*, and rice lost mass much more rapidly than those of *Inga edulis*. Large (diameter > 9 mm) soil macrofauna do not appear to play an important role in leaf decomposition.

2) Species exhibited greatly differing disappearance rates for fine and coarse roots, but for a given species, there was little difference in rates of mass loss for roots differing in diameter. Rapid losses of mucuna roots appear to be caused by termites.

3) Despite differences in location (upon the soil surface versus within the soil profile), disappearance rates of leaves and roots for a given species were generally similar.

Alley-cropping on Alluvial Soils: Y-417

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Alley-cropping has shown promise for sustained crop production on high base status Alfisols of West Africa, and therefore it is a potential alternative for food production on high base status alluvial soils in the Amazon Basin. An alley-cropping experiment was installed on a high base status alluvial soil in Yurimaguas in October 1985. The details of the experimental design are described in *TropSoils Technical Report, 1986-87*.

Objectives

The objectives of this study were 1) to determine the effects of prunings and alley width (4 m or 8 m) on crop yields and yield stability; 2) to assess the suitability of three leguminous tree species (*Leucaena leucocephala*, *Inga edulis*, and *Erythrina* sp.) based on their survival, biomass production, and ability to withstand repeated pruning; 3) to measure changes in soil chemical properties due to mulch additions; and 4) to measure changes in the biomass and species composition of weeds.

Results

An update of results for this experiment will focus on trends in crop yields. Yields will be compared to those of two control treatments without tree prunings, one with crop residues applied, the other with residues removed. Observations on tree growth and weed control will also be mentioned.

To date, nine crops have been harvested in a rice-cowpea-corn rotation. Prior to the fourth crop (rice), 125 kg/ha of triple superphosphate was applied because of declining yields and very low soil P (< 3 ppm Olsen P). Yields obtained for the nine crops are presented in Figures 1, 2, and 3, which represent rice, cowpea, and corn, respectively.

For all crops, yields are greater in alley widths of 8 m as compared to 4 m because less area is planted to trees in the 8-m treatment, resulting in less tree/crop competition.

There are little differences in crop yields among the three types of prunings. However, there are differences in crop yields between the alley-cropped trees and the controls. These differences, which change with time, depend on the type of crop growing between the alleys. Rice planted in alleys performed better than rice in control plots where crop residues were not returned, but yields were only 50 to 75% of those obtained in control plots where crop residues were returned. Cowpea yield response varies: yields are sometimes greater when cowpea is planted in alleys and other times greater when planted

alone. For the first corn crop, (3rd crop overall), yields were better in the control plots, but the trend was reversed dramatically for the second corn crop (8th crop overall).

The results indicate that alley-cropping yields for corn and cowpea are maintained with time when compared to cropping without trees. Rice yields were never greater than the control treatment with residues. Perhaps rice is affected more by shading than corn or cowpea. To avoid shade, corn is able to grow taller than trees, and cowpea is somewhat shade-tolerant. These observations are confirmed by the fact that yield reductions of rice growing near the tree rows are more pronounced than those of cowpea or corn.

Tree Performance

Inga edulis produced more leaf biomass than *L. leucocephala* or *Erythrina* sp. for the first two-and-one-half years. After that, the inga trees decreased in productivity, and many died. This decline was apparently caused by the pruning regimes. Initially, the trees were pruned at exactly the same height (70 cm), often leaving no leaves on the trees and forming scars. Since that time, the remaining trees have been pruned at varying heights, the trees have recovered, and biomass production has increased.

Weed Control

The thick layer of mulch provided by the slowly decomposing inga leaves continues to provide effective weed control compared to the rapidly decomposing mulch of leucaena and erythrina.

Soil Properties

For the majority of the treatments, soil pH decreased slightly and Al saturation increased slightly with time (Table 1). For the check treatment in which crop residues were returned, the pattern was the opposite. Aluminum saturation in all treatments was very low and would not constrain crop production.

The continual decrease in soil P levels, despite P application, is difficult to explain, but it may be due to the large amount of P exported during crop harvest. Potassium levels decreased with time, and by 20 months, they were nearing the critical level of crop production. The Ca and Mg content of the soil increased with time in all treatments.

Conclusions

Alley-cropping appears to be a viable and sustainable option for corn and soybean production on high base status alluvial soils. In contrast, rice production does not benefit from alley-cropping. The efficient weed control provided by *Inga edulis* prunings is an additional factor to consider when planning an alley-cropping system. On-farm alley cropping trials using corn, cowpea, and *Inga edulis* will begin in the next year.

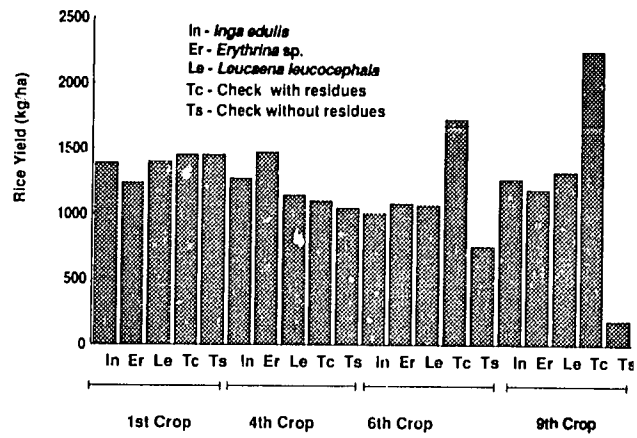

Figure 1. Effect of tree prunings on rice yields during four cropping seasons.

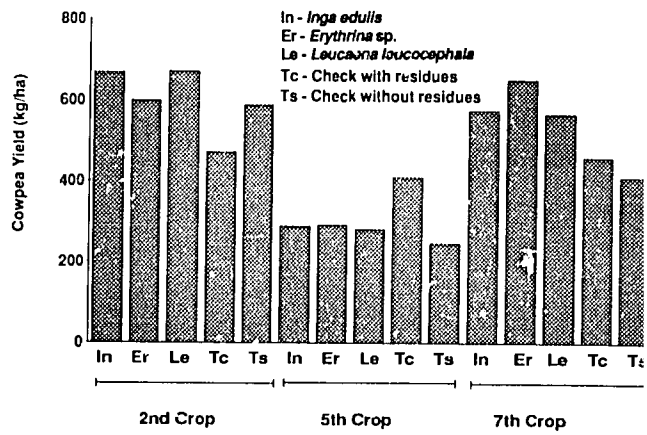

Figure 2. Effect of tree prunings on cowpea yields during three cropping seasons.

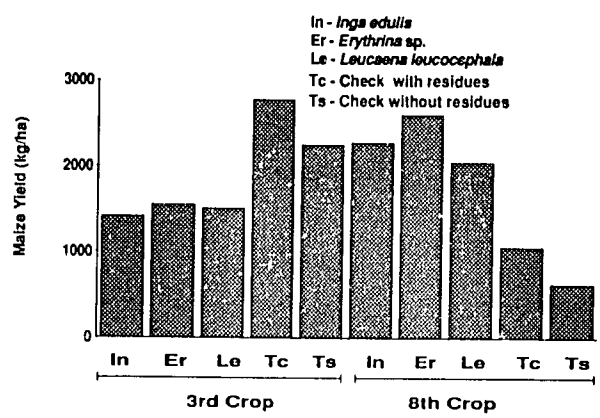

Figure 3. Effect of tree prunings on maize yields during three cropping seasons.

Table 1. Soil chemical characteristics (0- to 15-cm depth) at four and 20 months in three alley-cropping systems.

Tree species	Time	Ph	O.M.	P	Ac	Ca	Mg	K	Al sat.	N
			%	ppm	cmol (+)				%	%
Inga	4	5.7	3.2	2.6	0.4	18.09	2.55	0.17	1.9	0.12
	20	5.5	3.2	0.9	0.5	22.89	3.62	0.15	2.1	0.15
Erythrina	4	5.7	4.1	2.2	0.5	18.54	2.82	0.18	2.4	0.11
	20	5.7	3.4	0.7	0.2	24.59	3.85	0.16	1.0	0.15
Leucaena	4	5.6	2.9	1.9	0.3	17.00	2.84	0.22	1.5	0.10
	20	5.6	2.6	0.7	0.5	22.15	3.68	0.14	2.0	0.12
No	4	5.5	3.2	7.9	0.4	12.99	2.60	0.24	2.8	—
Residue	20	5.4	2.3	1.3	2.1	15.26	3.02	0.12	10.6	—
Residue	20	5.7	2.4	1.5	0.4	17.19	3.59	0.16	1.9	—

[§] Eight-meter alley widths only.

Alley-cropping on Ultisols: Y-425

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Most alley-cropping trials have been conducted on relatively fertile Alfisols and Inceptisols. In fertile soils, the hedgerow trees are able to pump up nutrients from the subsoil, and yields of the crops growing in the alleys are maintained by mulches supplied by the prunings of the hedgerow trees. Supplemental P and K fertilizers are often added, N being supplied by the N-fixing trees.

Alley-cropping may not be sustainable on acid, infertile Ultisols or Oxisols because there are few nutrients stored in the subsoil for hedgerow trees to recycle. Previous alley-cropping trials on Yurimaguas Ultisols were deemed unsuccessful because the leguminous trees used as hedgerows did not perform well, competition between crops and trees was severe, and soil P levels were quite low. Further tree-selection trials described in *TropSoils Technical Report, 1986-87* have provided several leguminous trees that have potential for use in alley-cropping on acid soils.

In 1987, a new alley-cropping trial was established on a loamy Ultisol of pH 4.4, 80% aluminum saturation, and 5 ppm Olson extractable P.

Objectives

The objectives of this study were 1) to assess the effects of P fertilization on tree biomass production, crop yields, and the sustainability of the alley-cropping system; 2) to assess the effects of alley width on crop yields; and 3) to address problems encountered in previous trials.

Procedures

The design used for the alley-cropping experiment was a split-split plot with three replications. Treatments included alley width (4 m versus 8 m) as the split-plot treatment, species of tree for the hedgerows (*Inga edulis, Gliricidia sepium*, or *Cassia reticulata*) as the main-plot treatment, and P fertilization (0 vs 25 kg P) for the split-split-plot treatment.

A cowpea-cowpea-rice rotation was interplanted with the trees. The phosphorus treatment was applied only to the rice crops. Each hedgerow consisted of two closely planted rows of trees, which were planted 0.5 m by 0.25 m within hedgerows.

Results

Pruning biomass production by hedgerow species does not appear to be significantly affected by P fertilization (Table 1), although there is a tendency for higher gliricidia production with fertilization. Information is not yet available on the P content of the prunings with and without P fertilization.

At 30 months, the *C. reticulata* trees began to produce less and to die. The pruning method was modified by pruning dead branches, a process which initiates resprouting from the trunk. This method is now being followed for all the tree species.

In general, crop yields are higher on plots with trees than on control plots without them (Table 2). Crop yields are somewhat higher in association with *Inga edulis* hedgerows than with the other two species. Alley width or P treatment have had no dramatic effect on crop yields.

Yields do not appear to decline with time as they have in previous trials on acid soils. This finding may be related to the higher clay content (25%) of the soils in this trial as compared to the others. The higher clay content could improve cation retention and recycling and also maintain adequate soil moisture levels for longer time intervals.

Changes in soil chemical parameters (Table 3) indicate a considerable decrease in exchangeable potassium but little change in other basic or acidic cations. Phosphorus levels have increased slightly even in the plots that receive no P fertilization. This finding contrasts with previous studies and raises interesting questions considering the large amount of P exported in crops relative to the amount recycled in prunings. This stability could indicate redistributing and recycling of soil P through the trees and into more available forms. Soil P fractions will be compared among the different treatments and controls to see if this recycling has happened.

Table 1. Pruning yields of three leguminous species as affected by P treatments.

Tree species	Phosphorus treatment + P	Phosphorus treatment – P
	—— kg/m of hedgerow ——	
Inga edulis	0.37	0.36
Cassia reticulata	0.39	0.39
Gliricidia sepium	0.20	0.16

Table 2. Grain yields of eight consecutive crops grown in alley-cropping with *Inga edulis* (Ie), *Cassia reticulata* (Cr), and *Gliricidia sepium* (Gs) at two alley widths, with and without P. Yields are compared to control plots without trees.

Treatments			Crop							
			1	2	3	4	5	6	7	8
			C§	C	R	C	C	R	C	R
Tree species	Alley width	P treatment	t/ha							
Ie	4	+	1.1	0.7	0.7	1.0	0.8	1.9	1.1	2.6
		−			0.6	0.8	0.9	1.7	1.0	2.7
	8	+	0.9	0.8	0.9	0.7	0.8	1.6	1.0	2.4
		−			1.0	0.7	0.8	1.8	0.9	2.4
Cr	4	+	1.0	0.3	0.5	0.7	0.7	1.1	0.8	2.3
		−			0.5	0.6	0.6	0.9	0.7	2.5
	8	+	1.1	0.5	0.7	0.6	0.8	1.2	0.8	2.3
		−			0.8	0.7	0.8	2.6	0.8	2.5
Gs	4	+	0.8	0.5	0.7	0.6	0.5	1.3	0.7	2.2
		−			0.7	0.5	0.4	1.4	0.5	1.7
	8	+	1.0	0.6	1.0	0.6	0.7	1.6	0.7	2.0
		−			0.9	0.5	0.7	1.6	0.7	2.0
Control		+	—	—	—	—	—	1.1	0.6	1.0
		−	—	—	—	—	—	1.0	0.4	1.3

§ C = Cowpea; R = Rice.

Table 3. Changes in soil chemical characteristics after eight consecutive crops.

Treatment	pH	P	Acid	Ca	Mg	L	Al sat.
		ug/ml	cmol(+) /L				
C1	4.46	4.87	4.86	0.83	0.27	0.18	78
C8 +P	4.31	5.94	4.91	0.75	0.23	0.07	82
C8 -P	4.33	5.27	4.51	1.02	0.23	0.09	77

Alley-cropping on an Ultisol in the Peruvian Amazon: Mulch, Fertilizer, and Hedgerow Root-pruning Effects: Y-433A

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Alley-cropping has received considerable attention over the last decade as an agroforestry technology with the potential to sustain crop productivity via enhanced soil protection, nutrient cycling, and/or reduced weed pressure. Experimental results from several studies on high base status soils (mainly Alfisols and Entisols) show that alley-cropping can sustain crop yields, maintain soil nutrient status, and prevent organic-matter decline. Hedgerows planted along the contours on sloping land can minimize runoff and soil erosion.

On some high base status soils (Alfisols, Entisols, and Andisols), nutrients recycled in hedgerow prunings vary between 50 to 180 kg N, 2 to 10 kg P, 10 to 150 kg K, 10 to 60 kg Ca, and 5 to 25 kg Mg/ha/pruning on a two- to three-month pruning cycle. The nutrient-cycling potential of hedgerows on acid soils (Ultisols and Oxisols) is lower than for fertile soils. The nutrient content of prunings on acid soils varies from 20 to 100 kg N, 2 to 5 kg P, 10 to 90 kg K, 2 to 25 kg Ca, and 1 to 10 kg Mg/ha/pruning on a three- to four-month pruning cycle. Nutrient uptake by the trees is likely to result in greater nutrient competition between trees and agronomic crops on soils with low subsoil nutrient status (e.g. Ultisols) than on base-rich subsoils (e.g. Alfisols).

Many alley-cropping studies have shown that crop yields tend to decrease close to hedgerows. It is hypothesized that the lowered yields are due to aboveground competition for light and belowground competition for nutrients and water. Hedgerow shoot prunings can alleviate shading of crops, and they may also reduce root competition because some of the hedgerow roots die immediately following such prunings. No published data from unambiguous studies on root competition between hedgerows and crops were found for acid soils in the tropics.

Objectives

The objectives of this study were to evaluate the effects of mulch, a moderate level of fertilizer, and root pruning of hedgerows on the following: 1) crop yields with time and distance from hedgerow, 2) weed biomass, 3) hedgerow biomass and nutrient content of prunings, and 4) soil chemical properties with time.

We hypothesized that on acid mineral soils, high levels of aluminum saturation in the subsoil restrict hedgerow root growth largely to the topsoil. As the hedgerows age, their increasing root biomass in the crop rooting zone (close to the hedgerow and within the alleys) results in greater root competition between the hedgerows and crops, thus offseting the beneficial effects of mulch additions and the nutrients recycled in the mulch.

Procedures

The study was conducted in a secondary forest on an upland terrace, cultivated and abandoned approximately 12 years previously. A portion of the site was on a north-facing slope of 21%. The soil was a fine-loamy, siliceous, isohyperthermic Typic Paleudult. Clay content in the top 15 cm averaged 16.5% with kaolinite as the predominant mineral in the clay fraction. The vegetation was cleared manually in October 1987, and after being allowed to dry for 10 days, it was burned *in situ*. Partly burned logs and branches remaining after the burn were removed from the site by hand. After burning, the topsoil (0 to 15 cm) had an effective-cation exchange capacity of 5.62 $cmol_c L^{-1}$, acidity of pH 4.3, and aluminum saturation of 74%. Total carbon and nitrogen in the soil were 1.10 and 0.11%, respectively.

The experimental design was a randomized complete block with four blocks and eight treatments. The site was blocked on the basis of clay content, Al saturation, and slope, so as to maximize the variation of these variables between blocks and minimize the variation within blocks. Blocks 1 and 2 were located on a flat portion of the site, whereas blocks 3 and 4 were located on uniform north-facing slopes of 17% and 21% respectively. The eight treatments comprised a 2^3 factorial (i.e. all combinations of the two levels—presence and absence—of each of the factors: mulch, fertilizer, and hedgerow root pruning). The full factorial not only was more precise, but it also estimated interaction effects. Except where stated otherwise, means were further examined only if the corresponding main effect or interaction effects were significant at $p < 0.05$.

An alley-cropping plot with double hedgerows of *Inga edulis* Mart. was used. Hedgerows were established using bare-root plants (two months old) that had been raised from seed in a cleared area adjacent to the site. At sowing, inga seeds were immersed for 12 h in a slurry of soil, fine roots, and nodules collected from mature inga trees in the area. The slurry served as a source of inoculum of native rhizobia and VA mycorrhizal fungi. At field planting, all inga seedlings were profusely nodulated, and an examination of the nodules revealed that most had leghemoglobin, as evidenced by a reddish pink coloration.

The hedgerows in all blocks had an east-west orientation to minimize the shading of crops in the alleys. Hedgerows were inspected weekly for a month after establishment, and dead trees were replaced with healthy seedlings of the same age. The test crops grown in the alleys followed an annual rotation of upland rice (*Oryza*

sativa L. var. africano desconocido)-rice-cowpea (*Vigna unguiculata* L. var Vita 7). The first rice crop after burning (subsequently referred to as Rice 1) was harvested in March 1988. The mean grain yield harvested from the site was 1.5 Mg/ha, while 2.3 Mg/ha of dry crop residue was left in place. The next six crops were referred to as Rice 2, Cowpea 3, Rice 4, Rice 5, Cowpea 6, and Rice 7. Crop residues were retained on the plots for all crops.

Beginning with rice, treatments were as follows: the mulch (M) consisted of inga prunings (leaves + branches) applied at a rate of 3.33 Mg/ha dry matter (DM) per crop. Prunings were applied approximately four weeks after crop germination because prior experiments with inga mulch showed that the slowly decomposing mulch layer prevented the emergence of germinating rice and cowpea crops. Plots not receiving mulch had the hedgerow prunings placed within the hedgerow so as to minimize nutrient export from the site.

The fertilizer (F) contained 50 kg N/ha (urea), 25 kg P/ha (triple superphosphate), 20 kg K/ha (KCl), 35 kg Ca/ha, and 16 kg Mg/ha (dolomite). It was broadcast evenly in the alley portion of the plot. Nitrogen was only applied to rice crops, not cowpea, and applications were split, 30% prior to sowing and 70% at tillering. Other nutrients were applied prior to sowing each crop.

Root pruning of inga hedgerows (R) was done by slicing vertically to a depth of 20 cm with a square-end machete at a distance of 25 cm from the base of the hedgerow. For each crop, hedgerow roots were pruned immediately after sowing the crop and again just prior to tillering (rice) or flowering (cowpea).

Plots were 7-m long by 4-m wide. As each hedgerow comprised two rows of trees, prunings for each plot were obtained from the tree row immediately adjacent to the plot. The hedgerows were pruned only once per crop. An informal survey of 16 local farmers had revealed that most would be unwilling to prune hedgerows twice per crop because of the extra labor required. Hedgerows were first pruned 11 months after field establishment. A pruning height of between 0.65 and 0.75 m was selected, as this is a comfortable height to prune with machetes or pruning shears. Varying the pruning height up or down by 5 to 10

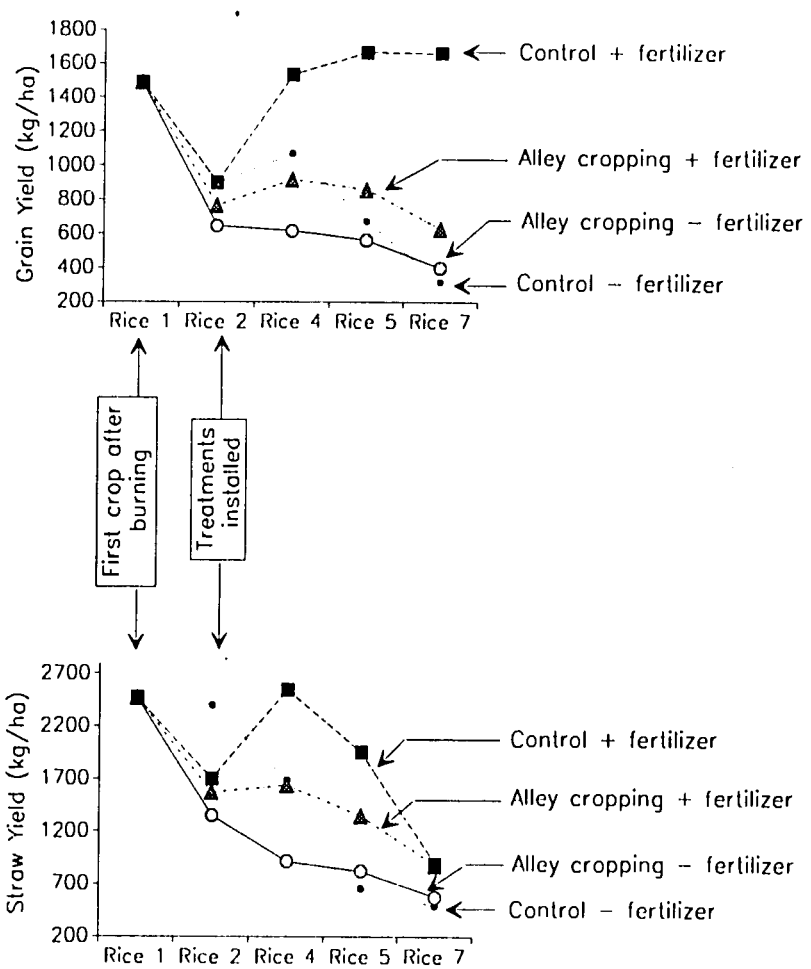

Figure 1. Mean rice grain and straw yields for alley-cropped and non-alley-cropped (fertilized and unfertilized) controls for five consecutive rice crops.

cm at each pruning appears to be important for *Inga edulis*, as observations indicated a marked decrease in vigor and resprouting if the stem were repeatedly pruned at the same height.

Crops were harvested by row in order to estimate the regression relationship between crop yields and the distance from the hedgerow. The remainder of the within-plot variation was used as an error term to test the polynomial components of the row-to-row variation.

Results

Data for seven consecutive crops show that alley-cropping yields were generally lower than non-alley-cropped controls (Figure 1). In alley-cropped plots, grain yields were significantly higher for +M versus –M only for crop 2, higher for +F versus –F for crops 4 to 7, and higher for +R versus –R plots for crops 5 to 7 (Figure 2). Reduced crop yields due to root competition between hedgerows and crops in the alleys were detected at 11 months after hedgerow establishment, and competition increased with the age of the hedgerow, as measured by steadily declining crop yields close to the hedgerow (Figure 3).

Soil available P, along with exchangeable Ca and Mg, increased significantly only in +F versus –F plots, with exchangeable acidity and Al saturation showing a reverse trend. Weed biomass was significantly higher in +F versus –F plots and significantly lower in +M versus –M plots. Mean pruning yields of inga hedgerows ranged from 2.69 to 3.72 Mg/ha/pruning, with significantly higher N, P, K, Ca, and Mg content of prunings from hedgerows next to fertilized alleys than from nonfertilized alleys. The data provide evidence of the nutrient recycling capacity of the hedgerow trees.

Despite the large amount of nutrients recycled in inga prunings applied as mulch and the reduced weed biomass in mulched versus nonmulched plots, crop yields from alley-cropped plots were generally lower than yields from non-alley-cropped controls. Other studies have shown that inga leaves decompose slowly, with close to 70% of original leaf mass remaining after 30 weeks of decomposition. The major factors responsible for low crop yields are probably increasing root competition between hedgerows and crops, asynchrony of nutrient release from slow-decomposing inga mulch, and nutrient demand by crops.

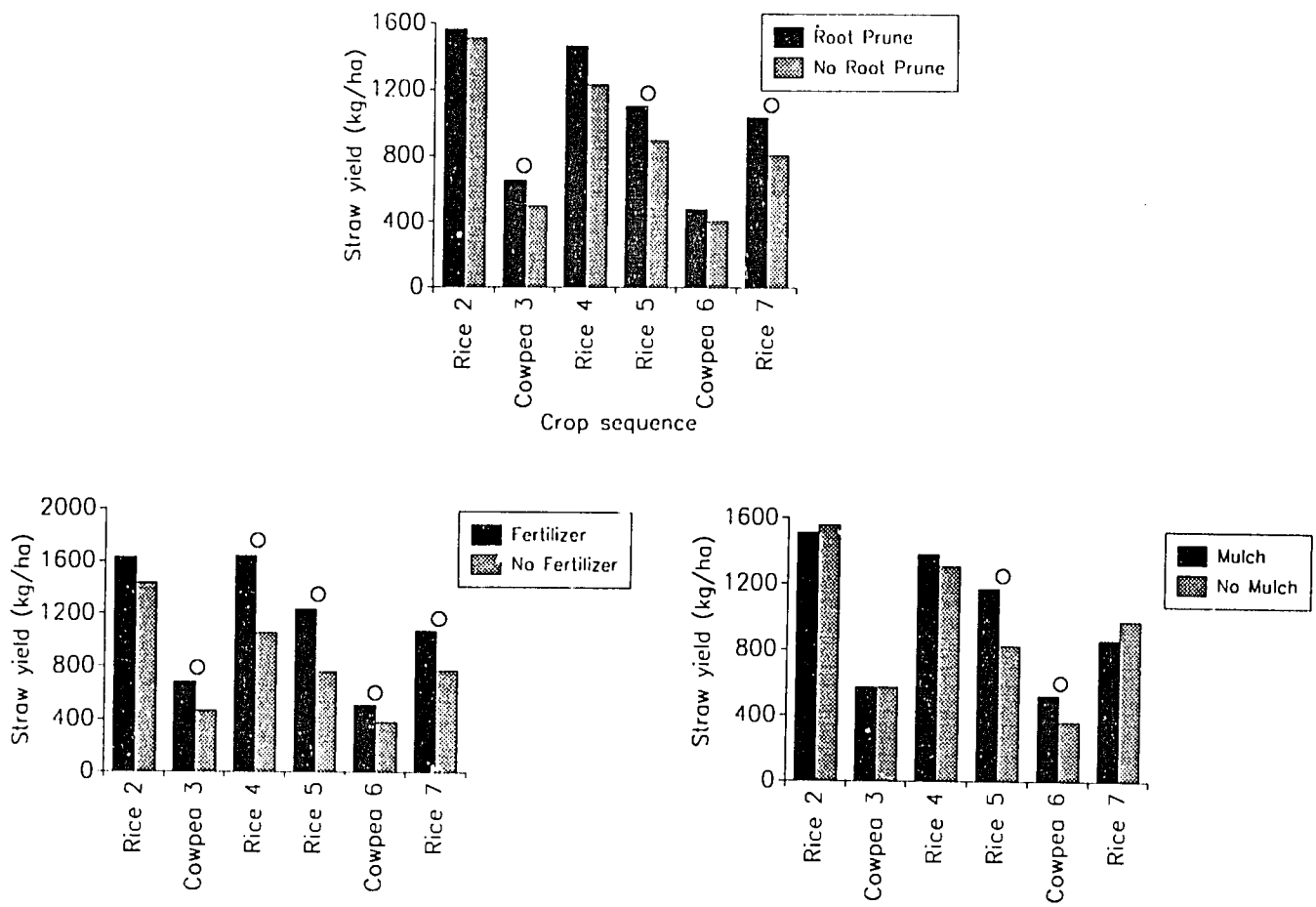

Figure 2. Mulch, fertilizer, and hedgerow root-pruning effects on rice and cowpea straw yields (circles indicate significantly different at $p < 0.05$).

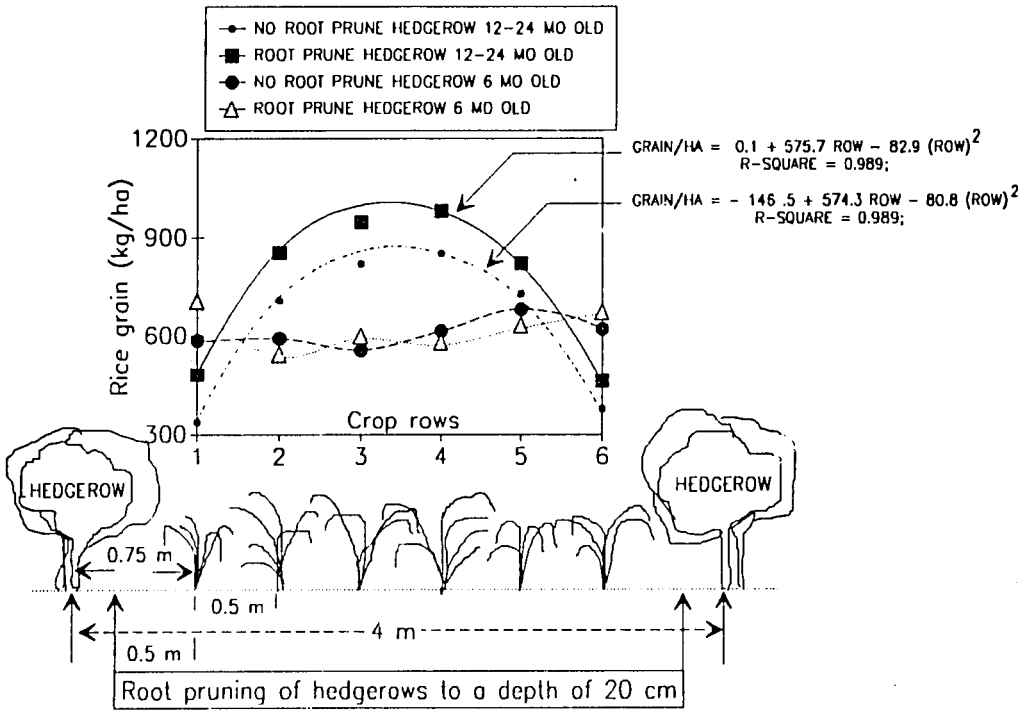

Figure 3. Rice grain yield with distance from hedgerow as affected by age of hedgerow and pruning of hedgerow roots.

Runoff and Erosion Losses Under Forest Low-input and Alley-cropping on Slopes: Y-433B

Julio C. Alegre, N.C. State University
Erick C. M. Fernandes, N.C. State University

Mulch or crop residues have proven very efficient in soil and water conservation. Furthermore, on-site vegetation can provide a barrier to soil erosion, especially on slopes. Alley-cropping originated on the heavily populated slopes of southeast Asia. The tree hedgerows planted along the contour help stabilize the slopes and allow for continued crop production. Although slopes provide perhaps the most promising use of this land-management practice, little research has been done on them.

Objective

The objective of this study was to measure and compare soil and water erosion on slopes for three systems: forest, low-input, and alley-cropping.

Procedures

The study was installed in the previously descril ley-cropping study. Slopes at the site ranged betwee. 5 and 20%. The soil's texture was a relatively uniform sandy clay loam.

One rice (Carolina var.) crop was planted to reduce site variability. In March 1988, two treatments with three reps were installed: 1) low-input continuous cropping with a rotation of rice and cowpea planted in rows along the contour (all residues were left on the soil surface); 2) hedges of *Inga edulis* planted along the contour with 4 m between hedges. A rice-cowpea rotation was grown between the hedges, and prunings from the trees and crop residues were placed on the soil surface. Two additional plots (secondary-forest and bare-plot) with no replications were also included.

Table 2. Erosion and runoff from December 1988 through August 1989.

Treatments	Erosion	Runoff	Runoff
	t/ha	mm	%
Continuous cropping	2.32	57.4	4.4
Alley-cropping§	0.60	11.0	0.8
Forest§	0.07	3.5	0.3
Bare plot¶	13.00	241.0	4.4

§ Total rain: 1317 mm (nine months).
¶ From March 1989 to August 1989: 545 mm rain.

Eight runoff plots 22 m long by 2 m wide were installed in December 1988. Each runoff plot had wooden borders on three sides to keep out runoff from surrounding areas. On the remaining downhill side, a system of cylinders collected water and sediment. The first cylinder (200 L) of each plot had a multislot divisor with eleven slots. The central slot led to a second cylinder (100 liters), which accumulated one-eleventh of the runoff water that overflowed from the first cylinder. Rainfall was read daily from a recording rain gauge, and water runoff was read the day after a rainfall event.

Results

During 1988, the total precipitation was 1700 mm, well below the long-term average of 2200 mm. Rainfall in 1989 was also below the long-term average. Crop yields were not significantly different for the hedge and low-input systems (Table 1). In general, yields were low in both due to late planting or diseases (virus in cowpea).

Preliminary data for soil erosion and runoff during nine months are shown in Table 2. There were few intense

Table 1. Grain and stover yields for five crops grown on slopes by different management practices.

	2nd Rice		3rd Cowpea		4th Rice		5th Rice		6th Cowpea	
Treatment	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
	t/ha									
Continuous cropping	0.93	1.79	0.38	0.52	1.09	1.43	0.52	0.55	0.53	0.43
Alley-cropping	0.93	1.70	0.33	0.49	0.81	0.90	0.44	0.43	0.35	0.32

§ The first rice crop was planted uniformly over the whole area before the treatments were installed. Mean grain yield was 1.5 t/ha.

rainfall events during the period of measurement. The low-input cropping system had approximately four times the erosion and runoff of the alley-cropping system. Runoff losses from the secondary forest were very low. Losses from the bare plots were very high, five times that of continuous-cropping plots and 21 times that of the alley-cropping systems. Consistent long-term data are not yet available, but the preliminary results are promising for slope stabilization through alley-cropping.

Vesicular-Arbuscular Mycorrhizae and the Growth of Tropical Leguminous Tree and Pasture Legumes in Acid Soils, Part I: Rock Phosphate Effects: Y-437

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G. Meléndez, INIAA, Yurimaguas, Peru

The potential contributions of leguminous tree, crop, and pasture species to the productivity and sustainability of low-input land-use systems are often not realized on acid soils because of low phosphorus availability, high aluminum toxicity, low exchangeable base contents, and low nutrient reserves.

Leguminous species require large amounts of P for growth, nodulation, and nitrogen fixation. Consequently, they are often unable to grow on acid soils with low available P. Research has shown that effective associations between many leguminous species and VA mycorrhizal fungi significantly improve growth and nitrogen fixation relative to nonmycorrhizal plants in P-deficient soils. Increased productivity of mycorrhizal leguminous species has also been reported for soils with low P content where 20 to 50 kg/ha of P was applied either in soluble form or as rock phosphate.

In P-deficient soils, VA mycorrhizal fungi increase plant growth by enhancing P uptake. Plant species differ in their growth responses to VAM fungal infection depending upon their demand for P and their ability to absorb it from the soil. Species having a low root density or few root hairs are very dependent on mycorrhizae. Although leguminous species are generally quite dependent on VAM for good growth on P-deficient soils, the dependency varies with the plant species, the soil-available P level, and the species of VA mycorrhizal fungi involved.

Despite the potential of agroforestry systems to contribute to a sustainable level of production on acid soils in the tropics, relatively few leguminous tree species have been systematically evaluated for their mycorrhizal dependencies and for associations with VA mycorrhizal fungi adapted to acid soils. Effective VAM in leguminous species could be important for increasing plant productivity in the tropics for several reasons: the low available soil P of many tropical soils, the high cost of importing soluble P fertilizers or the raw materials (e.g. H_2SO_4) for manufacturing soluble phosphate fertilizers, and the mycorrhizal dependency of many tropical legumes.

Objectives

The predominant VA mycorrhizal fungi in Ultisols at Yurimaguas were identified and used as inocula in a

greenhouse experiment. The objective was to determine the effects of levels of rock phosphate applications and mycorrhizal infection on nitrogen and phosphorus accumulation in several leguminous species used in alley-cropping and pasture systems on acid soils in the humid tropics.

Procedures

A Yurimaguas series soil was collected from a 15-year-old secondary forest. The soil was sieved (4 mm) and thoroughly mixed. Portions (7 kg, dry weight basis) were then transferred to heavy-gauge polythene pots. The pots containing the soil were fumigated in a gas-tight enclosure by exposing them to 48 g of methyl bromide and 1.0 g of chloropicrin for five days. The pots were removed from the enclosure and left to stand for 10 days to allow the fumigants to dissipate from the soil. Before sterilization, the soil pH was 4.6; P 5.9 mg/kg (modified Olsen extract); exchangeable acidity 0.89; Ca 0.50, Mg 0.10, K 0.06 cmol$_c$/L; and aluminum saturation 57%. Fumigation doubled the level of available soil P but did not significantly change the nutrient levels. Since the soil was thoroughly sieved before fumigation, it is assumed that the increased P after fumigation originated mainly from microbial biomass.

Pot cultures of native VAM fungal species were established by inoculating fumigated soil with fine roots from a range of annual crops, pasture, and tree production systems at the experiment station. Corn was the host plant, and after three months of growth, spores of VA mycorrhizal fungi were excised by wet-sieving and decanting.

The experimental design was a 4 x 4 x 3 factorial consisting of four plant species, four inoculation treatments, and three P treatments. The plant species comprised two tree species (*Inga edulis* Mart. and *Erythrina* sp.) and two pasture species (*Centrosema macrocarpum* Benth. CIAT 5412 and *Desmodium ovalifolium* Wall). The inoculation treatments included no inoculation (OI), native rhizobia (R), native VA mycorrhizal fungi (M), and native VA mycorrhizal fungi plus native rhizobia (MR). The P treatments were 0, 7.7, and 15.4 mg P/kg as Bayovar rock phosphate (equivalent to 0, 20, and 40 kg P/ha, assuming a 20 cm depth of soil/ha and bulk density of 1.3 g/cm). The 48 treatments were replicated six times and arranged on greenhouse benches in a completely randomized design.

Plants were harvested after 80 days of growth because differences between treatments appeared to be at a maximum. In addition, rerandomization of plants became increasingly difficult because they were large. Plants of *Desmodium ovalifolium* failed to grow in all the treatments, so the species was eliminated from the trial.

Results

The most prevalent species of VA mycorrhizal fungi encountered in the acid soil at Yurimaguas and used as inocula included *Acaulospora foveata*, *Acaulospora spinosa*, *Scutellospora heterogama*, and *Gigaspora decipiens*. Percent root length of *Erythrina* sp. and *I. edulis* colonized by VA mycorrhizal fungi increased with added P, while that of *C. macrocarpum* increased to a maximum at 20 kg P/ha and then declined slightly at 40

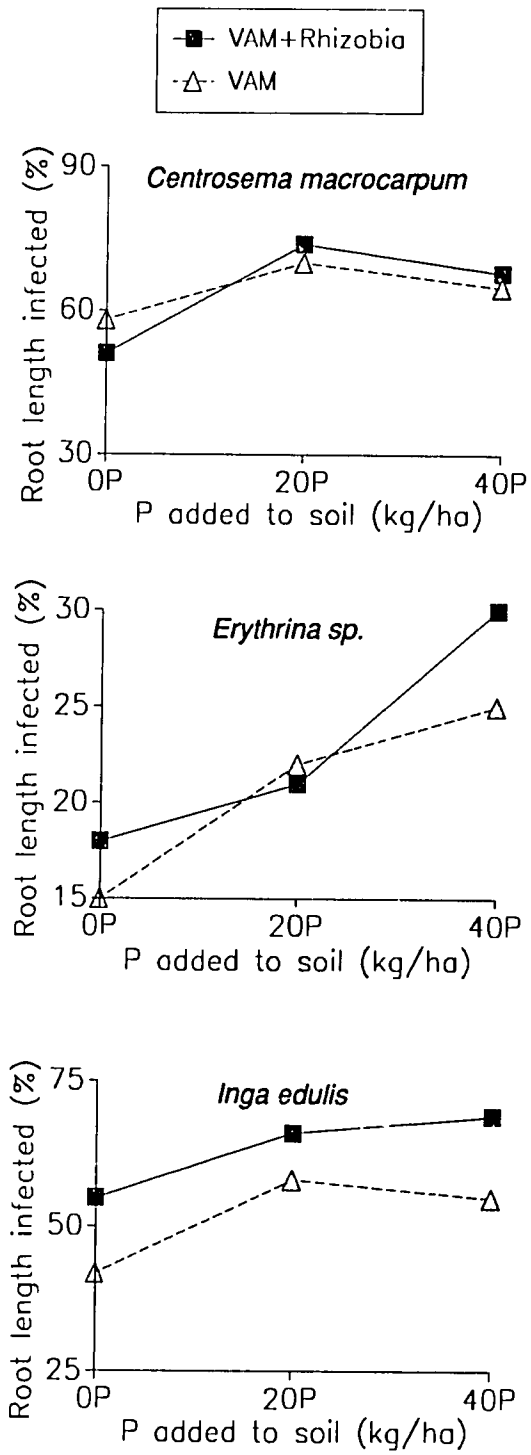

Figure 1. Effect of P applied as rock phosphate on infection by VAM fungi.

kg P/ha (Figure 1). The exception to the decline was erythrina, whose percent root length colonized by VAM increased continuously with added phosphorus.

Shoot, root, and total plant dry weights were significantly correlated with percent root length infected with vesicular-arbuscular mycorrhizae (VAM). Shoot dry weights of all species increased significantly with the addition of 20 and 40 kg P/ha. Plants without mycorrhizae needed additions of between 30 and 40 kg P/ha (Bayovar rock phosphate) to achieve the same shoot dry weight as mycorrhizal plants without P additions (Figure 2). Increasing plant P content increased the nodulation and nitrogen content of inga, erythrina, and centrosema. Plants inoculated with both VA mycorrhizal fungi and rhizobia had more nodules and higher shoot N than plants inoculated with rhizobia alone.

Increasing soil phosphorus availability via the addition of rock phosphate increased shoot P content, shoot N content, and the numbers of nodules of *C. macrocarpum*, *Erythrina* sp., and *I. edulis*. Increasing plant P content increased the nodulation and nitrogen content of centrosema, rythrina, and inga. Plants inoculated with MR had a significantly greater number of nodules than plants inoculated with R.

Native VA mycorrhizal fungi effectively colonized the roots of *Centrosema macrocarpum*, *Erythrina* sp., and *Inga edulis* at available soil P levels between 11.3 and 20.8 mg/kg (modified Olsen extract). It is important to note that the responses to VAM were obtained despite an initial available-P level of 11 mg/kg (Olsen), which is probably above the critical level for acid-tolerant legumes. The improvement in growth and nodulation by VA mycorrhizal fungi at this relatively high P level supports the importance of VAM for inga, erythrina, and centrosema.

Implications

Since the status of VAM fungal inoculum in the field is unpredictable, the initial survival and subsequent productivity of nitrogen-fixing tree species used in agroforestry could be significantly improved by ensuring adequate levels of effective VAM fungal inoculum in the nursery seed beds used for seedling production. Tree seedlings with a high percentage of their root systems infected with VAM fungi are likely to establish quickly and be more productive in the field than directly seeded or poorly mycorrhizal plants.

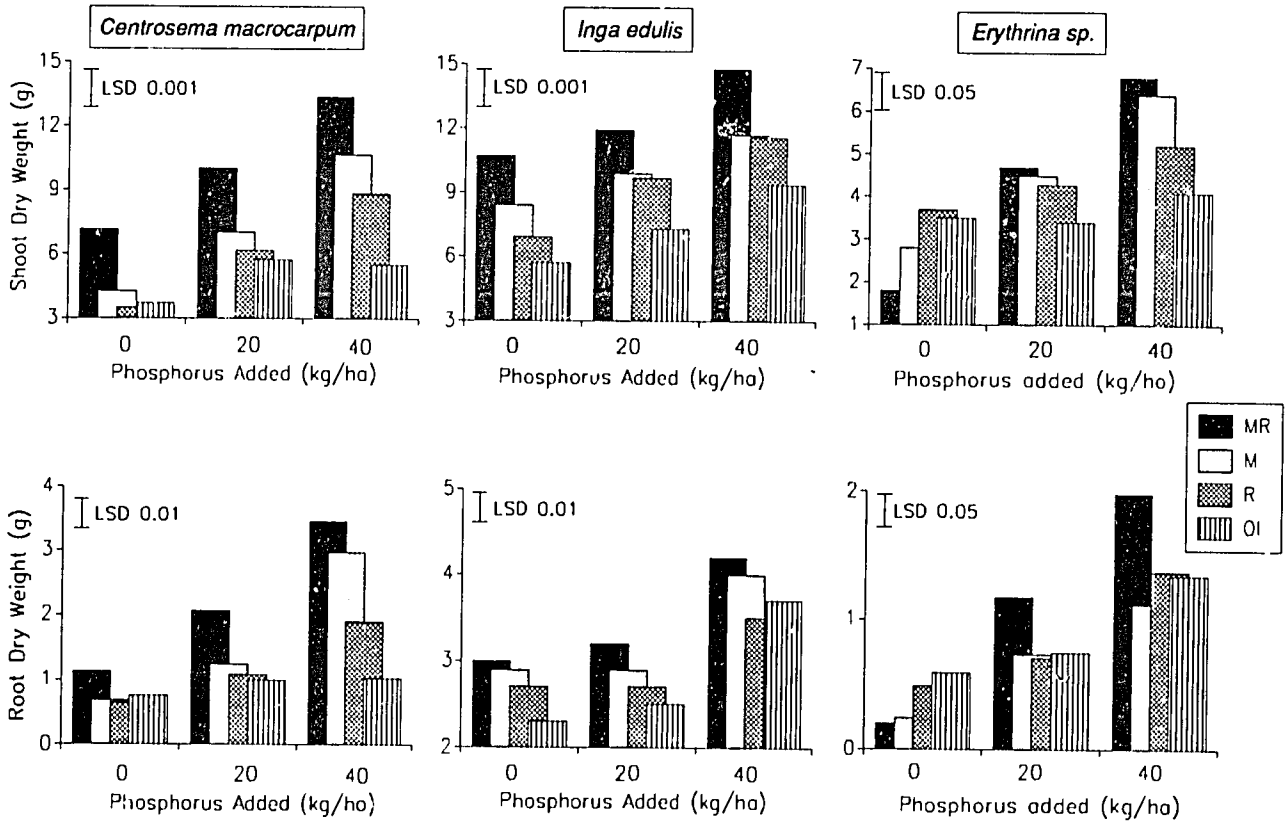

Figure 2. Effect of inoculation with mycorrhizae + rhizobia (MR), mycorrhizae (M), and rhizobia (R), and no innoculation (OI) on shoot and root dry weight of *Centrosema macrocarpum*, *Inga edulis*, and *Erythrina* sp. in pasteurized soil.

Vesicular-Arbuscular Mycorrhizae and the Growth of Tropical Leguminous Tree and Pasture Species in Acid Soils, Part II: Shoot-Pruning Effects: Y-436

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The management of leguminous tree and forage species in many agroforestry systems involves cutting the shoots for green manure, mulch, wood, and livestock forage or fodder. The excessive removal of shoots can severely reduce regrowth, and in some cases, the plant dies. It is a common observation in the literature that shoot removal causes a reduction in root growth. Within a few hours following defoliation, all root growth can stop, a condition eventually leading to increased root mortality.

The effects of leguminous-species management (such as pruning or grazing) on the dynamics of root growth, infection by arbuscular (VA) mycorrhizal fungi, and nodulation are relatively unknown and constitute one of the fundamental research gaps in agroforestry.

In pastures, grazing of aboveground biomass results in decreased root biomass. Research on pruning the shoots of leguminous tree species indicates that the greater the shoot biomass removed in pruning, the slower the subsequent regrowth of the shoot, presumably due to greater reductions in root growth by the heavier pruning. In addition to reduced levels of available photosynthate for nodules and VA mycorrhizal fungi, root mortality due to shoot pruning or grazing may result in decreased levels of infection by VA mycorrhizae, thereby reducing P uptake, nodule activity, and regrowth of the entire leguminous host species.

Objectives

The objectives of this study were to measure how shoot pruning of *Inga edulis* Mart. (a tree species) and *Centrosema macrocarpum* Benth. (a forage species) influences the following: 1) shoot and root dynamics, VAM fungal infection, and nodulation and 2) nitrogen and phosphorus accumulation in shoot regrowth.

Procedures

The experiment was conducted in a greenhouse as a 2 x 4 x 5 factorial consisting of two plant species, four shoot-pruning intensities, and five sampling times. The plant species included a tree species (*Inga edulis* Mart.) and a herbaceous forage species (*Centrosema macrocarpum* Benth. CIAT 5412). Shoot-pruning treatments removed 0%, 25%, 50%, and 75% of the leaf biomass. Nonpruned controls were also performed. Shoots were pruned 90 days after sowing the seed. Plants were sampled at 4, 8, 16, 32, and 64 days after shoot pruning. It was decided to sample more frequently immediately after shoot pruning because exploratory observations in the field revealed that rapid changes in the growth of fine roots occurred in the first two weeks following shoot pruning. The 40 treatments were replicated 10 times and arranged on greenhouse benches in a completely randomized design.

Soil for the experiment (Typic Paleudult) was collected from the topsoil (0 to 15 cm) of a secondary forest. The soil had a pH value of 4.7; P 2.6 mg/kg (modified Olsen extract); exchangeable acidity 1.5; Ca 0.42, Mg 0.06, K 0.05 cmol$_c$/L; and an aluminum saturation of 74%. The soil was sieved (4 mm) and thoroughly mixed. Portions (7 kg, dry weight basis) were then transferred to heavy-gauge polythene pots. Bayovar rock phosphate (13% P content) equivalent to 20 kg P/ha was added to each pot and thoroughly mixed into the soil. Before the seed was sown, the soil received the following nutrients in solution: the equivalent of 30 kg K, 50 kg Ca, 20 kg Mg, 3 kg Zn, 1 kg Cu, 1 kg B, and 0.5 kg Mo/ha.

Results

Intensified shoot pruning reduced the total root biomass of both inga and centrosema. Pruned inga (Figure 1) regrew roots more rapidly than did centrosema. At a shoot-pruning intensity of 75%, centrosema plants recovered total root biomass within 64 DASP (day after shoot pruning), whereas inga had a significantly lower total root biomass for the lowest shoot pruning intensity of 25%, even at 64 DASP.

Shoot pruning significantly reduced only the fine-root growth of centrosema, whereas both fine- and coarse-root biomass of inga decreased with increased pruning intensity. Remobilization of root-storage carbohydrates and/or proteins may be important in shoot and root regrowth following pruning of inga. As root biomass declined, P concentration in the shoots increased (especially for inga), despite increasing shoot biomass. The data suggest translocation of P from dying roots to the shoots.

Shoot pruning resulted in a decline in percent root length infected by VA mycorrhizal fungi (Figure 2). In Centrosema, recolonization of fine roots commenced within 16 DASP, and total root length infected with VA mycorrhizal fungi was significantly lower than control plants at 64 DASP only for 75% shoot-pruning intensity. Infection levels in inga did not increase till 32 DASP, and total root length infected at 64 DASP was significantly lower than controls for both 50% and 75% shoot-pruning intensities. Plant biomass was significantly correlated with total root length infected by VA mycorrhizal fungi at all pruning intensities for centrosema and the nonpruned plants of inga.

A significant decrease in the number of active nodules in pruned relative to nonpruned plants was detected at 16 DASP for inga and 32 DASP for centrosema. Inga plants at 75% shoot-pruning intensity had significantly lower numbers of active nodules than did controls and other pruning intensities. Despite the significant increase in active nodules between 32 and 64 DASP at shoot-pruning intensities of 25% and 50%, shoot nitrogen content equalled or exceeded that of control plants only for the 25% shoot-pruning level. At higher shoot-pruning intensities, the percentage of total root length infected with VA mycorrhizal fungi and shoot P content was significantly lower than for nonpruned plants.

Conclusions

Caution is required in the extrapolation of these results to the field management of tree and pasture species. Nevertheless, the general trends of shoot and root responses to pruning are likely to be similar. For the forage legume *C. macrocarpum*, plant biomass and N and P contents recover to original levels within 32 DASP at a pruning level of 25%. The data fit the specifications for the rotation of animals in pastures where the animals are allowed to graze for 14 days and the grazed pasture is then allowed to recuperate for 28 days (assuming no overgrazing).

The responses of *I. edulis* to shoot pruning (as in alley-cropping) are likely to differ at the field level because the trees are generally much older (10 to 12 months) at first pruning. The data from this experiment show that both fine- and coarse-root biomass decrease after pruning, probably due to the remobilization of storage carbohydrate for shoot regrowth. If one assumes that shoot pruning affects the root growth of 10-month-old hedgerow trees in the same way it affects three-month-old seedlings, root competition between hedgerows and crops for the nutrients released from the prunings might be minimized by cutting the hedgerows two to three weeks prior to sowing the crops.

At shoot-pruning intensities between 25% and 50%, inga plants formed new and active nodules between 32 and 64 DASP, suggesting that the shoot-pruning intervals of between three to four months commonly used in alley-cropping systems would allow the hedgerow trees to improve the soil's N status via nitrogen fixation. On acid soils, more intensive shoot pruning (greater than 50% shoot biomass removed) or more frequent cutting (intervals of 60 days or shorter) is likely not only to reduce root growth, VA mycorrhizal infection of roots, and nitrogen fixation by the hedgerow trees, but may also lead to tree death.

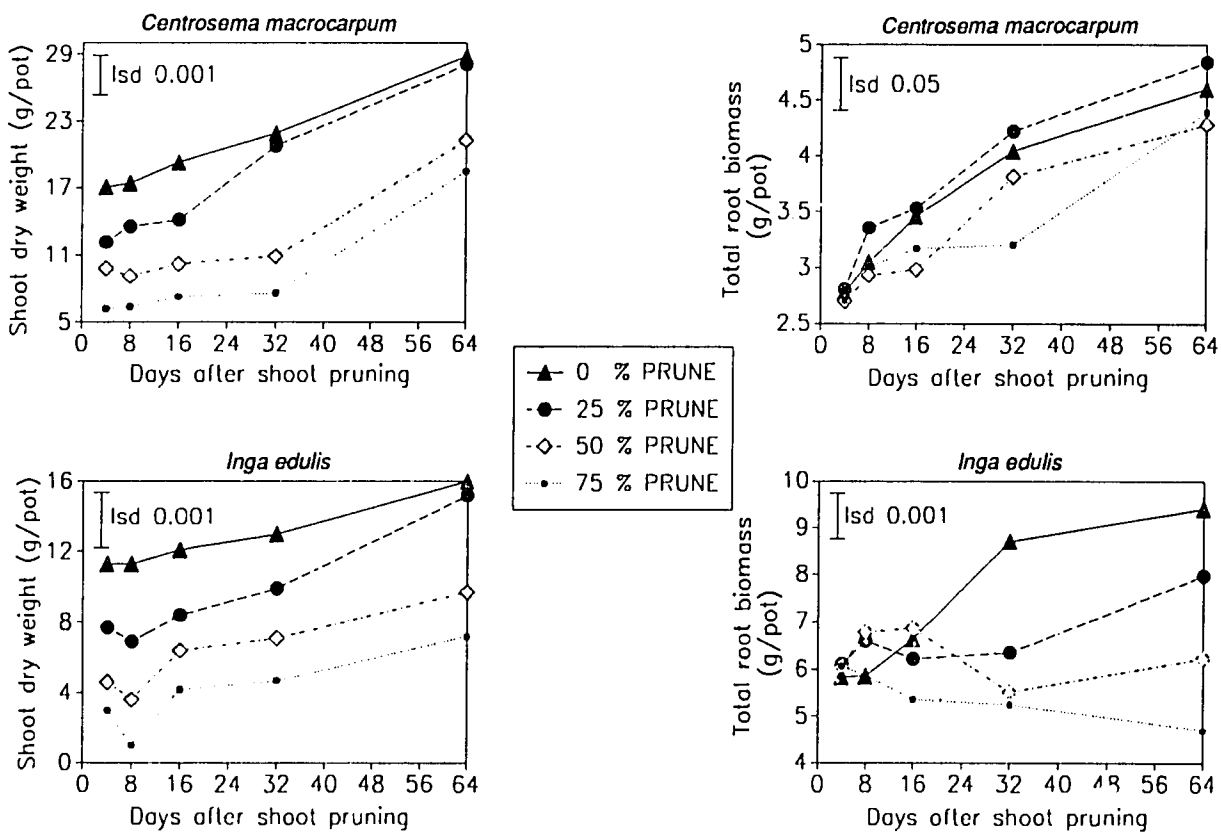

Figure 1. Effect of shoot-pruning intensity on shoot and root biomass of *Centrosema macrocarpum* and *Inga edulis* at different times after shoot pruning.

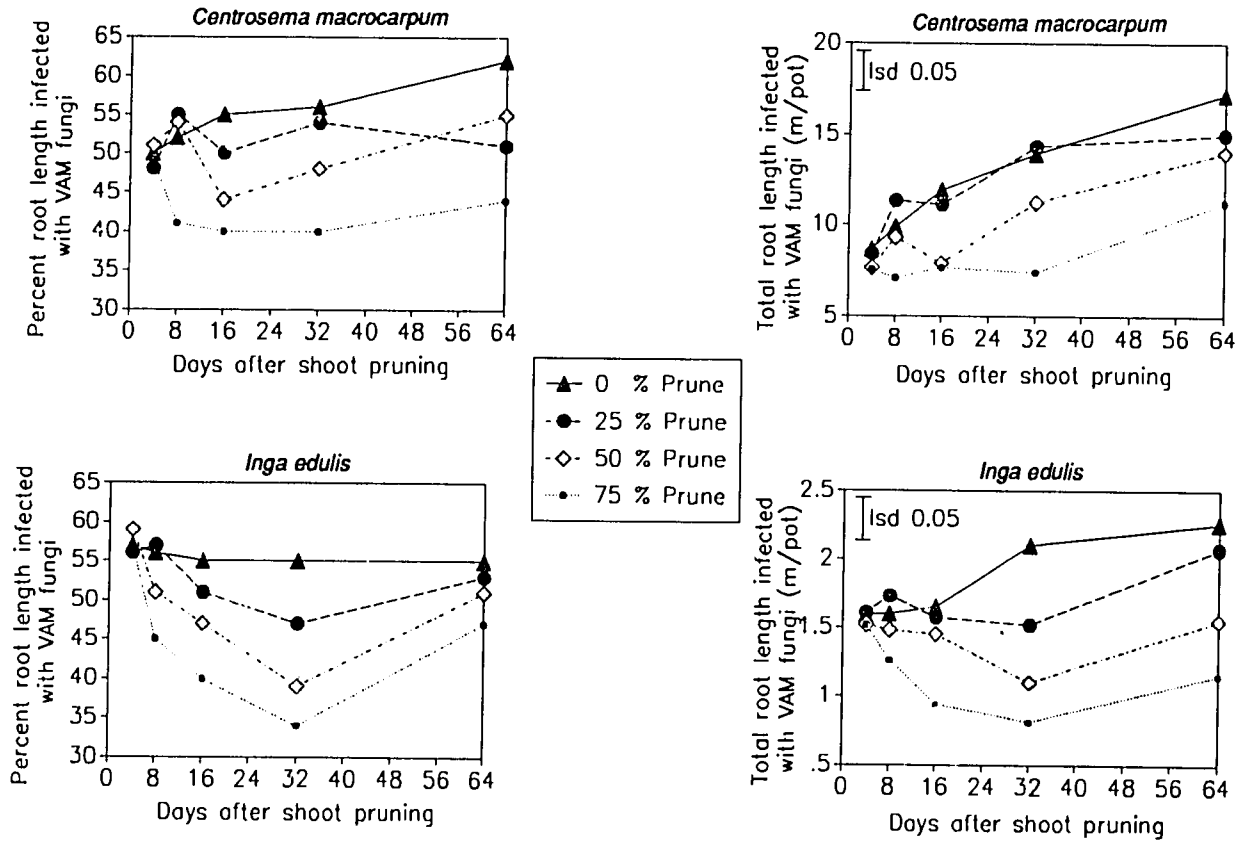

Figure 2. Effect of shoot-pruning intensity on percent root length of *C. macrocarpum* and *I. edulis* infected with VAM fungi at different times after shoot pruning.

Crop Yields, Soil Nitrogen Mineralization, and Soil Chemical Properties Following 4.5 years of Managed Leguminous Fallows: Y-409

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Gloria Meléndez, INIAA, Yurimaguas, Peru

In January 1984, seven fallow treatments were established in an abandoned field in a randomized complete-block design with four repetitions. The treatments included the following: *Centrosema macrocarpum* (CM); *Stylosanthes guianensis* (SG); *Pueraria phaseoloides* (PP); *Cajanus cajan* (CC); *Desmodium ovalifolium* (DO); *Inga edulis* (IE); and purma (PUR), the secondary vegetation which invaded naturally. Apart from a hand weeding in the first month after planting, the vegetation was allowed to grow without management for 4.5 years. Results on biomass and nutrient content have been published in previous TropSoils Technical Reports. At 4.5 years, biomass in the fallows was measured, the fallows were cut and burned, and an upland rice-rice-cowpea rotation was planted.

Objectives

The objectives of this study were to determine the effect of the fallow treatments on soil chemical properties, patterns of N mineralization in soil, and crop yields.

Procedures

Grain yields in each of three continuous crops were determined. Routine soil chemical analyses were performed after burning the fallows and after harvesting each crop. Soil N mineralization was also measured two or three times during each crop; two composite samples (0- to 10-cm depth) were taken from each plot, and extractable NH^+_4 and NO^-_3 contents were measured. The soil was incubated in the laboratory under ambient temperature and 75% field moisture capacity. After 10 days, the soil samples were again extracted for NH^+_4 and NO^-_3. The difference in NH^+_4 and NO^{-3} between the two dates was considered the net N mineralized. That figure indicated the N availability of the different treatments

Results

Total mass (live aboveground biomass + roots to a 45-cm depth + litter) at 4.5 years was greatest in the natural fallow and least in the centrosema treatment (Table 1). Treatments with trees (IE, DO, CC, and PUR) had much greater biomass than those without (or with few) trees. Generally, grain yields for all three crops were greater in the IE, DO, CC, and PUR treatments than in the others (Table 2). In comparison with the control (PUR) treatment, relative total yields for the three crops were greater by 21% and 34% in the DO and IE treatments, respectively, but lower by 17%, 35%, and 40% in the SG, CM, and PP treatments. Relative total yields in the CC treatment were similar to the control.

Table 1. Mass accumulated by the fallow treatments after 4.5 years of growth. Mass includes live aboveground biomass, litter, and roots to a soil depth of 45 cm, Yurimaguas, Peru.

Treatment	Mass (t/ha)
CM	7.86
SG	26.33
IE	43.75
CC	35.04
PP	9.28
DO	56.14
PUR	66.42

Changes with time in N mineralization are shown in Table 3. Generally, mineralization was at a maximum in the initial phase of the first crop cycle, declined in the mid-cycle, and then remained relatively constant until the mid-cycle of the second crop. After that, mineralization declined with time, becoming negative in the mid-cycle of the third crop. At the last sampling, mineralization was positive, but very low.

Soil mineralization differed significantly among treatment for certain sampling dates. Except for the control, treating the first crop with greater amounts of biomass at clearing (IE, CC, DO) tended to produce higher mineralization rates. At the other dates, this pattern was reversed, again with the exception of the control. At all dates, mineralization in the control tended to be an intermediate value when compared to the other treatments, even though the control had the highest biomass.

Chemical properties of soil collected 27 days after burning were similar in all treatments. Levels of exchangeable nutrient cations (0.13, 0.54, and 0.25 cmol /L for K, Ca, and Mg, respectively) and available P (6.0 mg/L) were low, and Al saturation percentage was high (85%). After three crops, exchangeable nutrient cation values had decreased in the CM, SG, and PP treatments, but had remained constant or even increased in the IE, DO, CC, and PUR treatments (Table 4). Available P decreased slightly in all treatments, with the exception of IE.

In the first crop cycle, crop yields were more highly correlated with the amount of biomass present at fallow clearing than with the amount of net N mineralized during the cycle (Table 5). In subsequent crop cycles, the correlations of crop yields and net N mineralized were negative. A possible explanation for this pattern is that crop production was limited by nutritional factors, including N, and that treatments with greater biomass (IE,

DO, PUR, CC) contributed greater amounts of nutrients in ash and thus enriched the soil more than did the other treatments. Lower rates of mineralization in the IE, DO, CC, and PUR treatments may have been due to the greater quantity of woody material present in these treatments. Besides buffering the release of nutrient cations, this low-N-containing material may have immobilized N, hence the lower rates of N mineralization.

Conclusions

After 4.5 years of fallow growth, accumulation of biomass and litter was greater in the natural secondary vegetation than in the managed leguminous fallow treatments. Nevertheless, crop yields in the desmodium and inga treatments were 21 and 34% greater than in the natural fallow treatment, indicating that it is possible to improve crop yields by managing fallow vegetation. Crop yields in the other fallow treatments were equal to or less than those in the natural fallow. The improved performance of the desmodium and inga fallows may be related to the storage of greater quantities of nutrients that become available for crop growth upon fallow clearing.

Crop yields in the best treatments were typical of those obtained in the region. Further research is needed to determine how fallow length and the sequence of fallow and cropping periods can be manipulated to improve yields.

Table 2. Absolute (t/ha) and relative (%) grain yields* obtained after clearing and burning the 4.5-year-old managed fallow treatments, Yurimaguas, Peru.

Treatment	Rice 1	Rice 2	Cowpea 1	Total	Relative total yield§
IE	1.82 a	1.14 a	0.62 a	3.58 a	1.34
DO	1.65 ab	1.09 a	0.49 a b	3.22 a b	1.21
CC	1.32 abc	1.12 a	0.54 a b	2.72 a b c	1.02
PUR	1.13 bc	1.08 a	0.46 b	2.67 a b c	1.00
SG	1.43 abc	0.50 b	0.29 c	2.21 b c d	0.83
CM	0.91 c	0.56 b	0.26 c	1.73 c d	0.65
PP	0.98 c	0.41 b	0.20 c	1.60 d	0.60

* Within a given crop cycle, yields having the same letter are not significantly (p = 0.05) different.
§ Relative to the total yield obtained in the PUR treatment.

Table 3. Net N (NH_4 + NO_3) mineralized from soil obtained from the fallow treatments at various times during the first three crops following fallow clearing.

	Treatment						
N min	CM	SG	IE	CC	PP	DO	PUR
				(ug/g/10 days soil)			
Crop 1 (Rice)							
Post-plant.	24.2ab	14.2 b	37.7a	38.9a	25.8ab	34.2a	21.7ab
Mid-cycle	12.2	12.5	14.4	13.6	13.1	14.1	9,9
Harvest	15.5a	10.4 bcd	8.6 cd	7.7 d	12.7abc	10.5	14.31b
Crop 2 (Rice)							
Post-plant.	13.4	13.5	12.8	11.7	13.7	11.4	16.1
Mid-cycle	12.5	11.2	1.2	2.4	10.0	3.3	6.8
Harvest	9.9ab	8.9a bc	5.5 d	6.7 cd	7.6	9.7ab	
Crop 3 (Cowpea)							
Mid-cycle	3.9	-0.6	-0.4	0.6	-0.2	0.1	-1.4
Harvest	3.5ab	3.2a b	3.3a b	3.7a	3.1ab	2.9 b	3.0ab

* For a given date, treatment means followed by the same letter are not significantly different (p = 0.05).
NS = not significant.

Table 4. Topsoil (0 to 15 cm) chemical properties in the fallow treatments one year (three crops) after clearing, Yurimaguas, Peru.

	Exchangeable				
Treatment	Al	Ca	Mg	K	P
	(cmol/L)				(mg/L)
CM	6.0	0.39	0.12	0.07	5
SG	6.1	0.38	0.14	0.08	4
IE	5.1	0.85	0.29	0.14	6
CC	6.3	0.45	0.17	0.11	5
PP	6.2	0.27	0.07	0.06	5
DO	5.8	0.54	0.20	0.11	5
PUR	6.6	0.50	0.21	0.12	5

Table 5. Correlation coefficients (and significance levels) for the relationship between crop yield and fallow biomass present at clearing or total net N mineralized from soil during the course of the crop cycle, Yurimaguas, Peru.

Crop	Fallow biomass	Total net N mineralized
Rice 1	0.70 (0.0004)	0.16 (0.421)
Rice 2	0.38 (0.704)	-0.62 (0.0004)
Cowpea 1	0.35 (0.084)	-0.38 (0.0640)

Viable Weed Seed Pools in Managed Fallows: Y-409D

Lawrence T. Szott, N. C. State University

In comparison to natural secondary vegetation fallows, managed fallows may more rapidly suppress weeds and reduce weed seed pools in soil. Previous work (Szott, Ph.D. dissertation, 1987) has shown that the number of viable weed seeds in the soil 33 months after fallow planting is related to how quickly the planted fallows suppress weeds.

Objectives

The objectives of this study were to evaluate and characterize viable weed seed pools in soil: 1) after 4.5 years of fallow growth, 2) after cutting and burning the fallow vegetation, and 3) after one year of short-cycle food crops.

Procedures

Soil samples were obtained from each of the seven fallow treatments previously described. Two samples, each consisting of six 5.5-cm-diameter cores of the top 5 cm of soil, were taken from random locations in each plot. Each sample was mixed with vermiculite (approximately 10:1 ratio of soil to vermiculite by volume) and placed in a divided tray. Soil filled the trays to a depth of approximately 3 cm. Trays were placed outdoors under a roof and watered daily with rain water. Additional soil was heated at 250°C for five hours to destroy viable seeds. The soil was then placed in four trays as an assay to control for seed contamination during the course of the study.

During 12.5 months, seedlings growing in the trays were identified, counted, and then removed. Soil in the trays was mixed when germinations decreased; soil was mixed a total of four times (including the first). The numbers obtained serve as an index of readily germinating seeds, not the total soil seed pool, since a few seeds were still germinating after one year.

Results

The number of viable weed seeds in the soil before cutting and burning ranged from 3400/m^2 in the stylosanthes treatment to 79000/m2 in the pueraria treatment (Table 1). The low number of germinations in the stylosanthes treatment may be due to the reported allelopathic effects of that species. The high germination rate in pueraria was primarily due to a greater number of germinations of *Lindernia humilis*.

Germinations were distributed among 25 identified species and an additional category: unidentified broad-leaved species. Germination of lindernia accounted for approximately 60 to 70% of the total seed germinations in all treatments. The majority of the remaining germinations

were accounted for by *Panicum trichoides* (5 to 15%), *Pteridium aquilinum* (3 to 10%), *Digitaria sanguinalis* (1 to 8%), *Cyperaceae* spp. (3 to 7%), *Axonopus compressus* (2 to 7%), and unidentified broad-leaved herbaceous plants (2 to 8%). Few seeds from the leguminous fallows or the secondary forest tree species germinated.

After clearing and burning were completed, the number of germinations was reduced by 50 to 75% (Table 2). The number of seed germinations was greatest, and the percentage reduction in germinations least, in the desmodium treatment, mainly due to greater numbers of lindernia, *Cyperaceae* spp., and pteridium than in the other treatments. The number of germinations was least in the stylosanthes treatment, chiefly due to fewer germinations of *Cyperaceae* spp., *Phillanthus corcovadensis*, lindernia, and pteridium than in the other treatments. The greatest percentage reduction in seed germination (approximately 50%) due to clearing and burning was measured in the centrosema and pueraria treatments.

After burning, lindernia still accounted for 45 to 70% of the germinations in all treatments, followed by pteridum (6 to 17%), unidentified broad-leaved weeds (6 to 14%), *Cyperaceae* spp. (3 to 9%), phillanthus (1 to 8%), and *Panicum trichoides* (2 to 5%).

Viable seeds of most species were reduced by clearing and burning. Phillanthus seedlings increased in all treatments, and desmodium increased in the desmodium treatment, perhaps because seeds from desmodium bushes fell onto the soil as a result of clearing. The effect of clearing and burning on the germination of pteridum and unidentified broad-leaved weeds varied. There is a suggestion that germinations in both classes of weeds increased when fires were hotter.

For most weed species in both sets of samples (pre- and post-clearing), the majority of the germinations occurred within a few months of incubation. Germinations of *Cyperaceae* spp., phillanthus, lindernia, and unidentified broad-leaved weeds, however, continued to occur during the latter part of the incubation period, suggesting that soil seed pools of these species are large and/or that these seeds possess dormancy mechanisms.

Conclusions

1) Before and after clearing, *Lindernia humidilis*, a nonpernicious weed, contributed most to the soil's readily germinating seed pool. Grasses and sedges accounted for most of the remaining seed germinations.

Table 1. Numbers (#/m²) of seedlings germinating in soil (0 to 5 cm) obtained from 4.5-year-old managed fallow treatments, Yurimaguas, Peru.

	Fallow treatments[§]						
Weed Class[¶]	CM	SG	IE	CC	PP	DO	SF
TOU	1200	1065	5118	2134	4239	2479	2479
CYP	2319	960	3999	1705	2319	2079	3077
CHP	0	0	0	0	0	0	0
DIG	3877	2134	1065	1974	1599	3093	2678
ESP	30311	18395	39294	35030	54503	46121	18155
HAD	1158	2454	4479	1225	2879	2294	3279
BOR	201	0	374	640	720	54	240
PAT	2601	3413	7838	6024	4917	4693	7998
SHA	3317	2774	4053	3305	7198	1654	3557
TREES	160	854	54	214	281	54	438
LEGS	160	1599	265	105	0	3413	278
OTHER	320	265	214	320	160	54	358
TOTAL	45624	33913	66753	52676	78815	64948	42537

[§]CM = *Centrosema macrocarpum*, SG = *Stylosanthes guianensis*, IE = *Inga edulis*, CC = *Cajanus cajan*, PP = *Pueraria phaseoloides*, DO = *Desmodium ovalifolium*, and SF = natural secondary vegetation.

[¶]TOU = *Axonopus compresus*, CYP = *Cyperaceae* spp., CHP = *Phillanthus corcovadensis*, DIG = *Digitaria sanguinalis*, ESP = *Lindernia humilis*, HAD = unidentified broad-leaved weeds, BOR = *Borrerla leavis*, PAT = *Panicum trichoides*, SHA = *Pteridium aquilium*, TREES = various secondary forest tree species, LEGS = planted leguminous fallow species, and OTHER = other weed species.

2) Clearing and burning reduced readily germinating seed pools by 25 to 50%. The numbers of germinations were reduced for the majority of weed classes. Germinations of phillanthus, pteridium, and some unidentified broad-leaved weeds increased, indicating that these species may become a problem with increasing use of fire as a management tool.

3) Treatments which suppressed weeds during the fallow period (centrosema and stylosanthes) also had smaller soil pools of readily germinating weed seeds. This finding suggests the importance of controlling within-field weed reproduction as a means of reducing weed seed pools in soil and weed populations in succeeding cropping periods.

4) Germinations of weed seeds in soil after one year of cropping are being evaluated.

Table 2. Numbers (#/m²) of seedlings germinating after clearing and burning in managed fallows, Yurimaguas, Peru.

	Fallow treatments§						
Weed Class¶	CM	SG	IE	CC	PP	DO	SF
TOU	560	438	1078	480	601	720	800
CYP	640	601	3237	2038	1238	3519	1855
CHP	281	400	1999	2601	2038	1919	1376
DIG	0	160	240	240	281	121	352
ESP	15714	12956	19393	17153	24911	28152	12828
HAD	1280	2518	3039	2118	2639	2879	3903
BOR	0	80	201	80	41	121	96
PAT	720	1040	1958	1439	1001	1040	1408
SHA	3039	1360	4677	4239	6958	6398	4703
TREES	80	281	201	678	201	160	192
LEGS	0	320	80	80	281	3717	64
OTHER	80	240	358	160	201	240	192
TOTAL	22394 (49%)	20394 (60%)	36461 (55%)	31306 (59%)	40091 (51%)	48986 (75%)	27769 (65%)

§CM = *Centrosema macrocarpum*, SG = *Stylosanthes guianensis*, IE = *Inga edulis*, CC = *Cajanus cajan*, PP = *Pueraria phaseoloides*, DO = *Desmodium ovalifolium*, and SF = natural secondary vegetation.

¶TOU= *Axonopus compressus*, CYP= *Cyperaceae* spp., CHP= *Phillanthus corcovadensis*, DIG= *Digitaria sanguinalis*, ESP= *Lindernia humidilis*, HAD= unidentified broad-leaved herb, BOR= *Borreria leavis*, PAT= *Panicum trichoides*, SHA= *Pteridium aquilinum*, TREES= a variety of secondary forest species, LEGS= planted leguminous fallow species, OTHER= other weed species.

Root Dynamics in a Peach-Palm Plantation and an Undisturbed Forest: Y-435

L. T. Szott, N. C. State University

There are few data on root dynamics in agroforestry systems or undisturbed forests in the humid tropics. Such data are necessary in order to develop an understanding of organic matter and nutrient cycling in these systems.

Objectives

To qualitatively and quantitatively describe root production, mortality, and disappearence during a year in an old secondary forest and a five-year-old peach-palm plantation associated with a leguminous (*Centrosema macrocarpum*) cover crop.

Procedures

Two compelementary techniques were used to gather root data: sequential coring and mini-rhizotrons.

Sequential Coring

Sequential coring was done at monthly intervals. At each date, five random points were sampled along three transects in the undisturbed forest. In the palm plantation, a stratified random sampling method was used: at each of four trees, samples were taken at 0.5, 1.0, 1.5, and 2.0 m from the trunk along a compass heading randomly chosen for each tree. A fifth point, whose distance from the trunk along the same heading varied randomly between 2.0 m and 5.0 m, was also included. A preliminary study has shown that at distances from the trunk greater than 2.0 m, root biomass distribution was effectively random with respect to distance.

Soil cores 42 mm in diameter were taken to a depth of 50 cm, separated into three portions (0 to 15, 15 to 30, and 30 to 50 cm), and the roots were separated from the soil by hydropneumatic elutriation. After elutriation, live and dead roots were manually separated from intermixed organic detritus and were then further divided into two classes based on diameter: fine (< 2 mm diameter) and coarse (> 2 mm diameter). Roots from the palm plantation were also classified according to plant types—palm and other—resulting in a total of eight root categories for the plantation.

After classification, roots were dried and weighed. Subsamples were then taken for nutrient analyses and ashing. All weights reported were corrected for ash.

Mini-rhizotions

Root observation boxes, or rhizotions having a wood frame and a plexiglass viewing surface, were constructed. Four boxes were installed at four random locations in the undisturbed forest and palm plantation so that the viewing surface (20-cm width by 12.5-cm length) began at a soil depth of approximately 4 cm. Each box had four viewing surfaces.

At intervals of two weeks, live and clearly dead roots found next to the viewing surface were traced onto transparent plastic sheets with waterproof pens.

Lengths of live and dead roots will be estimated using a leaf-area meter or the modified Newman root-intersection method. The results will provide a qualitative estimate of temporal patterns of root production and mortality.

Results

Root sampling has been performed at monthly intervals for six months and will continue for another six months.

Undisturbed Forest

Figure 1 depicts the temporal changes in root mass (live and dead) to a depth of 50 cm in the undisturbed forest. Total live and dead roots fluctuated over time, and the mass of live roots greatly exceeded that of the dead.

Temporal fluctuations in live root mass may in fact have occurred. However, since 65 to 80% of live roots are coarse, the fluctuations may also be an artifact of the sampling method: it is difficult to obtain good estimates of coarse root mass by sequential coring.

The mass of live fine roots fluctuated around 3 to 4 t/ha during the first four months, but remained constant thereafter at around 3.5 t/ha. Live fine-root mass appears to increase with increasing rainfall and to decrease during dry periods. The mass of dead fine roots declined slowly with time (from approximately 1.5 t/ha to 0.7 t/ha), without large temporal fluctuations. The decline in dead root mass appears to accelerate with the onset of rains, perhaps because of the decreased mortality of live fine

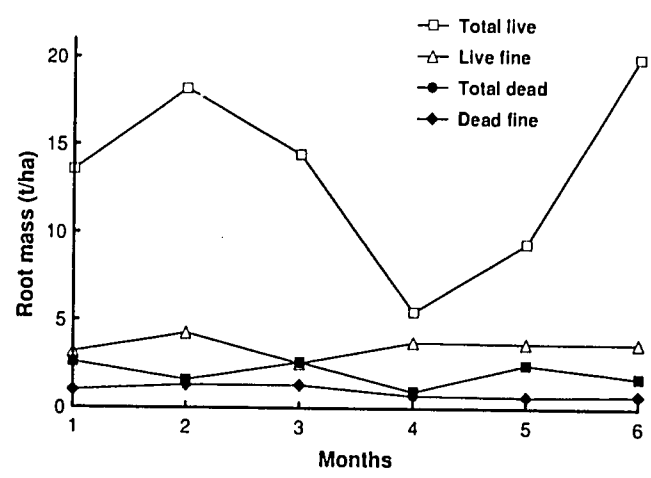

Figure 1. Temporal changes in root mass to a depth of 50 cm in an undisturbed, old secondary forest. Fine roots are those with diameters < 2 mm. Data were obtained by sequential coring, Yurimaguas, Peru.

roots and/or the increased decomposition rates (and disappearence) of dead roots.

Both total live and live fine roots were concentrated in the top 15 cm of soil (50 to 90% and 60 to 70%, respectively, depending on the sampling date). The remaining roots were about equally distributed between the 15- to 30-cm and 30- to 50-cm soil layers. Given this pattern, it is not surprising that 60 to 75% of the dead fine roots were also found in the top 15 cm of soil; the percentage of dead fine roots in the lower soil horizons, however, declined with depth.

Peach-palm Plantation

Total live-root biomass exceeded total dead-root biomass by four to six times, and the majority of live- and dead-root biomass in the peach-palm plantation was contributed by the palms (Figure 2). Due to the predominance of peach-palm roots, the remaining discussion will focus on those roots alone.

Most live peach-palm roots were coarse (> 2 mm diameter). Fine roots accounted for 20 to 30% of the total live-root mass, and 50 to 60% of the total dead-root mass. Live fine-root mass fluctuated greatly over time; fluctuations in dead fine-root mass were of lesser magnitude.

Approximately 65% of the mass of the peach palms' live roots and live fine roots were concentrated in the top 15 cm of soil; about 20% in the 15- to 30-cm layer; and 15% in the 30- to 50-cm layer. Approximately 70%, 20%, and 10% of the total dead and dead fine roots were found, respectively, in the following horizons: 0–15, 15–30, and 30–50 cm.

Mass tended to decrease curvilinearly with distance from the bole for the following root categories: live fine, total dead, and dead fine. Quantities of root mass found at distances greater than 2.5 m from the bole were about 50% of that at 0.5 m from the bole. Total live roots, however, tended to increase between 2.0 and 2.5 m from the bole. Since total live root mass showed a clear trendency to decrease with distance (up to 2 m) from the bole, the increase at distances greater than 2 m may be an artifact of the sampling method.

The magnitudes and temporal trends of live fine-root masses in the palm plantation and the undisturbed forest were very similar. The mass of total dead and dead fine roots in the plantation exceeded that in the forest. However, temporal trends in total dead-root mass were similar in both systems during the latter four months. Temporal fluctuations in the mass of dead fine roots were greater in the plantation than in the forest.

Implications

Broadly similar temporal trends and fine-root masses suggest that root dynamics in both ecosystems are respoding similarly to environmental variation. Calculations of root production and mortality via the balancing transfer method will be based only on significant differences in root mass between sampling intervals. Calculations of live- and dead-root length using data from the rhizotions will serve as a check on the results from sequential coring and will enable us to estimate root production and mortality during periods when these appear to be constant based on the latter method.

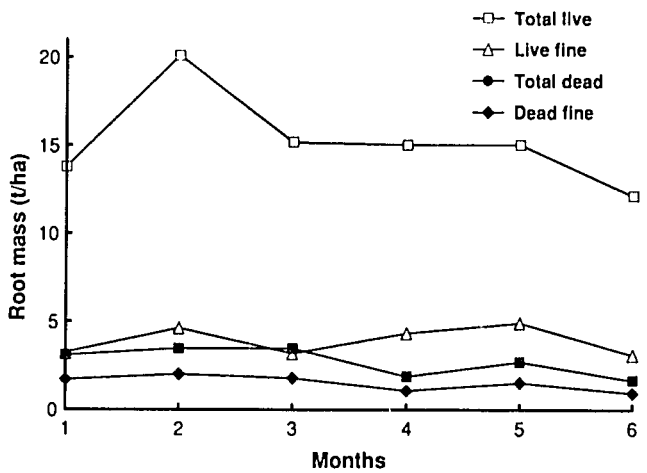

Figure 2. Temporal changes in root mass in a peach-palm (*Bactris gasipeaes*) plantation having a *Centrosema macrocarpum* cover crop. Fine roots are those with diameters < 2 mm. Data were obtained by sequential coring, Yurimaguas, Peru.

Continuous Cropping: NC-1

Alternatives to Tropical Deforestation: Y-100

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Recent estimates indicate that about 18% of all global warming is caused by the clearing of tropical rainforests. Each year, 14 million hectares of primary forests disappear. Deforestation is also decimating the world's largest depository of plant and animal diversity. Tropical deforestation is driven by a complex set of demographic, biological, social, and economic forces (Figure 1). Third World population growth continues at a high rate, while most of the fertile and accessible lands are used intensively. Government policies often exacerbate land scarcity by allowing gross inequities in land tenure. These factors increase the landless rural population, which essentially has three choices: stagnate where they are, migrate to the cities, or migrate to the rainforests that constitute the frontier of many Third World countries. Although urban migrations occur spontaneously, migrations to rainforests in such key countries as Brazil, Peru, and Indonesia are the result of national colonization programs.

Densely populated rural environments such as the Andean valleys, Northeast Brazil, and Java suffer from ever-decreasing farm size and overuse of steeplands. These changes cause widespread soil erosion, siltation of reservoirs, and other off-site problems. Migration to the cities brings disappointment rather than a better life, in part because populations far exceed cities' carrying capacity and infrastructure.

Migration to the humid tropics seldom results in a cornucopia (with a few notable exceptions). The equilibrium between the rainforest and the shifting cultivation practiced by traditional societies is broken by the colonists and, in some countries, by land speculators as well. As a result, shifting cultivation is quickly replaced by various forms of unsustainable agriculture. Traditional societies are disrupted, economic failures abound, and migration to urban centers follows.

The two end points are urban unemployment and further deforestation. The former causes abject poverty, which leads to widespread crime, poor health, and in many cases social upheaval. Deforestation depletes the ecosystems' limited nutrient capital; decimates plant and animal genetic diversity; and accelerates global warming due to carbon dioxide, methane, and nitrous oxide emissions.

Strategies Toward a Solution

Strategies that attempt to mitigate tropical deforestation include 1) developing both the economy and a more equitable system of land tenure in densely populated areas; 2) encouraging migration to less fragile areas, such as the Cerrado of Brazil; 3) preserving the remaining forests by a vast network of well-protected national parks; and 4) using forests as extractive reserves. While these four strategies are necessary and should be pursued, they are insufficient to stop deforestation. The first strategy requires long periods of real economic growth, which occur too slowly to offset current deforestation rates. The second strategy is demonstrably insufficient in deflecting migration; the third is unrealistic: hungry people will go on clearing the land; and the fourth, extractive reserves, is likely to support a very small segment of the region's population.

A fifth strategy is to stop deforestation in situ by eliminating the need to abandon cleared land. Urgently needed are land-management options that improve the economic status of subsistence farmers, maintain agricultural productivity on deforested lands, and recuperate productivity of degraded lands. Such options will provide sustainable development of the Amazon and other humid tropical regions in a way that satisfies human needs and preserves the ecosystem. These options must be compatible with the various socioeconomic needs in the region so that they are readily and widely adopted.

Is such an approach possible in the predominantly acid, low-fertility soils of the humid tropics? Our answer, based on long-term TropSoils research, is an emphatic *yes*—provided that alternatives to slash-and-burn methods are employed. The key is an integrated approach that 1) develops and applies sustainable management technologies for tropical soils, 2) establishes government policies to provide incentives against further deforestation, and 3) implements effective, economically sound conservation methods.

Farmers do not cut tropical rainforests because they like to; they clear them out of sheer necessity to grow more food. Deforestation, therefore, can be reduced by the widespread adoption of sustainable management practices. For acid soils of the humid tropics, such practices have been developed at Yurimaguas, Peru, and elsewhere to fit different landscape positions, soils, and levels of socioeconomic development.

The principal sustainable management options and alternatives to slash-and-burn methods are: paddy rice production on alluvial soils, low-input cropping, continuous cultivation, legume-based pastures, and agroforestry. Each option's place in the landscape is shown in Figure 2. Options developed by other research institutes include perennial crop production (rubber, oil palm), plantation forestry, and alley-cropping for the more highly fertile soils. Such practices are also part of the solution.

In spite of the continuing need for both strategic and applied research, there is no question that the technological basis for sustainable management options for acid soils

of the humid tropics is available now. The following describe some of the main management options.

Land Clearing That Does Not Damage the Soil

All the options are based on slash-and-burn clearing, using axes, machetes, and chain-saws as opposed to bulldozers. We found that the slash-and-burn system is better because the ash provides a liming and fertilizing effect and does not disturb the topsoil, while conventional bulldozer clearing often compacts the soil and removes valuable topsoil. We also found that the ash of secondary forests differed little in fertilizer content from the ash of primary

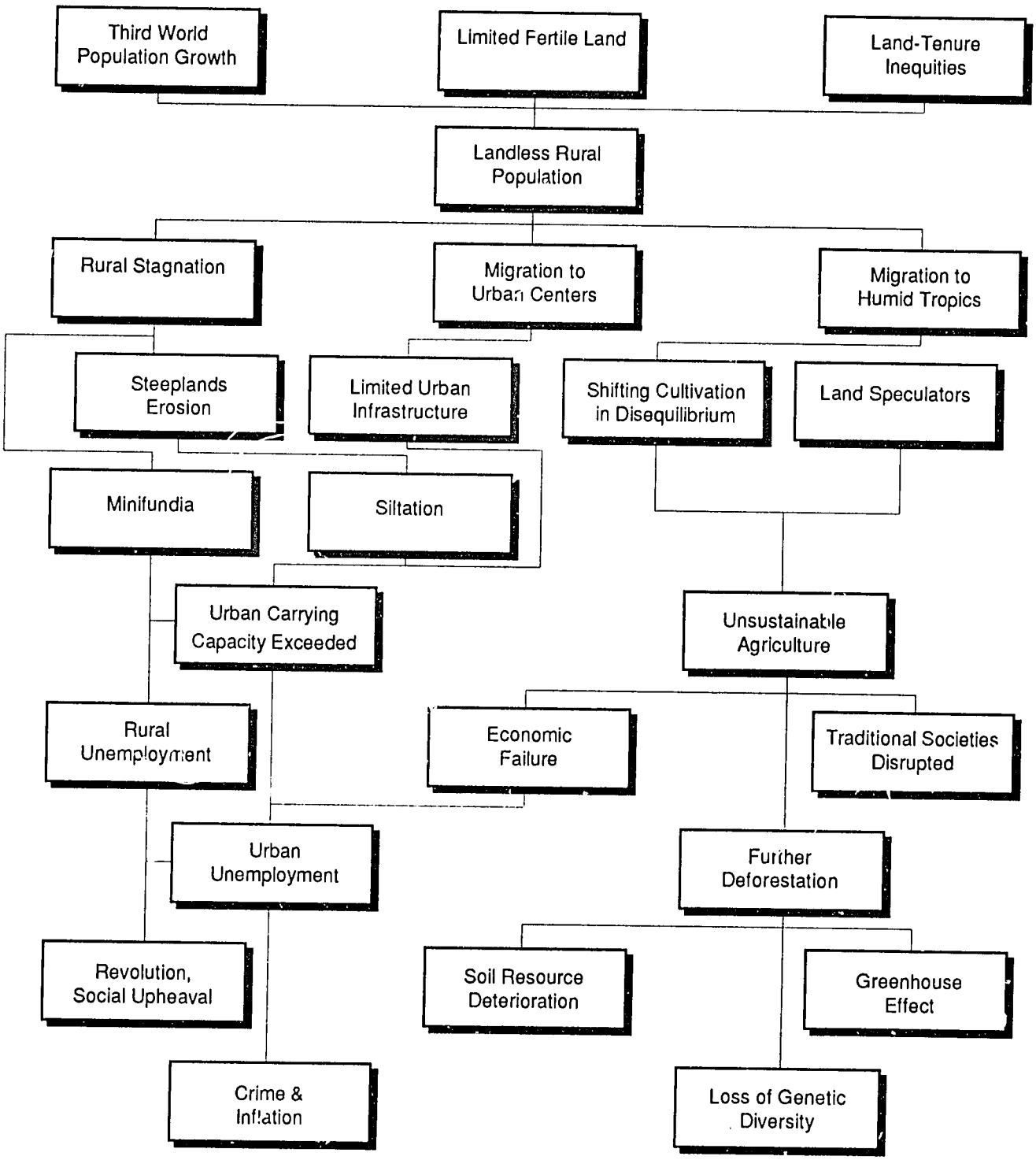

Figure 1. Cause-effect relationship related to tropical deforestation in developing countries.

forests, giving a further impetus to clear the former and conserve the latter.

Paddy Rice in Alluvial Soils

Alluvial soils encompass approximately 11% of the Amazon region. Situated near water supplies and river transportation, large proportions of these soils are highly fertile. Adaptation of Asian flooded rice technology to Yurimaguas' alluvial soils has established the following management principles: 1) land is cleared by slash-and-burn, and land leveling is performed only to ensure the gravity flow of water along natural contours; 2) supplemental irrigation, either by gravity flow or by pumping rivers, increases yields by about 50% relative to crops dependent on rainfall; 3) transplanting provides higher yields for initial crops but may be replaced by broadcasting pregerminated seeds in subsequent crops after paddies are adequately leveled; 4) fertilizer responses are thus far limited to nitrogen deficiencies with continuous use; and 5) with yields averaging 5.5 tons/ha/crop, at the farmer level, one hectare of paddy rice provides the equivalent of 14 hectares of upland rice under shifting cultivation, since two crops are grown per year.

This technology has been adapted rapidly by settlers migrating into the Amazon Basin from rice-producing areas in the coast of Peru. Approximately 75,000 new hectares of irrigated rice land were put into production within five years in the Peruvian Amazon, making it one of the major rice producing regions of Peru. In Brazil, the State of Amazonas alone contains about 25 million hectares of such soils, underscoring the vast rice-production potential of the Western Amazon.

Low-input Cropping

This management option has evolved as a transitional technology between shifting cultivation and several sustainable options. It enables the farmers to drastically increase short-term crop production while preparing themselves and their land for sustained land-use alternatives. This option is most suitable for farmers on acid, infertile soils in rural areas with limited capital and marketing infrastructure and is therefore applicable to large areas of the humid tropics. It involves 1) clearing secondary forest fallows by slash-and-burn; 2) using acid-tolerant upland rice and cowpea cultivars in rotation, with only grain removal to minimize nutrient export; 3) working without fertilizers, lime, or external organic inputs; 4) establishing legume fallows when weed competition and nutrient deficiencies make cropping unfeasible; and 5) eliminating the fallows by slash-and-burn after one year and shifting to other management options such as grass-legume pastures, agroforestry, or mechanized continuous cropping. Results indicate that the initial cropping cycle lasts two or three years and that there is a progressive reduction in cycle length after each legume fallow. The system is considered transitional because of two major constraints: nutrient depletion and weed encroachment. Ongoing investigations seek to prolong low input cropping by 1) broadening the base of acid-tolerant cultivars and species; 2) increasing knowledge on components of the nutrient depletion process; and 3) improving weed management through crop rotations, plant density, and both frequency and duration of legume cover-crop fallows.

Agroforestry

Comprehensive research on agroforestry for acid soils began in Yurimaguas in 1983. Agroforestry is an attractive management option for much of the humid tropics because it can be adapted to a wide range of socioeconomic and soil-landscape conditions. Research has focused on 1) selection and management of acid-tolerant leguminous trees, 2) food-tree production systems, 3) managed fallows, and 4) alley-cropping. Legume selection trials have identified *Inga edulis*, *Cassia reticulata*, *Erythrina* sp., and certain varieties of *Gliricidia sepium* as promising species. They grow fast and respond well to pruning, making them good multipurpose trees for acid soils.

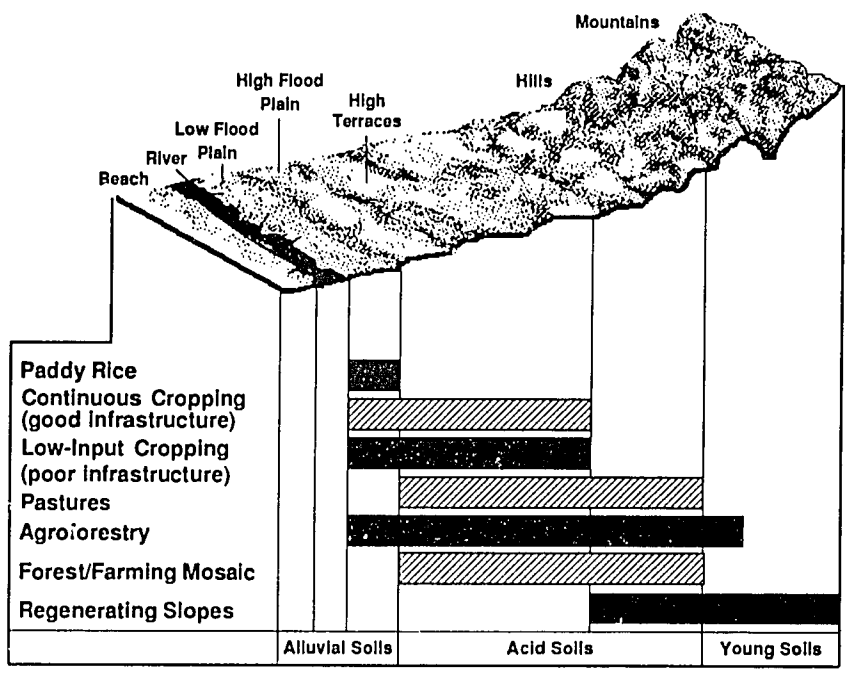

Figure 2. Some soil-management options for humid tropical landscapes dominated by Oxisols and Ultisols.

Work with native fruit trees has concentrated on peach palm (*Bactris gasipaes*) for fruit and heart of palm, but work has also begun on arazá (*Eugenia stipitata*), achiote (*Bixa orellana*), and carambola (*Averrhoa carambola*). Managed leguminous fallows performed well compared to natural secondary fallows. Some of the managed fallows restored stocks of nitrogen, phosphorus, and potassium and suppressed weeds faster than the natural fallow. Current work in managed fallows seeks optimum crop-to-fallow ratios.

Alley-cropping trials, however, have had limited success on acid soils. Soil phosphorus levels soon limit crop production because of severe competition between trees and crops. Current research is aimed at overcoming these problems and testing alley-cropping on slopes, where its obvious soil-conservation advantages could be maximized.

Grass-Legume Pastures

To avoid the problems associated with Amazon beef production, our soil-plant-animal research has focused on developing pastures for dual-purpose (beef-dairy) production in small land holdings where farmers will also grow crops and trees. Initial investigations sought to adapt technology from CIAT's Tropical Pastures Program (developed primarily in savanna ecosystems) to humid tropical conditions. Legume and grass ecotypes were screened for their performance under acid soil conditions and subsequently evaluated for their persistence and compatibility when subjected to various grazing intensities. An ongoing 11-year-old grazing trial in Yurimaguas is among the longest replicated trial test of an acid-tolerant grass-legume mixture in the humid tropics. If the legume-dominated pastures prove sustainable, then a new concept for cattle production may emerge in the humid tropics. New studies are also under way to provide further insight into nutrient cycling and to refine management practices for transitions between pastures and crop or tree production.

Mechanized Continuous Cropping

Initial investigations seeking to quantify the production potential and primary soil constraints of humid tropical ecosystems focused on this management option. It is intended for farmers near urban areas where markets are favorable for fertilizer-based, continuous food-crop production. Large Amazonian cities currently import most of their food from other areas. There is a potential comparative advantage in growing such food crops near the marketing centers. Sustained crop yields have been obtained with continuous cropping trials for 37 crops (17 years) in Yurimaguas Ultisols and 17 crops (9 years) in Manaus Oxisols. The keys to continuous production are effective crop rotations and the judicious application of lime and fertilizers. If vigorous crop growth is ensured by adequate liming, fertilization, and mechanization, then soil chemical properties improve with continuous cultivation. Primary research thrusts in this soil-management option are currently directed toward improving nutrient-use efficiency, weed control, and tillage practices.

Nutrient Cycling Efficiency

Nutrient cycling must be maximized in all systems in order to minimize the need for external nutrient inputs. The management of crop and root residues is crucial in this regard. Approaches proposed by TSBF (Tropical Soil Biology and Fertility Program) on quantifying the nutrient release of organic inputs and the management of soil organic carbon, nitrogen, and phosphorus are major components of low-input cropping, agroforestry, and pasture research. The promising results at Yurimaguas in predicting the rate of nutrients released from leguminous sources provide an opportunity for the quantitative management of organic inputs in a manner comparable to the management of chemical fertilizers.

Deforestation Reduction Potential

For every hectare put into these sustainable soil-management technologies by farmers, five to ten hectares per year of tropical rainforests can be saved since the new technologies are more productive than traditional shifting cultivation. Estimates at Yurimaguas for the various management options are shown in Table 1. These estimates will vary with climate and soils.

Soil-management technologies are particularly applicable to secondary-forest fallows, because clearing small-tree biomass does not contribute significantly to global warming. Such clearing offers a viable alternative to primary-forest clearing. Many pastures or croplands degraded by poor management practices can also be reclaimed using some, but not all, of these technologies.

Such technologies, however, are useless without effective government policies that encourage, support, and regulate them. Likewise, well-conceived policies will fail without sustainable technologies. Therefore, the hope lies

Table 1. Potential for reducing deforestation using technologies developed at Yurimaguas.

One hectare in sustainable management options	Hectares saved from deforestation annually
Flooded rice	11.0
Low-input cropping (transitional)	4.6
High-input cropping	8.8
Legume-based pastures	10.5
Agroforestry systems	not determined

on a joint policy-technology approach: a worldwide deforestation reduction initiative.

The present situation is analogous to the Green Revolution launched by the world's technical-assistance community in the late 1960s. At that time, sustainable technologies for high-yielding rice and wheat production were sufficiently developed to be tested at a large scale. Key government officials were convinced of the technologies' importance by leading scientists and instituted the necessary policies to ensure their adoption in India, Pakistan, the Philippines, and other countries. The Green Revolution became a worldwide success during the next twenty years: it arrested worldwide famine. Unlike the Green Revolution, however, a deforestation reduction initiative will have a gradual and less spectacular impact because we are focusing on marginal ecosystems and on more complex technological and policy problems.

A worldwide deforestation reduction initiative will provide direct help to both Third-World and developed countries. Sustainable agricultural options for the humid tropics are necessary but not sufficient conditions to stop tropical deforestation. Coupled with appropriate, conservation-oriented government policies, the following objectives can be achieved simultaneously: 1) increasing food and fiber production by farmers now practicing shifting cultivation; 2) reversing the pattern of land degradation in tropical rainforests; 3) preserving much of the remaining tropical rainforests with their rich genetic diversity; and 4) reducing the emission of greenhouse gases by as much as 18%.

Approach and Strategy: Y-100A

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Most of the population in the Amazon is urban, not rural. Large cities are many: Belem (1.5 million people), Manaus (1 million), Iquitos and Ciudad Guayana (over half a million), Pucallpa, Porto Velho, Rio Branco, Leticia, Tarapoto, Florencia, Santarem, and others (over 100,000).

These cities provide favorable markets for intensively managed, sustainable, and continuous crops. Continuous production would avoid further deforestation by shifting cultivation and would ensure a steady food supply to urban areas. Fertilizers, lime, and farm machinery, although expensive, are increasingly available in these urban centers of the humid tropics. When chemical inputs and mechanization are introduced to new areas, they are often used excessively and inefficiently. Well-managed continuous cropping systems would avoid this waste.

Because farmers using this technology are not likely to depend exclusively on hand labor, land-preparation studies are being conducted in both conventional and conservation tillage. Conventional tillage in sandy Ultisols has resulted in poor plant anchorage during wet periods. Conservation tillage is considered to be any form of tillage that conserves natural resources such as soil, water, and energy. Various conservation tillage systems using tractor-drawn equipment alter both chemical and physical soil properties. A key question is this: Can timely conservation-tillage practices by tractor-drawn machinery be effective in the humid tropics under high rainfall conditions?

New land-preparation practices minimize tractor passes. Mechanization has identified the need for further refining the interactions among weed control, tillage, and fertilization. The inability to perform mechanized land preparations during the peak of the rainy season has led to reductions in annual cropping frequency and thus increased opportunities for weed encroachment, surface runoff, and erosion. Weed populations also have changed in response to chemical weed-control practices.

The goal of this project is to develop soil-management practices for fertilizer-based mechanized cropping systems. The practices should sustain long-term productivity in humid tropical areas with favorable infrastructure.

Operational Plan

The project's operational plan approved by TropSoils for the 1987-1991 quinquenium is illustrated in Figure 1, starting from the problems, continuing with component research and its interactions, and integrating the result into

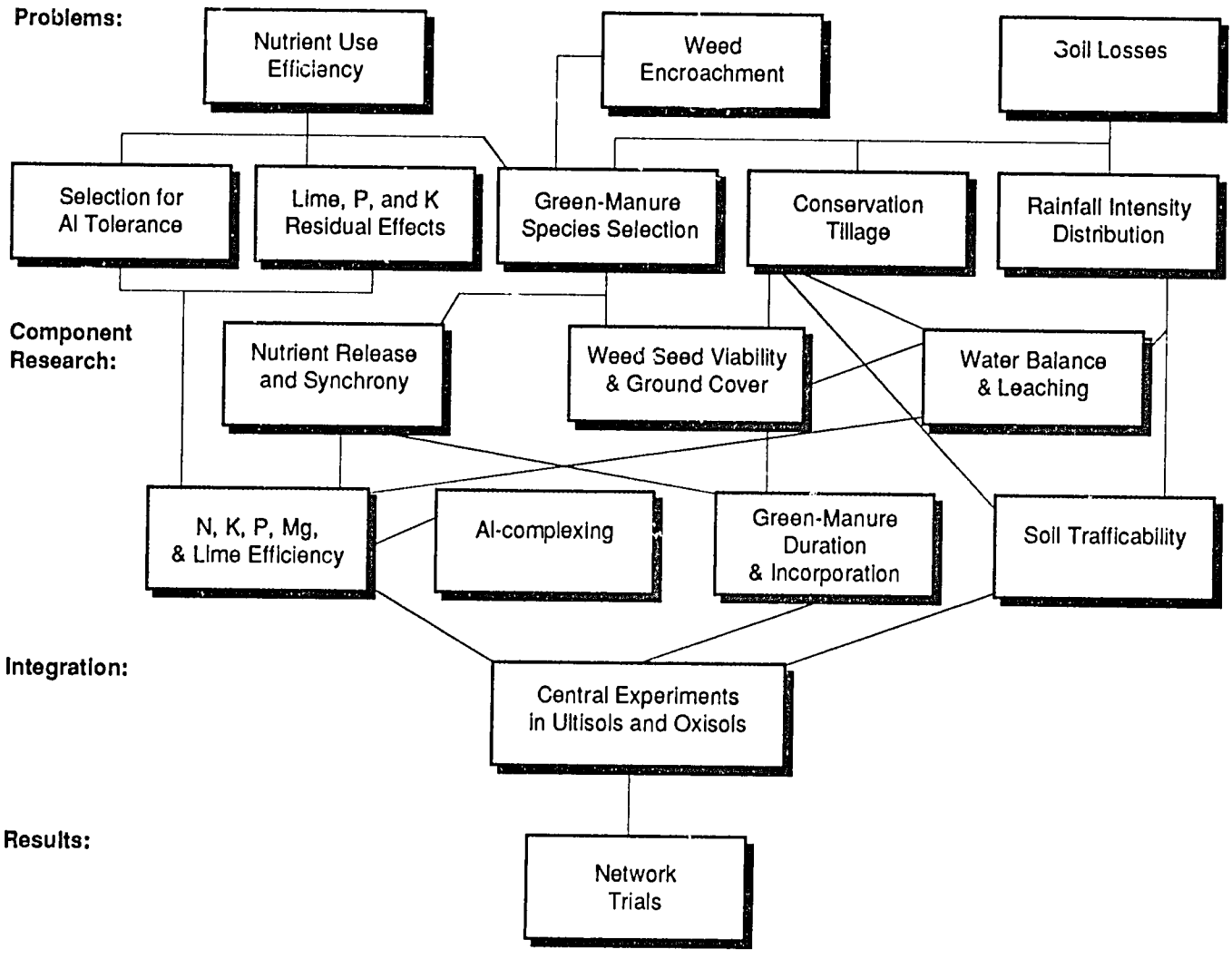

Figure 1. Continuous cultivation project flow. Shaded boxes indicate research sponsored by TropSoils.

continuous cropping systems for sandy Ultisols and clayey Oxisols. Information about these systems can be passed on to the network project. Rounded boxes represent TropSoils-sponsored research. Experiment codes are indicated in the text as appropriate.

This project used primary sites at Yurimaguas and Manaus to provide a range of soil and climatic conditions. Several experiments initiated during the last quinquennium are being continued, due to either their long-term nature or the timing of their initiation. Examples of the former are the central continuous cropping study in Ultisols (Y-101) and the nutrient dynamics study in clayey Oxisols (M-901). Examples of the latter are the conventional (Y-104) and conservation tillage (Y-113) studies and studies on potassium fertilizer efficiency (Y-103) or nitrogen management (M-910) and the potential of green manures in ameliorating soil acidity (Y-117).

Summary of Results

Sustainability

The long-term sustainability of intensively managed crop rotations requiring crops such as corn, soybeans, and other grain legumes is amply demonstrated by the two long-term experiments reported in this section: 37 consecutive crop harvests during 17 years of continuous cultivation in a sandy Ultisol of Yurimaguas, Peru, and 17 consecutive crop harvests during 9 years of continuous cultivation in a clayey Oxisol of Manaus. In both cases, crop yields have been maintained at adequate levels and soil properties have improved rather than deteriorated, contrary to common beliefs. Without adequate management, however, yields drop to zero and soil properties deteriorate rapidly under continuous cultivation.

Management of Physical Soil Properties

Improvements in these systems are becoming evident, but the switch from conventional to minimum tillage has yet to produce significant yield differences during the first five

crops. Subsoiling conventionally tilled fields increased corn grain yields by 30%, indicating the presence of compacted layers due to mismanagement. Switching from conventional to minimum tillage reduced runoff losses by half, in an environment where 50% of the rainfall events are highly erosive. Soil trafficability studies show that conventional tillage the day after a heavy rain does not reduce yields in a loamy sand soil (10% clay), but such practices produce severe compaction and yield losses in a sandy loam soil with 20% clay.

Fertilizer-use Efficiency

Considerable advances were made towards improving the efficiency of nitrogen, phosphorus, and potassium fertilization in corn-based systems. The nitrogen studies conducted in Manaus show that native-soil nitrogen is initially higher in the Entisols of várzeas, or alluvial plains, than in the upland Oxisols. Management practices to alleviate subsoil aluminum toxicity allow corn roots to penetrate deeper into the Oxisol, making use of available subsoil nitrogen, which results in increasing yields and fertilizer recovery. In the high soil fertility, low solar-radiation environment of the várzeas, favored upland rice requires less fertilizer nitrogen for maximum yields than corn, even though their nitrogen-use efficiency and nitrogen-uptake efficiencies were the same.

An 11-crop experiment with a corn-cowpea rotation in Manaus' clayey Oxisols with high phosphorus-fixation capacity shows the phosphorus fertilizer needs for sustainable crop productivity to be much smaller than commonly thought: banded applications of 22 kg P/ha per corn crop and 44 kg P/ha per cowpea crop, under manual-tillage practices used in the region. Critical soil test and tissue phosphorus levels were established for corn, cowpea, and peanut crops growing in clayey Oxisols. Among the findings was the calcium requirement for peanuts.

Efficiency in the use of potassium fertilizers was also dramatically increased in a corn-soybean rotation, decreasing the recommended fertilizer rates by half. A six-crop experiment conducted at Yurimaguas on sandy and loamy Ultisols shows that with appropriate timing and crop-residue return, a single annual potassium application of 60 to 90 kg K/ha applied to the corn crop is sufficient to meet the potassium needs of both crops. Previous recommendations were on the order of 160 to 200 kg K/ha per year.

Green Manures

Incorporating green manures instead of a third annual crop in corn-grain legume rotations would provide a ground cover during the rainiest part of the year, smother weeds, fix nitrogen, and complex aluminum. Advances have been made in some of these approaches. The rate of decomposition of green manures after incorporation into the soil will determine how fast nutrients will be released. We found that for leguminous green manures, the conventional criterion for predicting rate of decay, the C/N ratio, was useless. Instead, the lignin and polyphenolic contents of green manures were the main determinants of their decay-rate under extremely acid soil conditions. Furthermore, high-quality green manures that have low lignin and polyphenolic contents, such as kudzu and rice straw, ameliorated soil acidity temporarily. Low-quality green manures like *Inga edulis* exacerbated soil acidity.

Included in the rotation to control weeds, *Centrosema macrocarpum* proved disappointing. A four-month green manure crop did not control weeds in a subsequent corn crop as well as did chemical herbicides, particularly when the green manure crop was grown during the wettest time of the year. *Centrosema macrocarpum* needed a minimum of six to eight months of growth in order to control weeds more effectively than herbicide applications.

Future Plans

Research for the next period should concentrate on understanding the water balance and nutrient movement in the most efficient systems that contrast conventional tillage with no tillage. It should fully concentrate on the practical incorporation of green manures into these rotations, including species and weed-control effects.

Central Continuous Cropping Experiment in Yurimaguas: Y-101

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Objectives

The objectives of this study were 1) to maintain a fertilizer-based continuous cropping system that effectively manages the physical and chemical properties of acid soils in the humid tropics and 2) to assess the long-term sustainability of such a system.

Procedures

The experiment was initiated in September 1972 at Yurimaguas, and the results have been reported periodically. The 34th crop (corn cv. Marginal 28) was planted on October 17, 1986, at a spacing of 20 cm; 100, 45, and 83 kg/ha of N, P, and K, respectively, were applied. Residues from the previous corn crop were chopped with a bush-hog and disked with a five-tine field cultivator-disk bedder at 80 cm between beds. The residues were disked simultaneously with a disk shaper and planter. Dual herbicide was applied at the rate of 2 L/ha after planting.

The 35th crop (soybean cv. Jupiter) was planted June 17, 1987; 36 kg P/ha and 3 t lime/ha were applied. After residues from the previous corn crop were chopped with a bush-hog, lime was broadcast on the surface with a Gandy broadcast applicator, and the soil was disked with a five-tine cultivator and flat planted. No N or K was applied. The herbicide Poast was applied at the rate of 2 L/ha.

The 36th crop (corn cv. Marginal 28) was planted November 11, 1987, by the same methods as the 34th crop. Nitrogen (120 kg/ha), but no P or K, was applied.

On March 29, 1988, the whole area was planted with *Mucuna cochinchinensis* as a fallow to give the soil its first rest in 16 years. Mucuna density was 10,000 plants/ha. Mucuna was weeded manually once; complete soil cover was obtained after two months. In September 1988, the soil cover produced seed and began to die, but newly produced seeds germinated, resulting in canopy recovery within one month.

On May 30, 1989, the mucuna fallow was cut with a bush hog and incorporated with a disk plow followed by a disk harrow. The 37th crop (corn cv. Marginal 27) was planted shortly afterwards. Fertilizers were applied at the rate of 40-45-67-10 kg/ha of N, P, K, and Mn, respectively. On September 26, 1989, the 37th crop (corn cv. Marginal 27) was harvested, and the soil was sampled at depths of 0 to 20, 20 to 40, and 40 to 60 cm.

Results

Mean yields for the 34th crop (Figure 1) were 2.49 t/ha of corn grain for the complete fertilization treatment and zero for the nonfertilized check. Average yield for the 35th crop was 2.34 t/ha in the fertilized treatments; in the check plot, the yield was around 0.7 t/ha due to fertilizer contamination from surrounding fertilized plots. The mean yield of the 36th corn crop was 3.4 t/ha for the complete fertilizer treatment and zero for the check.

Mucuna produced 9.85 t/ha of dry matter at the time of incorporation. The corn crop (37th) following mucuna performed very well with a mean yield of 4.0 t/ha in the complete fertilizer treatment and 0.98 t/ha for the check. It was estimated that mucuna contributed around 400 kg of N/ha (approximately 4% N in the biomass).

The effect of fallow on crop is not apparent. The yields obtained with the 37th crop (4 ton/ha) are similar to the equivalent treatment obtained in an adjacent experiment (3.75 tons/ha) of a corn crop planted the same day (Experiment Y-113, Table 5, this report). In this experiment two extra crops were planted and harvested during the time mucuna was planted in the long-term plots.

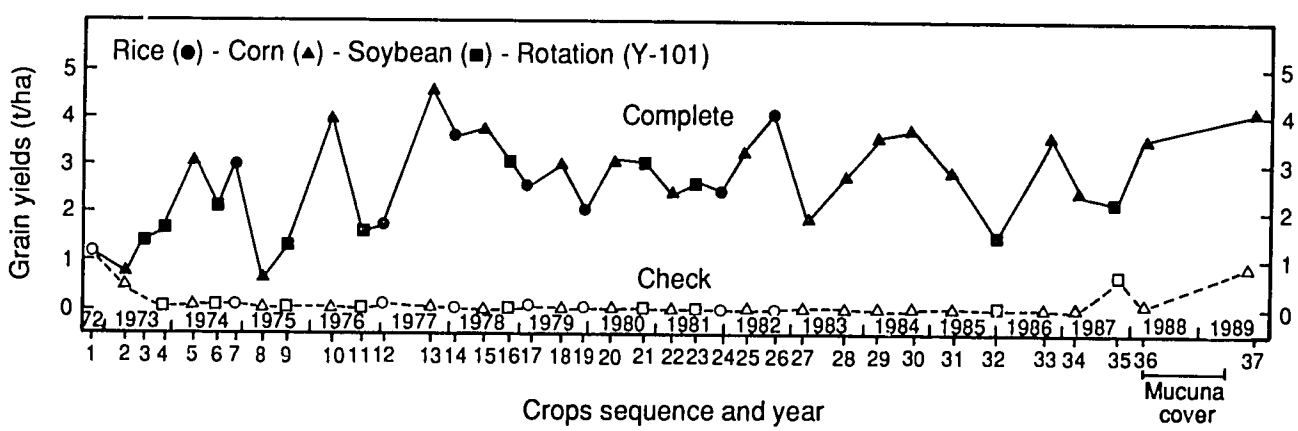

Figure 1. Crop yields in the continuous cropping experiment, Yurimaguas, Peru. A 14-month fallow was grown between crops 36 and 37.

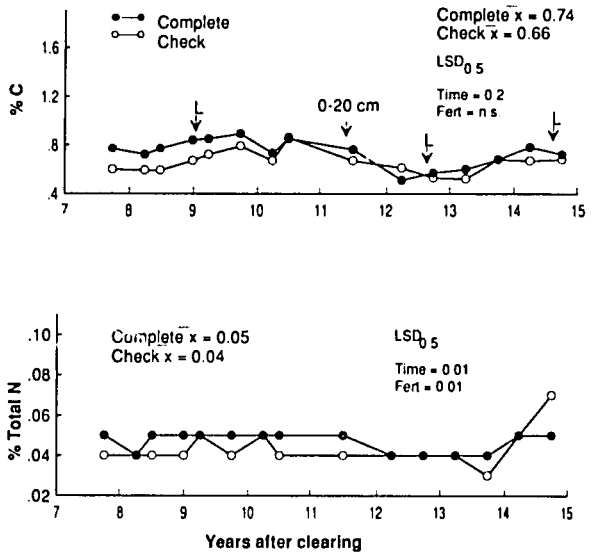

Figure 2. Organic matter and N dynamics in Chacra 1. Arrows denote liming applications.

The changes in topsoil (0 to 15 cm) organic carbon and total N from years 7 to 11 and the changes at 0 to 20 cm (years 12 to 15) are shown in Figure 2. The complete fertilization treatment did not differ significantly from the nonfertilized treatment. With the change in sampling procedure at a depth of 0 to 20 cm, average organic carbon content decreased due to the mixing of a less fertile and more heavily textured soil layer with the 0- to 7-cm layer of topsoil. This change reflects increasing tillage depth. However, 14 years after clearing, organic C values began to increase. They stabilized at about 0.6%. Total N stabilized at 0.05% after the 14th year.

Until March 1988, topsoil pH was maintained around 6.0 with complete fertilization and around 4.9 in the nonfertilized check treatment. However, after 14 months of fallow, the topsoil pH increased to 5.2 in the nonfertilized check and was maintained in the complete fertilization treatment. Acidity and Al saturation were maintained at low levels in the fertilized treatment, but were higher in the check (Figure 3).

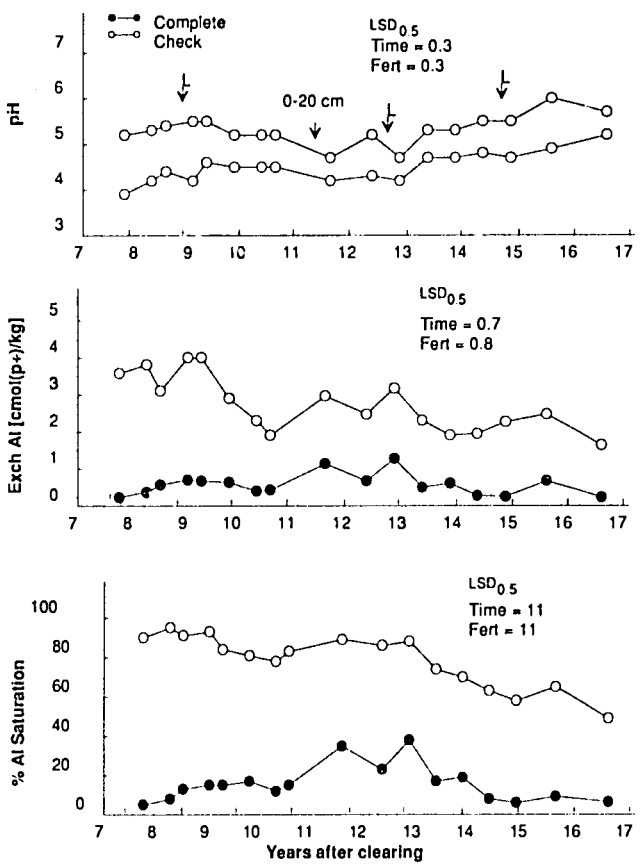

Figure 3. Soil acidity dynamics in Chacra 1. Arrows denote lime applications.

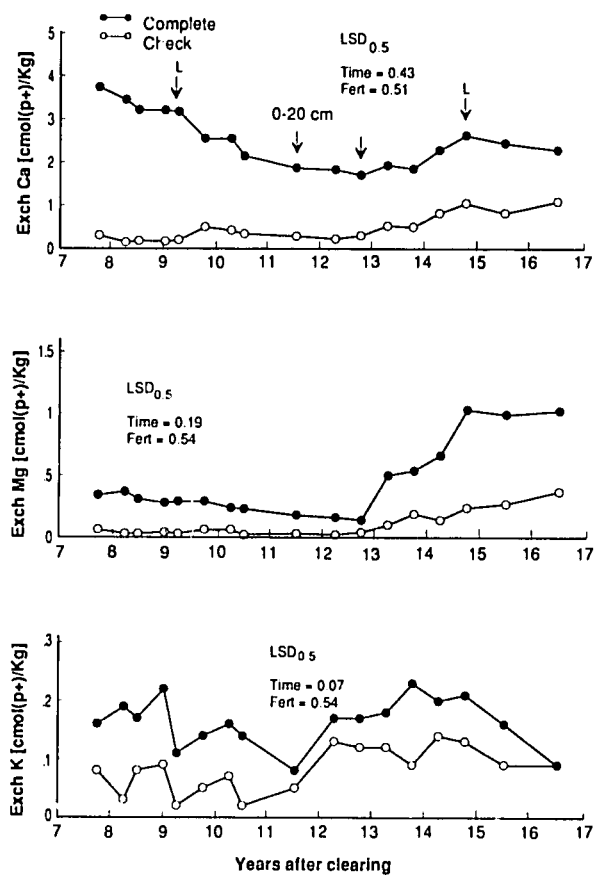

Figure 4. Dynamics of exchangeable bases in Chacra 1. Arrows denote lime applications.

The dynamics of exchangeable Ca, Mg, and K are shown in Figure 4. Lime application 12 years after clearing increased or stabilized exchangeable Ca levels between 2 and 3 cmol(p+)/L. After the application of 3 t/ha of lime and 14 months of mucuna, Mg levels stabilized at 1 cmol/L. Potassium levels in the fertilized plots fluctuated around 0.2 cmol(p+)/L until the 36th crop (March 1988). However, after 14 months, the levels for the check and complete fertilization treatments were similar: 0.09 cmol(p+)/L. Most of the K was probably located in the biomass since this analysis was done before cutting the fallow.

Ten years after continuous cultivation (April 1982) a significant movement of Ca and Mg down to a depth of 45 cm was observed. This movement was accompanied by a significant decrease in subsoil Al saturation at this depth (Figure 5). After 15 years of continuous cultivation (Figure 6), a downward movement of Ca and Mg and a reduction in the acidity to 40 cm were also apparent. The increases in topsoil Mg from years 10 to 15 appear to have provided a Mg bulge in the 20- to 40-cm layer. The Al saturation profile shows less subsoil acidity decrease in year 15 than in year 10.

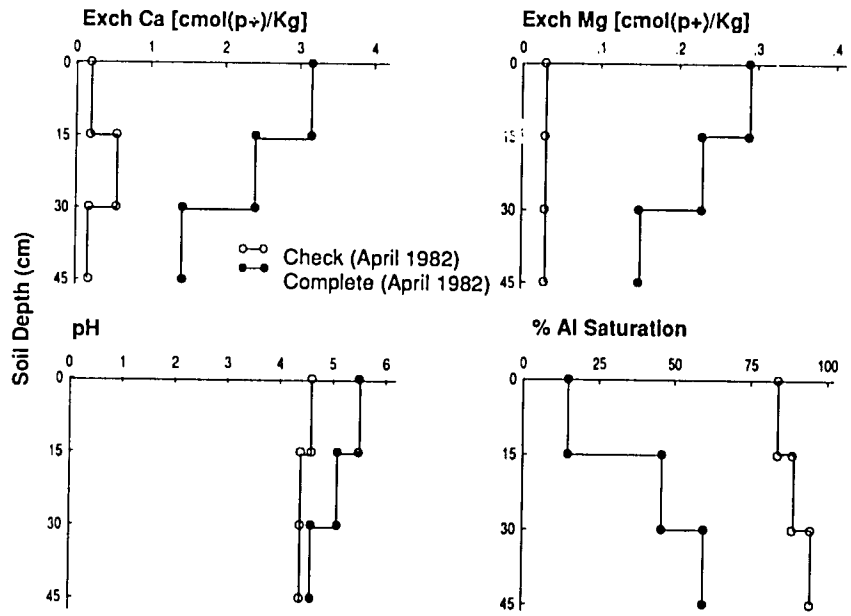

Figure 5. Improvement in subsoil chemical properties after 10 years of continuous cultivation in an Ultisol in Yurimaguas.

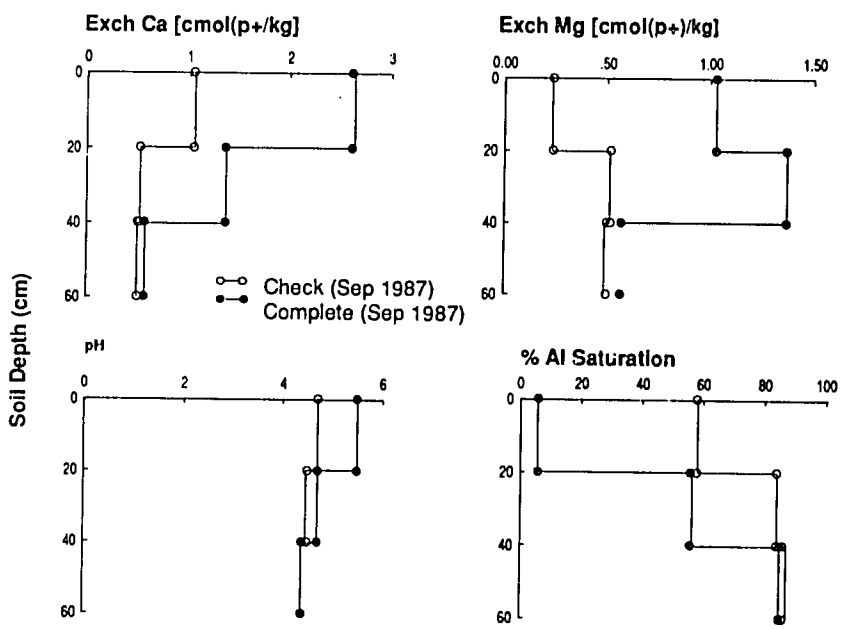

Figure 6. Improvement in subsoil chemical properties after 15 years of continuous cultivation in an Ultisol in Yurimaguas.

Implications

The continuous cropping system remains stable into its 17th year of operation with a continued improvement in subsoil chemical properties.

Continuous Cropping Experiment in Manaus: M-901

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In fields undergoing mechanized continuous cultivation, crop rotation and site-specific soil properties can influence the quantity, frequency, and timing of fertilizer and lime inputs.

Objective

The objective of this study was to determine the extent to which lime and fertilizer recommendations for the Yurimaguas Ultisols should be changed to sustain continuous cultivation in the clayey Oxisols, which are predominate in the Central Amazon.

Procedures

A long-term experiment was initiated at Manaus in 1981. The experiment involves 35 treatments with four replications in a randomized complete-block design. In addition to an absolute check, crop responses to N, P, K, S, Mg, Cu, B, Zn, Mn, and lime are evaluated individually by increasing rates in three or four treatments for each nutrient. Treatments for each nutrient were not initiated until the soil and plant analyses from preceding crops and the yields suggested that a particular nutrient deficiency was likely to occur. Once a yield response was obtained using a given nutrient, the nutrient was added to all subsequent treatments (except the absolute check) to avoid confounding yield responses to the other nutrients. Rates of individual nutrients included in the blanket applications were adjusted for each crop, based on previous crop performance on treatments designated to evaluate yield responses to each nutrient.

The sequence of crops, varieties, and fertilizer treatments initiated during the nine years since clearing the primary forest by slash-and-burn are shown in Table 1. Three treatments each for N and P were initiated with the first crop, because N needs are difficult to assess without local crop response data and because initial laboratory measurements of P sorption suggested that this element would be an immediate constraint for any crop in this Oxisol. Phosphorus was applied uniformly to all remaining plots before planting the subsequent soybean crop. Similarly, K and calcitic lime have been applied uniformly to all treatments after obtaining significant responses in the second and third crops, respectively. Responses to Cu were sporadic and not associated with any specific crop in the rotation. Nevertheless, Cu was included in the blanket applications for the first corn crop to avoid potential interaction with other nutrients under investigation. Potential Mo constraints were avoided with applications of 20 g/ha to the first soybean crop and the fifth cowpea crop.

Potential S losses during initial clearing (by burning) and the avoidance of S-carrying fertilizers for N, P, and K

Table 1. Cropping sequence and time after burning when lime and fertilizer treatments were initiated.

Crop	Variety	Time from planting to harvest	Treatments initiated
Rice	IAC 47	3.0 – 7.4	N & P
Soybean	Tropical	8.9 – 12.6	K
Soybean	Tropical	18.5 – 22.3	Lime & Cu
Cowpea	Manaus	22.9 – 25.2	
Corn	BR 5102	27.6 – 31.3	S
Cowpea	VITA 3	32.7 – 34.9	
Corn	BR 5102	37.2 – 41.8	B & Zn
Soybean	Tropical	42.3 – 46.2	
Cowpea	IPEAN V-69	46.9 – 48.9	Mn
Corn	BR 5102	52.1 – 56.2	
Cowpea	IPEAN V-69	58.1 – 61.0	
Corn	BR 5102	63.1 – 67.3	Mg
Cowpea	IPEAN V-69	69.2 – 71.5	
Corn	BR 5102	76.1 – 80.1	
Cowpea	IPEAN V-69	82.2 – 84.4	
Corn	BR 5110	87.0 – 91.2	
Cowpea	IPEAN V-69	93.9 – 96.2	

applications suggested a possible early depletion of soil reserves for this nutrient. Although treatments to evaluate responses to S and all remaining nutrients were initiated after the second year of cultivation, no significant responses have been obtained during any particular crop. During the last two cowpea crops, responses to Mg have been associated with imbalances caused by a buildup of soil K. Likewise, Mn deficiencies in legumes have only occurred with overliming at the highest lime rate.

In Figure 1, cumulative yield responses to variable rates of P, K, and lime during 17 consecutive crops are compared to yields obtained without lime and fertilizers (absolute check). Additional nutrients applied at constant rates to all fertilized treatments were 634 kg N/ha and 1 kg Cu/ha. Without lime and fertilizer inputs, total yield for 17 crops was 1.7 t/ha. The importance of lime to continuous cropping is exemplified by yield comparisons among 0, 2, and 4 t lime/ha at fixed levels of P and K. Across these lime rates, cumulative yield was increased from 8.5 to 32.5 t/ha.

Magnitude of the yield response to lime depended on both the crop and the time after lime was applied (Figure 2). Without lime, soybean yield declined markedly between 1983 and 1985. During the four initial corn crops, yields were not increased significantly beyond the rate of 2 t lime/ha. In the two final corn crops, yields were almost doubled between 2 and 4 t lime/ha. Therefore, the residual effect of 2 t lime/ha, for corn-based cropping systems on this Oxisol, would be about five years. In contrast to corn, cowpea yield response to lime was considerably lower, never exceeding the rate of 2 t/ha. Relationships between relative yield and soil acidity levels for corn and soybean differed from those observed for cowpea (Figure 3). Corn and soybean yields remained within 80% of the maximum, with Al saturation levels of less the 20%, as opposed to 58% with cowpea. Previous annual reports on comparisons between lime and gypsum treatments in this soil indicated that the cowpea response to lime was due primarily to a Ca effect rather than a reduction in Al toxicity.

Treatments in Figure 1 with 3 t lime/ha received an initial lime application of 2 t/ha in the first corn crop, followed by 1 t/ha in the fifth corn crop, when residual effects from the first application began to decline. Reductions in P inputs from an average of 16 to 8 kg/ha/crop decreased total yields by 10.5 t/ha. Similarly, reductions in K inputs from an average of 35 to 21 kg/ha/crop

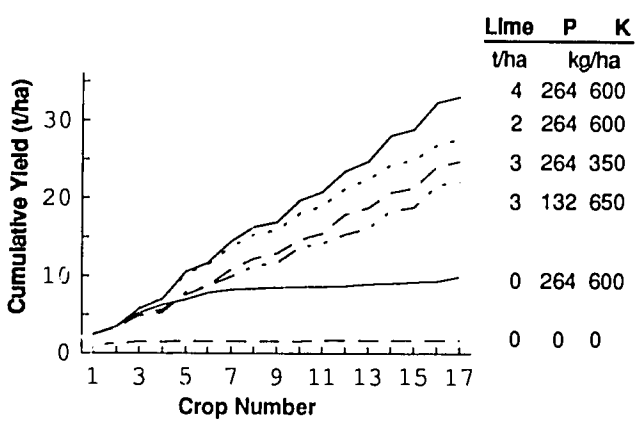

Figure 1. Cumulative yields of 17 consecutive crops of rice (1), soybean (3), corn (6), and cowpea (7), as a function of lime, P, and K inputs during nine years of cultivation in a clayey Oxisol of the Central Amazon.

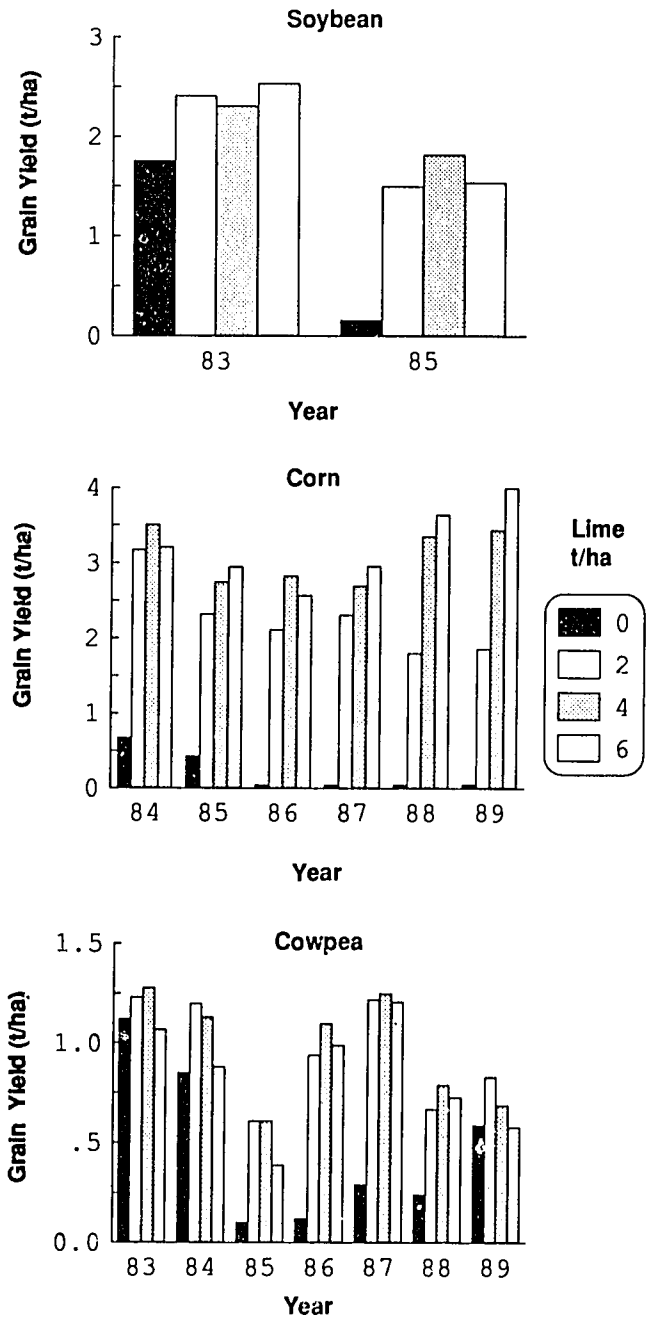

Figure 2. Grain yields for individual soybean, corn, and cowpea crops to lime rates applied to a clayey Oxisol before planting soybeans in 1983.

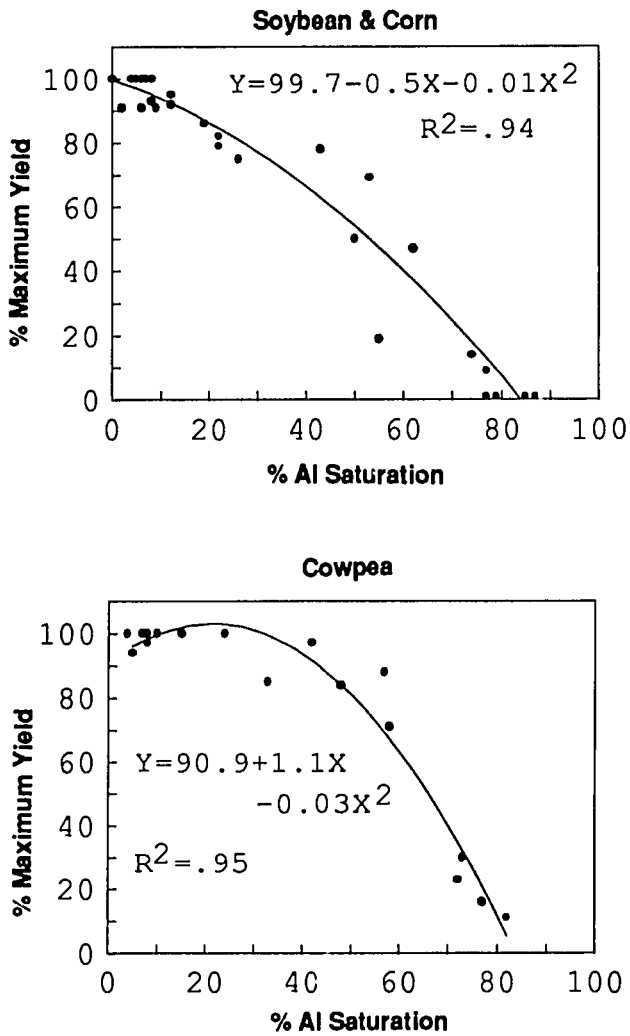

Figure 3. Relationships between relative yields of 15 consecutive crops of soybean, corn, and cowpea and Al-saturation levels of four lime rates in a clayey Oxisol of the Central Amazon

reduced yields by 9.2 t/ha. Individual response to applications of 25, 50, and 100 kg K/ha/crop are shown in Figure 4. Potassium was applied to all crops, except numbers 4 and 16. There was no yield advantage in any crop to rates greater than 50 kg K/ha. In general, the optimum rate for corn and soybean was 50 kg K/ha; the optimum rate for cowpea was 25 kg K/ha. Soil analysis data indicated that yield depressions with the highest K rate were associated with reductions in the Mg saturation to less than 5% of the effective CEC. The absence of a buildup in soil K levels during the 17 crops suggested that the frequency of K inputs should be based on individual crops.

Fertilizer N requirements for corn have been continually evaluated on treatments with three urea-N rates (Table 2). Within the range of 40 to 120 kg N/ha, there was no increase in yield for the two initial crops. With a subsequent reduction in N rates, yields for the third and fourth crops were increased with the application of 80 kg N/ha. In the two final crops, the fertilizer N requirement increased from 80 to 120 kg N/ha. Collectively, corn-yield response to variable rates of N suggested that N inputs should be increased progressively from 40 to 120 kg N/ha during six years of continuous cropping.

These data confirm that mechanized continuous cultivation is possible in clayey Oxisols, which represent one extreme in the range of well-drained acid soils of the humid tropics—the Ultisols of Yurimaguas representing the other. As in the Ultisols, judicious management of lime and fertilizer inputs guided by routine soil analysis plays a key role. The sequence of nutrient constraints, their remedies, and the residual effects of inputs during continuous cultivation differed between Manaus and Yurimaguas. There is no single fertilization recipe capable of replacing the requirement for soil-management expertise at the site-specific or regional level.

Table 2. Corn-yield response to N during six consecutive years of continuous cropping.

Applied N	Corn Crop 1984	1985	1986	1987	1988	1989
kg/ha	t/ha					
20	—	—	1.5	1.5	—	—
40	2.7	2.2	1.7	1.7	—	—
80	2.5	1.8	2.7	2.2	2.0	2.8
120	2.9	2.3	—	—	2.2	3.1
160	—	—	—	—	2.0	3.2

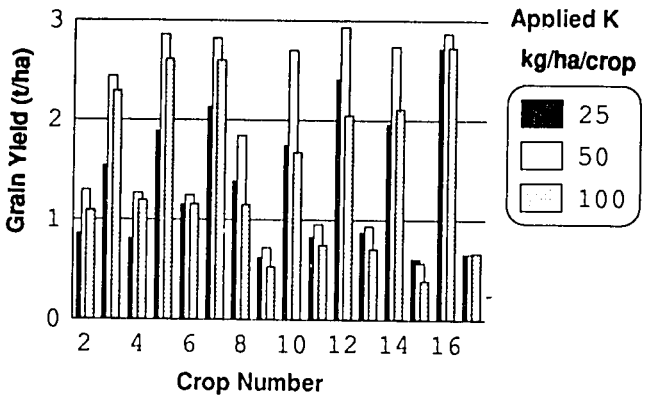

Figure 4. Grain yields for individual soybean, corn, and cowpea crops as a function of three fertilizer-K rates in a clayey Oxisol.

Introducing Conservation Tillage in Continuous Cropping: Y-113

Julio C. Alegre, N. C. State University
D. Keith Cassel, N.C. State University

Objectives

The objectives of this study were 1) to determine the feasability of introducing minimum and no-till planting practices into continuous crop-production systems in the humid tropics and 2) to compare conventional planting practices with minimum and no-till practices and to evaluate their impact on soil physical and chemical properties.

Procedures

The experimental area was located in part of Chacra 1, Yurimaguas, Peru. Chacra 1 has a Typic Paleudult soil and was intensively cropped from 1972 until September 1986, when tillage treatments were installed (Table 1). Planting and harvest dates and fertilization rates are given in Table 2.

The first crop was corn (Marginal 28) planted at 0.80 m x 0.20 m. Phosphorus was banded at planting. Two L/ha of Dual and Paraquat were applied in the minimum (MT) and no-till (NT) treatments before planting.

Before the second crop was seeded (soybean cv. Jupiter), lime, and phosphorus were broadcast, and they were incorporated with a disk plow and disk harrow in the conventional tillage treatments; with a disk harrow in the minimum-till treatments, and in the no-till treatments, the fertilizers were left on the soil surface. Nitrogen and K were not applied. Soybean was planted at 0.50-m x 0.05-m distance. Seeds were inoculated with appropriate *Rhizobium*.

The third crop (corn) was managed in the same way as the first. Nitrogen was applied at a rate of 120 kg/ha, but no P or K was applied. The fourth crop (soybean) was planted in the same way as the second soybean crop, but no fertilizers were applied since soil nutrient levels were adequate, with the exception of Mn. The next crop (corn) was fertilized with N, P, K, and Mn (Table 2). The sixth crop (corn cv. Marginal 27) was planted in the same way as the previous crop and was fertilized with N, P, and K. Chemical properties (P, Ca, Mg, and K) and physical properties (bulk density and mechanical resistance) were measured before planting and after harvesting each of the crops.

Results

Initial bulk density at a depth of 0 to 10 cm was 1.40 Mg/m^3 for all treatments (Table 3). After five crops, bulk density values in the subsoiling treatments were similar to initial values for both depths. In the nonsubsoiled treat-

ments, bulk densities at both depths increased over the initial values. Bulk density values at a depth of 0 to 10 cm in the nonsubsoiled treatments were significantly higher in the no-till treatment than in the others. At a depth of 10 to 20 cm, there were no significant differences among treatments.

In the top 5 cm of soil, P and Ca accumulated in the no-till subsoiling (NTS) treatment, whereas Mg accumulated in the conventional-till subsoiling treatment(CTS), the minimum-till subsoiling treatment (MTS), and the no-tillage subsoiling (NTS) treatment (Table 4).

Table 5 shows the grain and stover yields for the four corn crops. For the first crop, subsoiling resulted in increased yields in the NTS and MTS treatments. In general, yields were low due to high-intensity rains. Rainfall in December 1986 was 418 mm (Figure 1). The highest rainfall intensity was 50.8 mm/h. The no-till treatment without subsoiling was waterlogged during heavy rains, while the subsoiled treatment allowed free percolation. Leaching losses of NH_4 and NO_3 appear to be significant in all treatments (Table 6). In general, corn-grain yields tended to be greater for a given tillage practice when in-row subsoiling was performed at planting.

Soybean yields were higher in the no-till than in the conventional- or minimum-till treatments (Table 7). In the first soybean crop, yields were good despite the late planting date—due to low rainfall during November 1986 (110 mm)—which permitted the harvest of grain. In the second soybean crop, yields were lower, and there were no significant differences between treatments. Plants pre-

Table 1. Tillage treatments carried out since 1986, Chacra 1, Yurimaguas, Peru.

Treatment	Description
I. No tillage—subsoiling	Bush-hog, burn with herbicide (NTS) (Dual & Paraquat); no-till planting with subsoiler (Coulter subsoiler) and planter. Subsoil shanks extended to a depth of 0.30 m. Subsoiling was done for each crop.
II. No tillage (NT)	Same as I without subsoiling.
III. Minimum tillage—subsoiling	Bush-hog, treated with (MTS) herbicide (Dual & Paraquat) followed by no-till planting (Coulter subsoiler and planter). Lime and P incorporated every two years with disk harrow. Subsoiling was done for each crop.
IV. Minimum tillage (MT)	Same as III without subsoiling.
V. Conventional tillage—subsoiling	Bush-hog, disk plow, five-tine (CTS) field cultivator, disk bedder and subsoiler, bed-shaper, and planter. Subsoiler used once a year. Herbicide (Dual) weed control. Subsoiling was done for each crop.
VI. Conventional tillage (CT)	Same as V without subsoiling.

Table 2. Planting and harvesting dates and fertilization rates for six continuous crops in the conservation tillage experiment, Yurimaguas, Peru.

	Date		Fertilization				
No. Crop	Planted	Harvested	N	P	K	Mn	Lime
			kg/ha				
1 corn	Oct. 17, 86	Feb. 1, 87	100	45	67	—	—
2 soybean	June 17, 87	Sept. 25, 87	—	45	—	—	3000
3 corn	Nov. 11, 87	March 16, 88	120	—	—	—	—
4 soybean	May 23, 88	Sept. 1, 88	—	—	—	—	—
5 corn	Sept.13, 88	Jan. 5, 89	120	45	67	10	—
6 corn	May 29, 89	Sept. 26, 89	120	45	67	—	—

sented symptoms of Mn deficiency. Soil Mn levels were less than 1 ppm.

Conclusions

Based on this study, the following conclusions are drawn: 1) in-row subsoiling maintained initial bulk-density values over time and at lower values than non-subsoiled treatments, 2) crop yields for no-tillage, minimum-tillage, and conventional-tillage treatments were not different when accompanied by in-row subsoiling, and 3) P, Ca, and Mg accumulated in the topsoil under the no-tillage regime.

Table 3. Bulk density in the crop row at the 0- to 10-cm and 10- to 20-cm soil depths before and after growing five consecutive row crops using various types of tillage.

Tillage	0 to 10 cm		10 to 20 cm	
	Pre	Post	Pre	Post
	Mg/m³			
No tillage—subsoil	1.40	1.45	1.45	1.47
No tillage	1.40	1.55	1.45	1.56
Minimum tillage—subsoil	1.40	1.43	1.45	1.50
Minimum tillage	1.40	1.51	1.45	1.55
Conventional tillage—subsoil	1.40	1.41	1.45	1.44
Conventional tillage	1.40	1.44	1.45	1.55
LSD .05		0.05		0.07

Table 4. Nutrient contents in the 0- to 5-cm soil depth before and after growing three crops (soybean-corn-soybean) in different tillage systems.

Tillage	Olsen P		K		Ca		Mg	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
	ug/L		cmol/L					
Conventional tillage—subsoil	26	22	0.293	0.312	1.95	2.01	0.47	1.10
Minimum tillage—subsoil	32	29	0.345	0.270	2.38	1.73	0.46	1.22
No tillage—subsoil	28	36	0.335	0.312	1.47	2.45	0.41	1.23

Table 5. Grain and stover yield for the four corn crops as affected by tillage.

Tillage	1st crop		3rd crop		5th crop		7th crop		Mean	
	Grain	Stov.	Grain	Stov.	Grain	Stov.	Grain	Stov.	Grain	Stov.
	Mg/ha									
No till—subsoil	1.90	2.40	2.83	3.27	3.27	3.26	3.44	4.26	2.86	3.30
No till	1.39	1.89	2.58	2.21	2.90	3.53	1.78	2.86	2.16	2.62
Min till—subsoil	2.20	2.70	2.41	2.90	3.40	4.36	3.50	4.25	2.88	3.55
Min till	1.44	1.94	2.66	2.32	2.58	4.07	2.05	2.97	2.18	2.83
Conv till—subsoil	2.00	2.50	3.39	3.89	2.68	4.53	3.94	4.58	3.00	3.88
Conv till	1.90	2.40	2.35	1.94	2.91	3.99	3.16	3.75	2.58	3.02
LSD .05	0.63	NS	0.96	0.69	NS	NS	0.66	0.44		

Table 6. NO_3 and NH_4 concentrations in the water leached at 1-m soil depth for each treatment after 79 mm of rain on December 12, 1986, Yurimaguas, Peru.

Treatment	NO_3	NH_4
	ppm	
No tillage—subsoil	1.39	53
No tillage	1.81	28
Min till—subsoil	3.20	40
Min till	1.62	29
Conventional—subsoil	2.64	13
Conventional	2.40	23

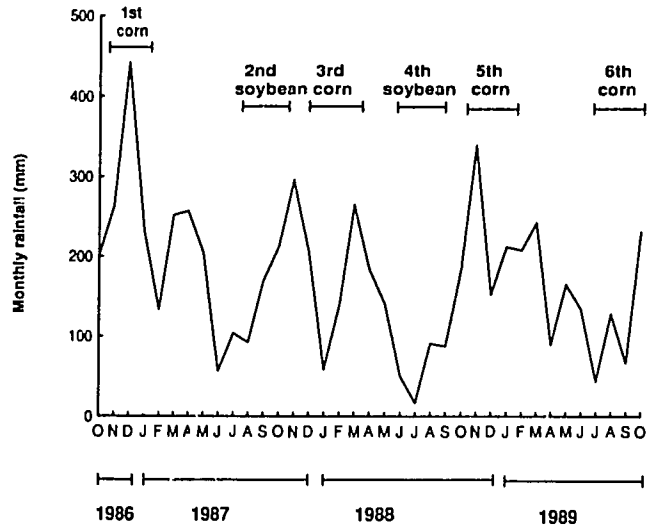

Figure 1. Monthly rainfall and chronological distribution of six crop seasons in an Ultisol in Yurimaguas.

Table 7. Grain and stover yield for the two soybean crops as affected by tillage.

Tillage	2nd crop		4th crop		Mean	
	Grain	Stover	Grain	Stover	Grain	Stover
	Mg/ha					
No tillage—subsoil	2.25	1.37	1.25	1.40	1.75	1.39
No tillage	2.18	1.20	0.90	1.15	1.54	1.18
Minimun tillage—subsoil	1.63	1.22	1.40	1.10	1.52	1.16
Minimun tillage	1.79	1.27	1.20	1.00	1.50	1.14
Conventional till—subsoil	1.99	1.42	1.18	1.50	1.59	1.46
Conventional	1.80	1.32	0.80	1.05	1.30	1.19
LSD						
.05	0.52	NS	NS	NS		

Subsoiling and Bedding Effects with Conventional Tillage: Y-114

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Objectives

The objectives of this study were to investigate the impact of subsoiling and bedding on compacted soil, root development, and yields in continuous cropping systems.

Procedures

Details about the experimental procedures were given in the *TropSoil Technical Report, 1986-87*. This experimental plot has been under continuous cultivation since 1972. Treatments are described in Table 1. Six crops were planted on a Typic Paleudult soil during September 1986 to October 1989 (Table 2). Each corn crop in treatments 1 to 4 received 45 kg P/ha incorporated with a disk harrow. Treatments 5 and 6 also were disk-harrowed, with P banded at planting. All crops received 120 and 83 kg/ha of N and K respectively, in a split application.

Two methods were used for root measurements. Roots were washed from cores of soil taken at different positions (on-the-row, non-trafficked, and trafficked inter-row). Roots were also counted in a grid of 0.10 x 0.10 m to a depth of 60 cm using the trench-profile method.

Results

The chemical constraints of these sandy-loam soils were eliminated by liming and fertilization (Table 3). Aluminium saturation was reduced from 80% to 10%, and the P, Ca, and Mg levels were increased. Only K was below the critical level, but with split-banding application after planting, the supply was sufficient for crop growth.

Table 2. Date of planting and harvesting of six consecutive corn crops in the conventional-tillage experiment.

Crop number	Date planted	Date harvested
1	Sept. 17, 1986	Jan. 23, 1987
2	June 4, 1987	Oct. 6, 1987
3	Dec. 15, 1987	March 28, 1988
4	May 11, 1988	Sept. 14, 1988
5	Nov. 18, 1988	March 17, 1989
6	June 7, 1989	Oct. 11, 1989

Monthly rainfall rates during the six corn seasons are shown in Figure 1 of the previous experiment. The first corn season occurred during the wettest period, and rainfall was normal. The second season was very dry, which is typical for that period; the third and sixth seasons were drier than normal.

After the third corn season, we measured bulk density and volume wetness (Table 4). At the 0- to 15-cm soil depth, there were no significant differences among treatments, but for the 15- to 30-cm soil depth, bulk density was significantly lower in the subsoiled than in the non-subsoiled treatment, and cone resistance to the 40-cm depth was also significantly lower in the former treatment than in the latter (Figures 1 and 2).

Corn-grain yields for the six treatments are shown in Table 5. The first crop did not respond to subsoiling. However, for the next five crop seasons, subsoiling produced significant responses. Moreover, the response was greater with lower amounts of rainfall. In general, the trend for grain yields was the same from year to year: The subsoiled treatments usually had higher yields than non-subsoiled treatments. When P was broadcast, the subsoiling treatments yielded 30% more grain than non-subsoiled treatments.

Table 1. Treatments in the conventional tillage experiment, Yurimaguas.

Treatments	Description
I	Bedding, subsoiling: beds of 0.8-m spacing with subsoiling at the 30-cm soil depth in one tractor pass; bed shaped and corn planted in another tractor pass. Herbicide (Dual) weed control after planting.
II	Bedding: similar to (1) without subsoiling.
III	Flat-planted, subsoiling: subsoiling at 0.8-m spacing and the 30-cm soil depth in the one tractor pass; corn planted in another tractor pass. Herbicide (Dual) weed control after planting.
IV	Flat-planted: similar to (3) without subsoiling.
V	Bedding and subsoiling with banded P: similar to (1). P was banded at planting using a Soda Flo applicator
VI	Beds with banded P: similar to (2). P was banded at planting time with Soda Flo applicator.

For the 4th crop, root distribution was measured by the trench-profile method. In the flat-planted subsoiling treatment, there were greater numbers of roots to the 50-cm depth, whereas in the non-subsoiled treatments, rooting depth was shallow. In the subsoiled treatment, roots tended to follow the slit of the subsoiler (Figure 3).

Conclusions

1) Subsoiling increased corn-grain yields 30% over that of non-subsoiled treatments; 2) subsoiling decreased bulk density and mechanical impedance to a depth of 40 cm; and 3) Subsoiling promoted higher root densities deeper in the soil profile.

Table 3. Soil chemical properties after installing the tillage treatments.

		Exchangeable			Avail.		
Depth	pH	Acidity	Ca	Mg	K	P	Al sat.
cm		cmol (+)/L				mg/L	%
0–15	5.6	0.33	2.1	0.6	0.08	18	10
20–40	4.8	1.84	1.0	0.2	0.04	5	58
40–60	4.7	2.10	0.1	0.14	0.03	5	86

Table 4. Bulk density (B.D.) and volume wetness (0) at 0- to 15-cm and 15- to 30-cm soil depths before harvesting the third corn crop.

	0 to 15 cm		15 to 30 cm	
Treatment	B.D.	0	B.D.	0
	Mg/m^3	cm^3/cm^3	Mg/m^3	cm/cm^3
Bed—subsoil	1.43	14.2	1.50	18.0
Bed	1.47	14.8	1.67	150
Flat—subsoil	1.45	16.4	1.52	17.6
Flat	1.51	15.0	1.65	16.8
Bed—subsoil—P band	1.42	14.0	1.55	17.0
Bed—P band	1.50	15.0	1.64	16.5
LSD (0.05)	0.09	1.8	0.08	2.5

Table 5. Grain yields for six corn crops as affected by tillage.

Treatment	1st crop	2nd crop	3rd crop	4th crop	5th crop	6th crop	Mean
				Mg/ha			
Bed—subsoil	3.54	3.97	3.61	4.23	4.09	4.49	3.99
Bed	3.44	3.15	2.47	2.46	2.32	2.68	2.75
Flat—subsoil	3.43	3.52	3.69	3.88	3.88	3.71	3.69
Flat	3.40	3.25	2.10	1.95	2.21	2.01	2.49
Bed—subsoil—P band	4.06	3.25	3.41	3.55	2.82	4.33	3.70
Bed—P band	3.82	3.41	3.21	2.35	2.82	3.21	3.14
LSD (0.05)	0.50	0.71	0.54	0.75	0.56	0.41	

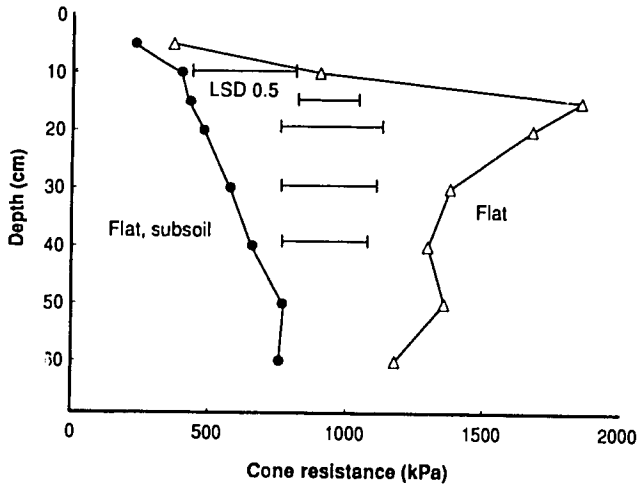

Figure 1. Cone resistance at a depth of 0 to 60 cm before harvesting the third corn crop in flat-planted treatments.

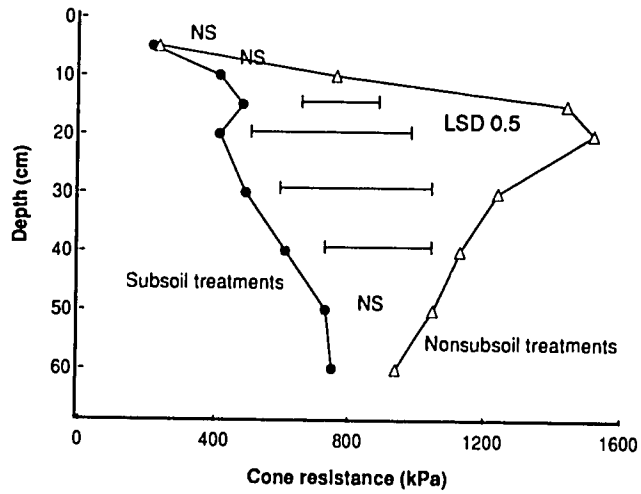

Figure 2. Cone resistance at a depth of 0 to 60 cm before harvesting the third corn crop in treatments with and without subsoiling.

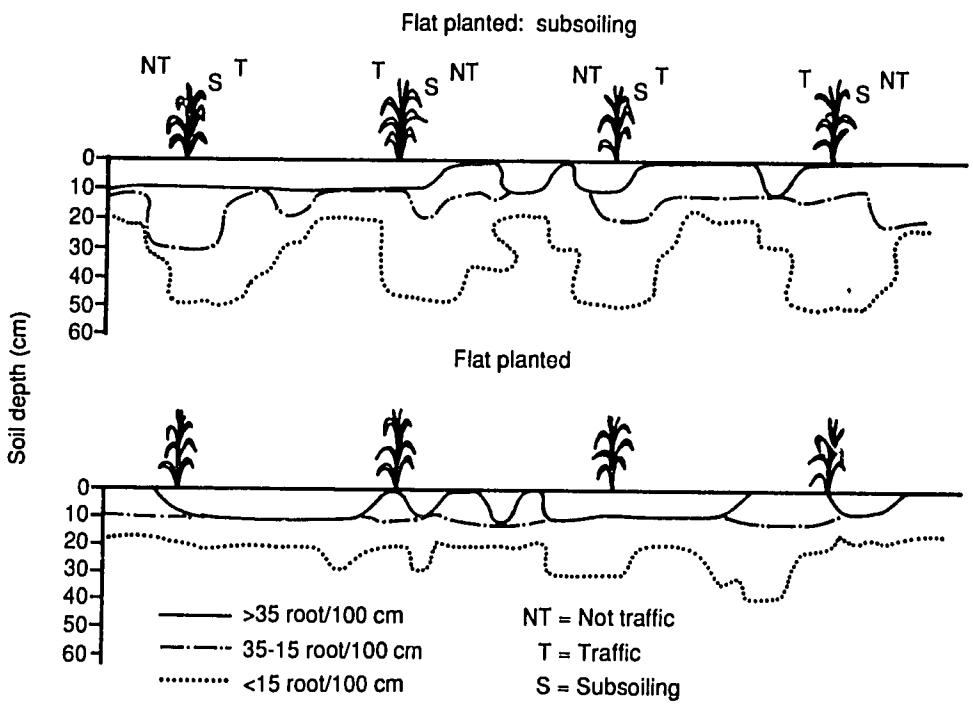

Figure 3. Root distribution for the fourth crop.

Rainfall Intensity and Runoff Losses in Yurimaguas: Y-115

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Objective

The objective of this study was to obtain a long-term record of rainfall intensities and relate them to soil management under intensive continuous cropping.

Rainfall Intensity

The total annual rainfall in 1986 was 2746 mm; in 1987, 2290 mm; in 1988, 1709 mm; and through October 1989, 1525 mm. Measurements taken during rainfall events of intensity greater than 10 mm/hr during 37 months are shown in Table 1. Such data sets are extremely scarce in the tropics. From October 1986 to October 1989, there were several long, intense rainfall events, the most intense being 55.9 mm/hr for 1 hr. These intense rainfall events produced runoff under conventional tillage, especially at the initial stage of crop development (see next report).

Rainfall in 1988 and 1989 was below the long-term annual average of 2200 mm. Rainfall events were also less intense and less frequent than average (Table 1). For this period of evaluation, we can conclude that 50% of the rainfall came in intense events.

Six runoff plots 10-m long by 3.2-m wide were installed in October 1987. Slopes ranged from 0 to 2%. Each runoff plot has wooden borders on three sides to prohibit runoff from surrounding areas. On the lowest side, a collection system of small channels and cylinders was installed to catch water and sediment. The first cylinder on each plot had an eleven-slot divisor. Only the central slot led to the second cylinder, so it accumulated one-eleventh of the runoff water from the first cylinder. Rainfall was recorded daily from the rain gauge, and water runoff was read the day after a rain.

The runoff collectors are being calibrated; preliminary data are shown in Table 2. Runoff was less with minimum-till subsoiling than with conventional-tillage subsoiling. Factors affecting the water balance will be monitored over a longer period.

Table 1. Record of high intensity (>10 mm/hr) storms at the Yurimaguas Experiment Station, October 1986 through October 1989.

Date	Time	Duration	Rainfall	Intensity	Monthly precip.	Monthly precip.
		minutes	mm	mm/hr	%	mm
1986						
October						201.4
11	05:30/06:15	45	26.7	35.6	17.7	
11	10:00/11:00	60	19.1	19.1	9.5	
26	16:30/17:00	30	29.8	59.6	14.8	
					42.0	
November						263.2
04	06:30/08:00	90	29.2	19.5	11.1	
11	09:30/12:00	150	26.7	10.7	10.1	
11	12:00/14:00	120	48.3	24.2	18.2	
17	04:00/05:30	90	45.7	30.4	17.4	
17	09:00/13:00	240	43.2	10.8	16.4	
24	11:30/12:00	30	15.2	30.4	5.8	
					78.9	
December						428.0
02	08:00/09:00	60	50.8	50.8	11.9	
02	09:00/10:00	60	20.3	20.3	4.7	
03	13:00/14:00	60	41.9	41.9	9.8	
05	02:00/03:00	60	26.7	26.7	6.2	
08	17:00/18:00	60	21.6	21.6	5.0	
09	16:00/18:00	120	38.1	19.1	8.9	
29	03:30/05:00	90	62.2	41.5	14.5	
29	05:00/06:00	60	22.9	22.9	5.4	
					66.4	

Table 1. (continued)

Date	Time	Duration	Rainfall	Intensity	Monthly precip.	Monthly precip.
		minutes	mm	mm/hr	%	mm
1987						
January						303.4
01	09:00/10:00	60	30.5	30.5	10.1	
03	20:50/22:00	70	77.6	66.5	25.6	
					35.7	
February						133.9
March						251.7
04	22:30/24:00	90	25.4	16.9	10.1	
05	05:00/06:00	60	55.9	55.9	22.2	
05	06:00/07:00	60	15.2	15.2	6.0	
06	19:30/20:00	30	15.2	30.4	6.0	
30	07:00/08:00	60	21.6	21.6	8.6	
					52.9	
April						257.1
09	09:00/10:00	60	21.6	21.6	8.4	
09	10:00/13:00	180	44.5	14.8	17.3	
28	07:00/11:00	240	53.4	13.4	20.8	
29	16:00/17:00	60	19.1	29.1	7.4	
					53.9	
May						205.1
06	02:00/03:00	60	19.1	19.1	9.3	
10	07:30/08:00	30	15.2	30.4	7.4	
17	05:00/06:15	75	12.7	10.2	6.2	
17	11:00/12:00	60	17.8	17.8	8.7	
23	03:00/05:00	120	44.4	22.2	21.6	
					53.2	
June						56.8
14	12:00/13:00	60	11.4	11.4	20.1	
July						103.6
10	03:00/04:00	60	17.8	17.8	17.2	
29	10:00/12:00	120	20.3	10.2	19.6	
					36.8	
August						92.7
18	00:00/00:30	30	14.6	29.2	15.7	
30	14:45/16:00	75	19.1	15.3	20.6	
					36.3	
September						169.4
07	11:00/12:00	60	12.7	12.7	7.5	
12	21:15/22:15	60	45.7	45.7	27.0	
16	14:00/15:00	60	17.8	17.8	10.5	
17	10:00/11:00	60	13.1	13.1	7.7	
					52.7	

Continued

Table 1. (continued)

Date	Time	Duration	Rainfall	Intensity	Monthly precip.	Monthly precip.
		minutes	mm	mm/hr	%	mm
October						211.5
14	16:00/17:00	60	15.2	15.2	7.2	
20	11:00/12:00	60	18.0	18.0	8.5	
22	15:30/16:00	30	12.7	25.4	6.0	
31	00:15/01:45	90	31.4	20.9	14.8	
					36.5	
November						295.8
02	10:00/11:00	60	47.0	47.0	15.9	
20	15:00/16:30	90	17.1	11.4	5.8	
24	05:00/06:00	60	14.0	14.0	4.7	
26	06:15/07:15	60	40.6	40.6	13.7	
					40.1	
December						209.6
07	04:00/08:00	240	85.2	21.3	40.6	
28	13:00/14:00	60	15.2	15.2	7.3	
31	12:00/13:15	75	14.0	11.2	6.7	
					54.6	
1988						
January						59.2
10	10:30/12:00	90	16.50	11.0	27.9	
February						139.7
27	05:00/06:00	60	10.3	10.3	7.4	
March						265.0
01	14:00/15:00	60	12.1	12.1	4.6	
02	17:00/17:30	30	30.5	61.0	11.5	
07	15:00/16:00	60	12.7	12.7	4.8	
08	06:00/07:00	60	33.7	33.7	12.7	
08	07:00/08:00	60	17.8	17.8	6.7	
14	12:15/13:15	60	20.3	20.3	7.7	
18	02:30/03:00	30	19.1	38.2	7.2	
					55.2	
April						183.7
02	12:00/13:00	60	14.0	14.0	7.6	
02	16:00/17:00	60	11.4	11.4	6.2	
17	14:00/15:00	60	15.2	15.2	8.3	
23	12:15/13:00	45	19.1	25.5	10.4	
					32.5	
May						137.1
04	14:00/15:00	60	12.7	12.7	9.3	
04	15:00/16:00	60	15.2	15.2	11.1	
					20.4	
June						54.0
23	15:00/16:00	60	27.9	27.9	51.7	
23	16:00/17:00	60	12.7	12.7	23.5	
					75.2	

Table 1. (continued)

Date	Time	Duration	Rainfall	Intensity	Monthly precip.	Monthly precip.
		minutes	mm	mm/hr	%	mm
July						16.7
August						90.8
17	02:00/03:00	60	24.1	24.1	26.5	
21	18:45/19:30	45	19.1	25.5	21.0	
27	12:30/13:00	30	21.6	43.2	23.8	
					71.3	
September						87.8
15	11:00/12:00	60	17.8	17.8		
October						184.3
03	02:30/04:00	60	27.9	18.6	15.1	
08	03:00/04:00	60	16.5	16.5	9.0	
08	04:00/04:30	30	15.2	30.4	8.2	
08	09:15/10:00	45	15.2	20.3	8.2	
27	08:00/09:00	60	12.7	12.7	6.9	
					47.4	
November						338.8
02	07:30/08:30	60	22.9	22.9	6.8	
09	12:00/12:30	30	13.9	27.8	4.1	
15	01:00/02:00	60	12.7	12.7	3.7	
15	18:00/19:00	60	35.6	35.6	10.5	
23	11:30/12:00	30	38.1	76.2	11.2	
23	12:00/13:00	60	25.4	25.4	7.5	
28	12:30/13:30	60	31.8	31.8	9.4	
					53.2	
December						152.6
08	11:00/12:00	60	10.2	10.2	6.7	
24	12:00/13:00	60	24.1	24.1	15.8	
24	14:30/15:00	30	16.5	33.0	10.8	
					33.3	
1989						
January						211.9
20	15:00/16:00	60	15.2	15.2	7.2	
23	05:00/06:00	60	29.2	29.2	13.8	
28	11:00/12:00	60	30.5	30.5	14.4	
					35.4	
February						208.3
02	03:30/04:30	60	24.1	24.1	11.6	
02	04:30/05:30	60	19.1	19.1	9.2	
28	12:30/13:00	30	25.4	50.8	12.3	
					33.1	
March						242.3
03	13:15/14:00	45	29.8	39.7	12.3	
16	16:00/17:00	60	20.3	20.3	8.4	
25	18:15/18:30	15	12.7	50.8	5.2	
28	02:00/03:00	60	20.3	20.3	8.4	
					34.3	

Continued

Table 1. (continued)

Date	Time	Duration	Rainfall	Intensity	Monthly precip.	Monthly precip.
		minutes	mm	mm/hr	%	mm
April						89.6
08	14:00/15:00	60	16.5	16.5	18.4	
27	10:00/12:00	120	21.6	10.8	24.1	
					42.5	
May						165.1
02	00:00/01:00	60	21.6	21.6	13.1	
04	08:15/09:00	45	13.1	17.5	7.9	
04	10:00/11:00	60	37.5	37.5	22.7	
06	18:00/19:00	60	11.4	11.4	6.9	
14	02:00/02:10	10	14.0	84.0	8.5	
					59.1	
June						134.1
11	09:30/11:00	9.0	33.0	22.0	24.6	
17	14:00/15:00	6.0	30.2	30.2	22.5	
					47.1	
July						44.2
02	21:30/23:00	90	26.7	17.8	60.4	
August						128.0
09	15:30/16:00	30	17.8	35.6	13.9	
18	09:30/11:00	90	28.6	19.[illegible]	22.3	
28	16:00/17:00	60	14.0	14.0	10.9	
					47.1	
September						67.4
29	14:00/15:00	60	19.1	19.1	28.3	
October						230.5
10	07:30/08:30	60	22.9	22.9	9.9	
13	06:00/07:00	60	20.3	20.3	8.8	
31	07:30/08:00	30	17.8	35.6	7.7	
					26.4	

Table 2. Preliminary runoff losses for various tillage practices for row crops from November 1987 through January 1989. Total precipitation was 1757 mm.

Treatment	Runoff losses	Runoff %
	(mm)	
Conventional tillage with subsoiling	249	14.0
Minimum tillage with subsoiling	120	6.8
No tillage with subsoiling	165	9.4
LSD 0.05	43	

Soil Trafficability in a Loamy Sand Ultisol: Y-111

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D. Keith Cassel, N.C. State University

Intensive continuous cropping in the humid tropics often promotes soil degradation and decreases crop yields when machinery is used under excessively wet soil conditions.

Objectives

The objectives of this study were 1) to examine soil compaction caused by tractor passes on a loamy sand Ultisol with varying water content in Yurimaguas and 2) to quantify the reduction in corn yields that one might anticipate from compaction.

Procedures

The experimental area was a loamy sand (80% sand, 10% clay) soil that had been continuously cropped by mechanical farm machinery since 1987. The whole area was treated with herbicide, and P was incorporated with a disk harrow.

The experimental design was a split-plot compacted by tractor traffic at three soil moisture contents (15, 25, and 35% by volume) at the 0- to 15-cm soil depth as main plots and zero to ten tractor passes (using a Kubota 65 HP tractor with disk harrow) as subplots. Three hours after 38 mm of rain on October 3, 1988, we imposed the subtreatments at 35% soil moisture. Seven hours later, we imposed the subtreatments at 25% soil moisture, and the next afternoon (24 hours later), we imposed the subtreatment at 15% soil moisture. Corn seeds were planted 0.2 m apart with a planting stick in the wheel track. Wheel tracks were 0.8 m apart. Nitrogen and potassium were applied after planting at 120 and 80 kg/ha in a split application. Bulk density, total porosity, soil water characteristics, and mechanical resistance were determined in the wheel track immediately after the tractor passes.

Results

Soil bulk density after compaction at different moisture contents is shown in Table 1. It is clear that the first tractor pass inflicts the greatest amount of compaction and that each succeeding pass causes little or no compaction. Only with ten passes did we observe a decline in yields at 35 and 25% moisture contents (Table 2). At 15% moisture content, no significant reduction in corn yields occurred. There was no significant correlation between crop yield and tractor passes (zero to five passes). This loamy sand soil has a very high infiltration rate, and it is difficult to find soil moisture contents higher than field capacity (25%).

A similar experiment in a sandy loam Ultisol (65% sand, 20% clay) found that one tractor pass under the highest soil moisture content caused soil compaction and a 50% reduction in corn yields (*TropSoils Technical Report, 1986-87*).

Conclusion

For this loamy sand soil, we conclude that one to five tractor passes reduced total porosity (Table 3) and increased bulk density, but did not significantly reduce corn yields.

Implication

This loamy sand Ultisol can be plowed (conventional tillage) the day after a heavy rain without negatively affecting corn yields.

Table 1. The impact of tractor passes and soil moisture on the bulk density of a loamy sand ultisol at 0- to 10-cm soil depth.

Soil moisture	Number of tractor passes							
	0	1	2	3	4	5	10	Mean
(m^3/m^3)	Mg/m^3							
0.35	1.45	1.65	1.67	1.69	1.68	1.70	1.71	1.65
0.25	1.45	1.58	1.63	1.63	1.67	1.67	1.69	1.62
0.15	1.47	1.58	1.61	1.64	1.65	1.66	1.65	1.61
Mean	1.46	1.60	1.64	1.65	1.66	1.68	1.68	

LSD .05
Soil moisture = 0.02
Tractor passes = 0.03
Two soil moisture in same tractor passes = 0.07
Two tractor passes in same soil moisture = 0.07

Table 2. Impact of tractor passes and soil moisture on corn grain yields in a loamy sand Ultisol.

Soil moisture	Number of tractor passes							
	0	1	2	3	4	5	10	Mean
% by volume	t/ha							
35	2.90	2.76	3.05	2.51	2.35	2.00	1.30	2.77
25	3.08	3.75	3.24	3.08	3.67	2.92	2.36	2.98
15	2.90	3.28	2.84	3.37	2.90	2.81	2.76	2.88
Mean	2.96	3.26	3.04	2.99	2.96	2.58	2.14	

LSD .05
Soil moisture = 0.94
Tractor passes = 0.58
Two soil moisture in same tractor passes = 0.90
Two tractor passes in same soil moisture = 0.95

Table 3. Impact of tractor passes and soil moisture on the total porosity of a loamy sand Ultisol at 0- to 10-cm soil depth.

Soil moisture	Number of tractor passes							
	0	1	2	3	4	5	10	Mean
% by volume	%							
35	45.3	37.7	37.0	36.2	36.6	35.9	35.5	37.7
25	45.3	40.4	38.5	38.5	37.0	37.0	36.2	39.0
15	44.5	40.4	39.3	38.1	37.7	38.1	37.7	39.4
Mean	45.0	39.6	38.3	37.6	37.1	37.0	36.5	

LSD .05
Soil moisture = 0.9
Tractor passes = 1.0
Two soil moisture in same tractor passes = 2.6
Two tractor passes in same soil moisture = 2.5

Fertilizer N Requirements for Long-term Corn Production: M-910A

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The Central Amazon is characterized by two major soil ecosystems. Upland landscapes occupy approximately 60% of the region and are predominated by Oxisols with high subsoil acidity, clay contents reaching 80%, strong aggregation, medium water-holding capacity, and high permeability. The heterogenous group of Entisols on the flood plains of sediment-rich rivers forms the second soil ecosystem. These soils have high fertility, negligible soil acidity, silty textures, poor aggregation, high water-holding capacity, and low permeability. Intensive annual crop production is possible in the Entisols during an eight-month flood-free period. Even when lime and fertilizers are applied to eliminate acidity and P and K constraints in the Oxisols, corn yields after initial slash-and-burn clearing are inferior to those obtained in the Entisols. Since apparent recovery of fertilizer N is similar between ecosystems, it is likely that there are intrinsic differences in the native soil's N supply or its availability during crop growth.

Objectives

Since 1984, the purpose of this study has been to conduct N fertilization trials with corn to compare the following qualities of an Entisol and an Oxisol: 1) the impact of fertilizer N on yield, the efficiency of N use, and the growth rate; and 2) the movement of inorganic soil N.

Procedures

Relevant properties for soil profiles at each site are shown in Table 1. One corn crop was grown at each site during the wet seasons of 1984 to 1987. An exception was the fourth crop in the Oxisol, which was planted in the wet season but completed its growth cycle during the dry season (<100 mm/month). A fifth crop was grown in the Entisol during 1988. Urea-N rates for each site and year are described in Table 2. In 1986 N was placed as a single broadcast application to monitor soil-N dynamics. Treatments were arranged in a randomized complete-block design with four replications in the Oxisol and three in the Entisol. Lime, P, K, Mg, S, and micronutrients were applied uniformly to treatments in the Oxisol, but only N was applied to the Entisol. Locally adapted, open-pollinated corn varieties were used in all crops.

Results

Grain yields for each crop are shown in Figure 1. In each year, maximum yields were greater in the Entisol than in the Oxisol. Nitrogen rates to achieve the yield plateaus at both sites increased with each successive crop. The linear response to N for the 1985 crop in the Oxisol may be due to the absence of an N rate between 60 and 120 kg N/ha. Yield performances in previous and succeeding crops in the Oxisol suggest that the yield plateau may have occurred between 60 and 80 kg N/ha.

In the absence of fertilizer N, yields declined with each succeeding crop. The magnitude of this decrease was greater in the Entisol than in the Oxisol. The trend in both soils suggests a decreasing supply of native-soil N, a view supported by laboratory measurements of the net inorganic

Table 1. Selected chemical and physical properties for the Oxisol and Entisol.

			Porosity				Total					Soil Charge	
Depth	Clay	Silt	Db	Micro	Macro	Hyd. cond.	C	N	pH	Al sat.	ECEC	Neg.	Pos.
cm	— % —		Mg/cm³	— m³ —		cm/hr	— % —			%	— cmol/kg —		
Typic acrudox													
0–15	82	7	1.04	516	278	28.1	20.4	1.8	4.7	38	2.36	2.06	0.88
15–30	82	9	1.12	703	132	8.1	11.2	1.0	4.5	68	2.24	0.77	1.55
30–45	85	8	1.11	731	136	9.6	5.8	0.6	4.5	72	1.65	0.82	1.82
45–60	92	1	1.04	685	127	10.4	—	—	4.4	73	1.56	0.43	2.12
Typic tropofluvent													
0–15	21	64	1.18	636	204	5.5	14.0	1.5	6.1	2	10.18	13.75	0.27
15–30	18	60	1.52	853	270	0.6	10.6	0.9	6.1	2	9.56	11.24	0.25
30–45	16	56	1.61	822	340	1.5	5.2	0.7	5.0	2	9.81	12.59	0.24
45–60	13	53	1.65	842	348	0.6	—	—	5.8	2	9.35	11.54	0.28

Table 2. Nitrogen rates and method of placement for each corn crop.

Soil	Year	Season	Placement	N Rates
				kg/ha
Entisol	1984	Wet	Split-applied	0,30,60,90,120
	1985	Wet	Split-applied	0,30,60,90,120
	1986	Wet	Single	0,40,80,120,160
	1987	Wet	Split-applied	0,40,80,120,160
	1988	Wet	Split-applied	0,40,80,120,160
Oxisol	1984	Wet	Split-applied	0,20,40,60,120
	1985	Wet	Split-applied	0,20,40,60,120
	1986	Wet	Single	0,40,80,120,160
	1987	Wet/Dry	Split-applied	0,40,80,120

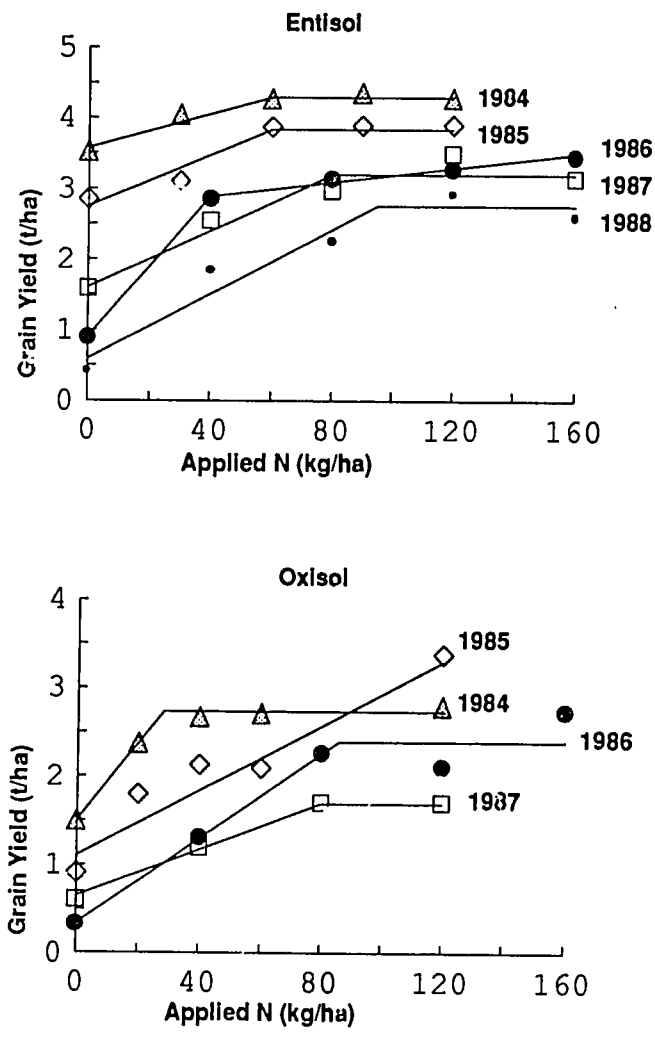

Figure 1. Corn-grain yields as a function of urea-N rates during consecutive years of cultivation in a Central Amazon Entisol and Oxisol.

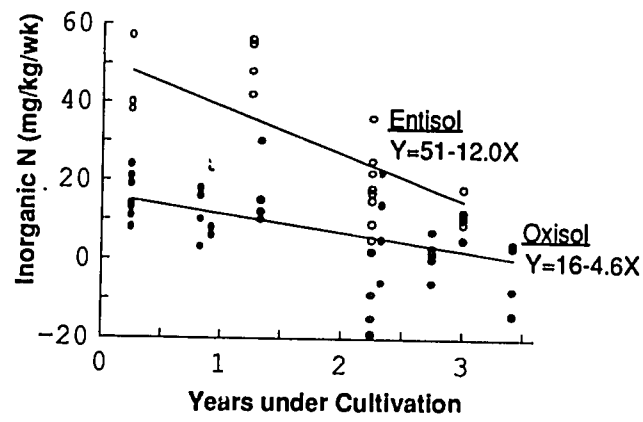

Figure 2. Relationships between time under continuous cultivation and net inorganic N mineralized from soil samples during seven days of anaerobic incubation for a Central Amazon Entisol and Oxisol.

N released by soil samples from these plots during seven days of anaerobic incubation (Figure 2). The higher initial levels of inorganic-N supply (51 vs. 16 mg N/kg/wk) and the greater rate of decline in inorganic-N mineralization for zero-N plots in the Entisol than in the Oxisol are consistent with the yield trends across time for these treatments (Figure 1). The Oxisol contained higher levels of total C and N than did the Entisol. The higher clay content and microaggregation of the Oxisol may have protected organic-N compounds from biological activity, resulting in a slower rate of inorganic-N release than in the Entisol.

Fertilizer N requirements (Nf) to obtain maximum yields in each crop were estimated by the following equation:

$$Nf = (Ny-Ns)/Ef$$

where Ny is the amount of N in aboveground biomass at the maximum yield, Ns is the amount of plant N derived

from native-soil N (as measured by N uptake in the zero-N treatments), and Ef is the amount of N uptake in above-ground biomass per unit of applied N. Predicted and observed fertilizer-N requirements for crops in 1984 to 1987 are compared in Table 3 for each site. There is closer agreement between predicted and observed fertilizer-N requirements during the two initial crops in both soils. Mean Ef values, although similar between sites, were also lower than values reported for corn hybrids in other temperate and tropical regions.

Crop growth and N uptake were measured throughout the 1987 crop cycle at both sites. Nitrogen fertilization increased mean crop growth rates (CGR) at both sites, but there was no site-by-N-rate interaction (Table 4). Mean CGR was higher in the Entisol than in the Oxisol during all growth intervals, but the major difference between sites occurred after silking: Growth rate was reduced in the Oxisol and relatively unchanged in the Entisol. Dry-matter accumulation patterns for leaves and stalks showed not only a greater buildup of these plant components but also a longer period of growth to reach the maximum levels (Figure 3). With the highest N rate, maximum dry-matter accumulation in leaves and stalks occurred at 70 days after planting in the Entisol as opposed to 56 days in the Oxisol. Leaf and stalk dry weight decreased during reproductive development because dry matter was partitioned to the developing ears. Grain production at both sites exceeded the amount of total aboveground dry matter accumulated after silking (Table 5). Consequently, their difference should indicate the net translocation of leaf and stalk dry matter accumulated in the developing ears prior to silking. Net translocation averaged across N rates was 666 and 541 kg/ha for the Entisol and Oxisol, respectively. Longer growth duration and higher rates of dry-matter accumulation and translocation in the Entisol resulted in higher yields than in the Oxisol. Without applied N, yields in the Entisol were 0.6 t/ha greater than in the Oxisol. Between 40 and 160 kg N/ha, grain yield in the Entisol exceeded yield in the Oxisol by about 1 t/ha.

Growth and yield of the 1987 crop could also have been related to climatic differences between sites (Figure 4). Rainfall in the Oxisol was greater than in the Entisol throughout the growing season. During the 105-day growing season, mean maximum and minimum temperatures differed by less than 1°C between sites, but mean

Table 4. Site and fertilizer-N effects on mean crop growth rates of corn during selected periods in the Entisol and Oxisol.

Applied N	Growth Interval V-8/V-11	V-11/R-1	R-1/R-3
kg/ha		kg/ha/day	
0	32	103	47
40	81	126	130
80	91	174	150
120	92	161	160
160	93	220	150
Site Means			
Entisol	86	164	163
Oxisol	72	151	103
LSD 0.05:			
N Rate	24	42	62
Site	NS	NS	48
N x Site	NS	NS	NS

Table 3. Observed and predicted fertilizer-N requirements (Nf) to produce maximum yields during four crops in the Entisol and Oxisol. Estimated by Nf = (Ny-Ns)/Ef.

Soil	Year	Maximum Grain yield	Maximum N uptake (Ny)	N form soil (Ns)	Required N (Ny-Ns)	N fertil. effic. (Ef)	Fertilizer N requirement Predicted (Nf)	Fertilizer N requirement Observed (Nf)
		t/ha	kg/ha	kg/ha	kg/ha	kg/kg	kg/ha	kg/ha
Entisol	1984	4.3	118	89	29	0.53	55	60
	1985	3.8	105	72	33	0.54	62	60
	1986	2.9	79	32	47	0.39	122	40
	1987	3.2	89	41	48	0.33	144	80
Oxisol	1984	2.7	75	48	27	0.54	50	28
	1985	3.7	102	31	71	0.38	188	120
	1986	2.4	66	24	42	0.34	123	86
	1987	1.7	46	34	12	0.36	35	80

solar radiation was 328 mWh/cm/day in the Entisol as opposed to 307 mWh/cm/day in the Oxisol. Crop growth simulations with the CERES-Maize model were used to assess how climatic differences between sites could influence corn yield. Two weather files were created using daily values of rainfall, solar radiation, and maximum and minimum temperatures measured at each site. Soil parameters were fixed to adequate N supply, and soil water and root distribution characteristics measured in the Entisol profile. Crop parameters were based on measurements made during the 1987 crop. Predicted yields for simulations under the climatic regime at each site and at several planting dates are shown in Table 6. Predicted yields for the Entisol were greater than in the Oxisol for planting dates from November 11, 1986, to January 10, 1987. A maximum yield difference of 0.3 t/ha was predicted by simulations at the actual planting dates. However, this yield difference would only account for

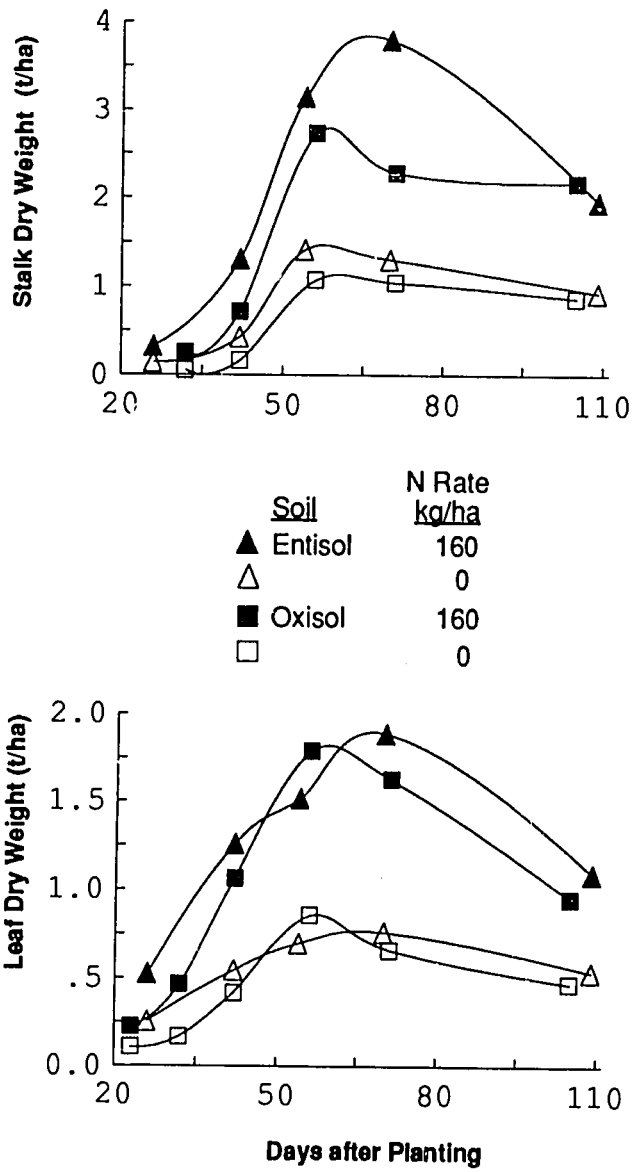

Figure 3. Accumulation of stalk and leaf dry matter during the 1987 corn crop at two rates in a Central Amazon Entisol and Oxisol.

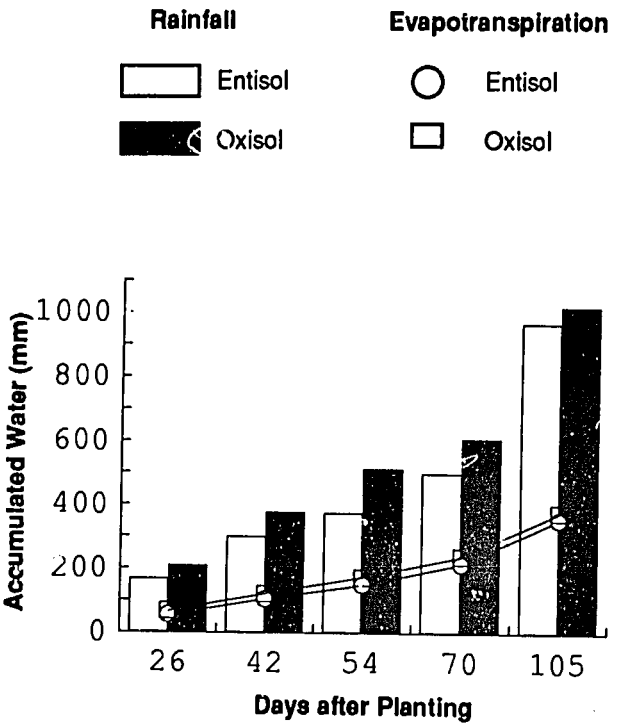

Figure 4. Rainfall and evapotranspiration patterns during the 1987 corn crop in a Central Amazon Entisol and Oxisol.

Table 5. Comparisons between final corn-grain yields and post-silking gains in aboveground total dry matter among N rates in the Entisol and Oxisol.

Soil	Applied N	TDM gain after silking	Grain yield
	kg/ha	– t/ha –	
Entisol	0	0.61	0.89
	40	2.11	2.86
	80	2.25	3.13
	120	2.85	3.26
	160	2.43	3.44
Oxisol	0	-0.03	0.33
	40	0.94	1.31
	80	1.32	2.16
	120	1.70	2.10
	160	1.93	2.73

Table 6. Predicted corn-grain yields by the CERES-Maize model for several simulated planting dates under actual climatic regimes at both sites.

Planting Date	Predicted grain yields	
	Entisol	Oxisol
	t/ha	
November 1	4.0	4.0
November 11	1.4	4.0
November 21	4.2	4.0
December 1	4.0	3.9
December 11	4.1	4.0
December 31	4.0	3.9
January 10	4.1	4.0
Mean	4.1	4.0

Actual planting dates for corn were November 21 in the Entisol and December 11 in the Oxisol.

30% of the observed yield variation between sites under conditions of adequate N supply (Table 5).

Soil inorganic N distribution in the profiles (0 to 60 cm) was also monitored during the 1987 crop. Fertilizer-derived soil N was estimated as the difference in inorganic N between urea-N treatments and the zero-N treatment at each sampling date. When averaged across N rates, quantities of fertilizer-derived soil N or its rate of disappearance from the 0- to 60-cm soil depth through leaching and crop uptake differed little between sites during the growing season (Figure 5). However, noticeable differences occurred between sites in the distribution of soil N within the 60-cm profile depth which was sampled. Whereas more than 60% of the N in the Entisol remained in the surface 30 cm during the period from planting to silking, N in the Oxisol moved progressively to lower depths during the same period (Figure 6). Faster movement of fertilizer-derived soil N into the Oxisol subsoil was attributed to superior hydraulic conductivity and porosity relative to the Entisol (Table 1). The greater anion exchange capacity and net positive charge of subsoil layers in the Oxisol would also favor a higher retention of NO_3, thus reducing downward movement. Measurements of corn root distribution in the Oxisol and Entisol profiles revealed a smaller proportion and total number of roots in the subsoil layers of the Oxisol (Figure 7). Although both soils contained similar amounts of fertilizer-derived soil N in the profile, this N was less accessibile in the Oxisol because it was primarily retained in the subsoil layers where root growth was restricted by high Al saturation.

Conclusions

Results from this study suggest that cropping history plays a major role in determining fertilizer N requirements for corn in this humid tropical environment. Native soil N supply to corn is initially higher in the Entisols than in the Oxisols, but decreases rapidly with progressive cultivation. Management practices to alleviate Al toxicity constraints to deep root proliferation in the Oxisol should improve the accessibility of subsoil N to corn and increase both yields and fertilizer-N recovery in this soil.

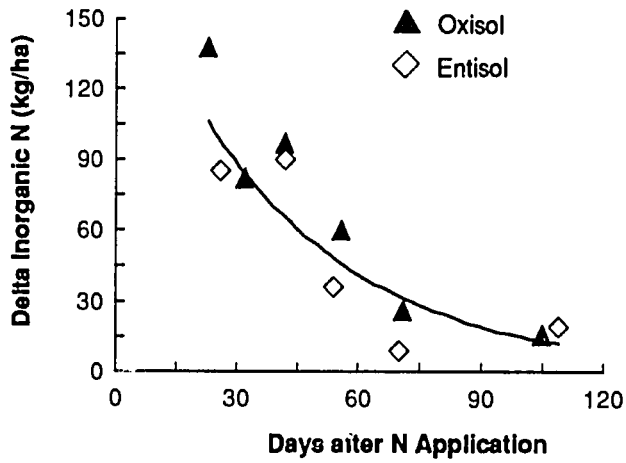

Figure 5. Fertilizer-derived inorganic N in the 0- to 60-cm profile depth of an Entisol and Oxisol during the growth cycle of the 1987 corn crop.

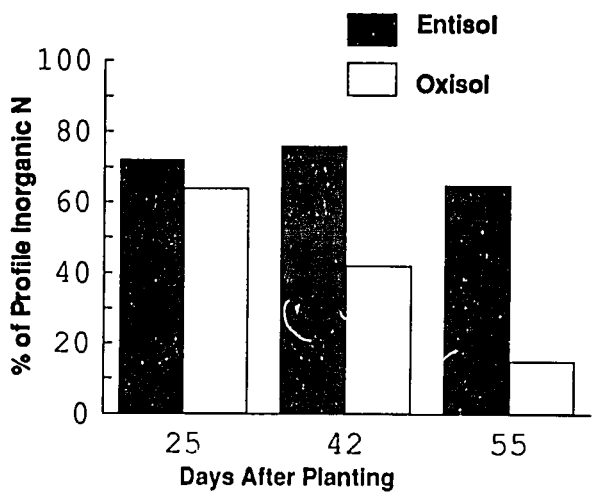

Figure 6. Proportion of fertilizer-derived N in a Central Amazon Entisol and Oxisol profile (0 to 60 cm) remaining in the surface 30 cm at three different sampling dates in the 1987 corn crop.

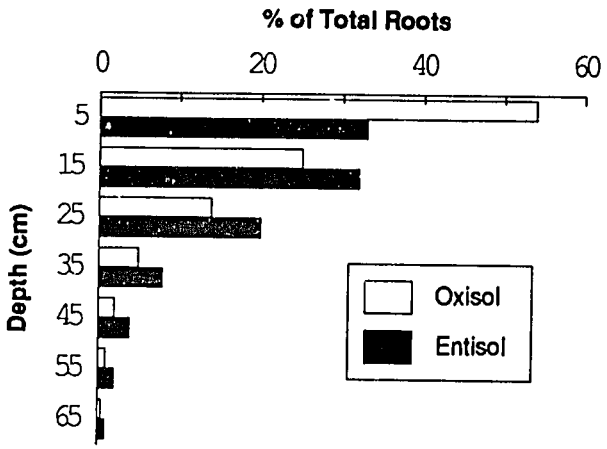

Figure 7. Corn root distribution as a function of soil depth in an Entisol and Oxisol during the 1987 crop.

Timing and Distribution of Fertilizer N Placement for Corn in a Central Amazon Oxisol: M-910B

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Thomas Jot Smyth, N.C. State University

Oxisols in the Central Amazon have a high permeability and a low water-holding capacity. The potential for N movement into the acid subsoil below the rooting zone is high under such conditions. Fertilizer N availability and recovery may be improved by distributing N in several applications when crop needs are high.

Objectives

The objectives of this study were 1) to determine the optimum rate and method of N application for corn and 2) to estimate the effect and efficiency of the different N rates and application treatments on corn growth, N uptake, and grain yield.

Procedures

Two consecutive corn crops were grown during the 1986 and 1987 wet seasons in the clayey Oxisol in Manaus. Experimental design was a randomized complete block with four replications. Treatments consisted of a factorial arrangement of three urea-N levels (40, 80, and 120 kg N/ha) split-applied in five methods. A control with no N applied was included as an additional treatment. Nitrogen was applied either by single application or by splitting rates into two or three equal parts. Single-application treatments occurred 1) at planting in the seed bed (1-0-0) and 2) at 25 days after planting (DAP) (0-1-0). Treatments with two equal split applications occurred either 3) at planting and 25 DAP (1/2-1/2-0) or 4) at 25 DAP and silking (55 DAP) (0-1/2-1/2). The fifth method consisted of three equal split applications made at planting and at 25 and 55 DAP (1/3-1/3-1/3). All N applications were banded and incorporated soon thereafter with a manual hoe. Phosphorus, K, micronutrients, and lime were applied uniformly to all treatments before planting the first corn crop.

Since there were no significant crop-by-treatment interactions, the effects of N rates, the timing of the applications, and the distribution of fertilizer N on measured plant variables are presented using the means of treatments across both crops. The absence of interactions between N rates and methods of N application also indicates that the effects of timing and distribution of fertilizer N on corn growth were similar across all fertilizer N rates evaluated. The primary difference between crops was a reduction in maximum grain yield (3.4 vs 1.8 t/ha) for the second crop, a reduction associated with a

lower plant population density (9.4 vs 5.7 plants/m²). There was a linear increase in grain yield, N uptake, and total dry matter to N rates when averaged across methods of N application (Figure 1). There was no yield advantage to distributing fertilizer N in multiple applications (Figure 2). However, yields among treatments with single N applications were improved when fertilizer N was delayed from planting (1-0-0) to 25 DAP (0-1-0). Among the five methods of N application, there was a trend for increasing yields as a greater proportion of applied N was concentrated in the two final application times.

Aboveground corn dry matter at silking represented an average of 57 and 78% of the total dry matter accumulated at harvest in the first and second crops, respectively. Nitrogen fertilization decreased the proportion of total dry matter at harvest which had accumulated in plants by the silking stage (Table 1). The highest proportions of total dry matter at harvest accumulated by silking stage were obtained with treatments receiving all fertilizer N between planting and 25 DAP. This suggested that dry matter accumulation was delayed to post-silking stages when fertilizer N was concentrated in applications at 25 DAP and at silking. The absence of a fertilizer N timing and distribution effect on measured dry-matter accumulation at either 25 DAP or at silking also supports this observation.

Nitrogen uptake at harvest in treatments without applied N decreased from 28 kg/ha in the first crop to 15 kg/ha in the second crop. Despite the lower contribution of native soil N to the second crop, apparent fertilizer N recovery was higher for the initial crop (46% in crop one vs 35% in crop two). Apparent N recovery decreased with increasing rates of applied N. When averaged across all application methods and crops, recoveries were 48, 36, and 36% for rates of 40, 80, and 120 kg N/ha, respectively. Single applications of N at 25 DAP gave higher apparent N recovery levels than single applications at planting (Figure 3). Maximum apparent recovery was 70% with the application of 40 kg N/ha at 25 DAP in the first crop. A mean of 46% N recovery was obtained with a single application of N at 25 DAP averaged across all N rates. Apparent N recovery decreased with both split applications and treatments having a greater proportion of N applied at planting. The lowest mean value of 30% apparent N recovery was obtained for treatments that received all N at planting.

Even the highest N recoveries for corn in this study are lower than the values achieved at equivalent N rates in the Brazilian Cerrados region, where corn-grain yields are approximately 6 to 8 t/ha. However, observed apparent N recoveries, grain yields, and recommended N rates are similar to values reported for corn in the high rainfall regions of Africa.

Corn-grain yield, total dry matter, N uptake, and apparent N recovery in this humid tropical environment were increased by delaying N applications from planting to 25 days after planting. There was no yield advantage to partitioning a single fertilizer N application at 25 days after planting into two or three equal split applications between the planting and silking stages. The higher yields

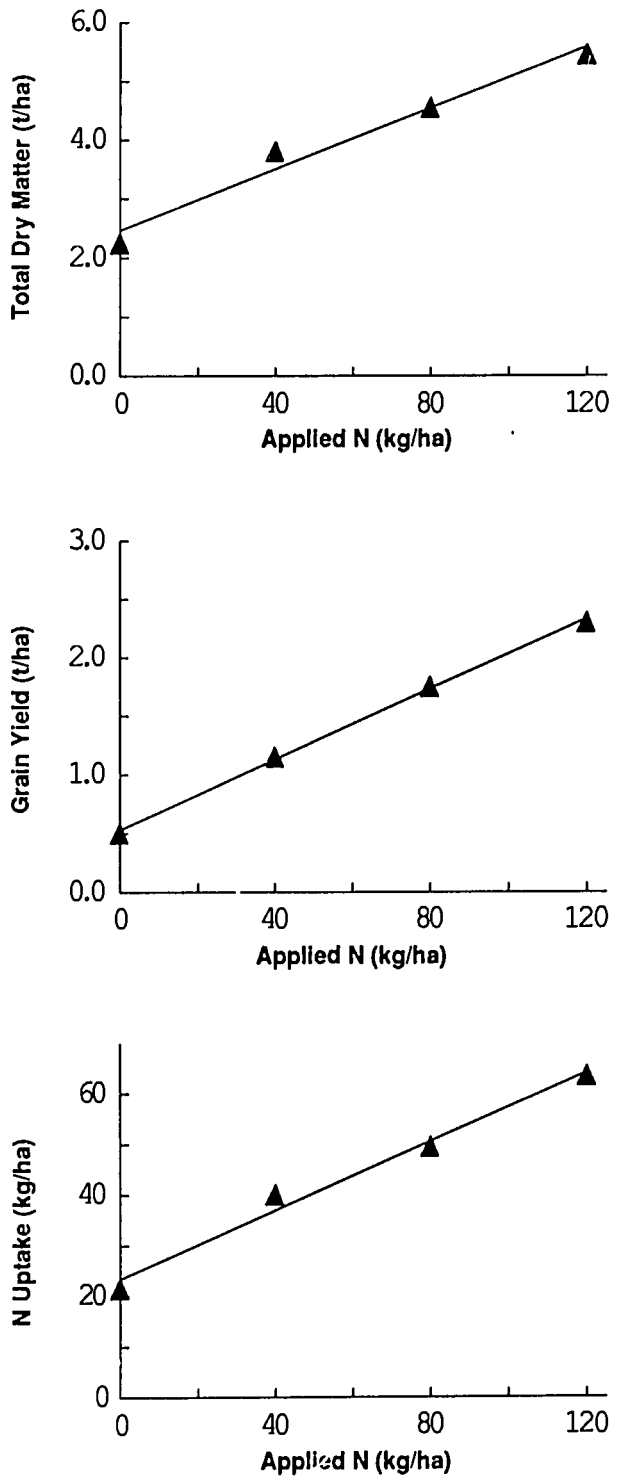

Figure 1. Total dry matter, grain yield, and N uptake at harvest as a function of applied N in a Central Amazon Oxisol.

obtained with N applications at 25 days after planting and silking, relative to planting, were associated with an increase in the proportion of total dry matter assimilated during post-silking growth.

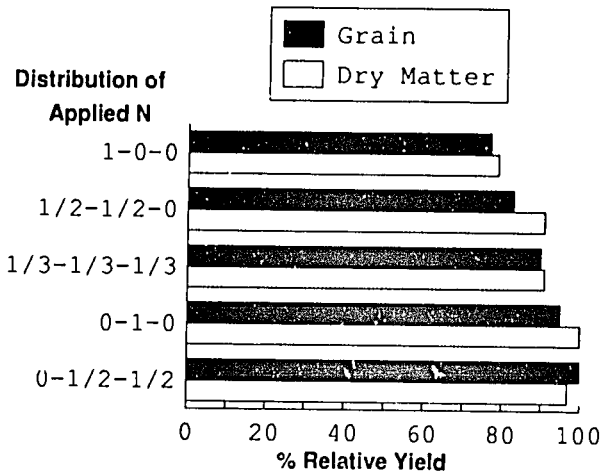

Figure 2. Relative corn-grain and total dry-matter yields as a function of fertilizer N timing and distribution methods in a Central Amazon Oxisol.

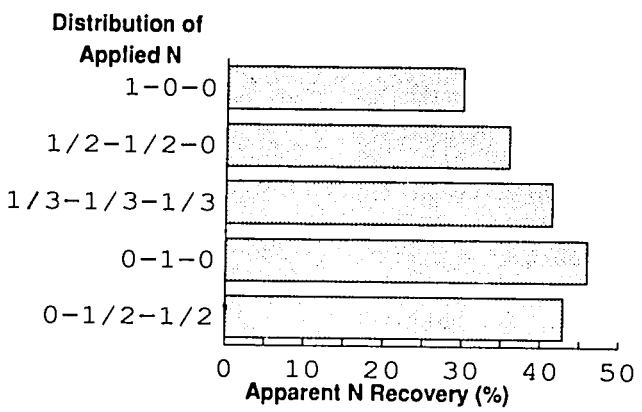

Figure 3. Apparent fertilizer N recovery by corn for different timing and distribution methods of applied N in a Central Amazon Oxisol.

Table 1. Effect of timing and distribution of fertilizer N on the ratio of total dry matter at harvest to the dry matter which had accumulated by silking stage in two consecutive corn crops in a Central Amazon Oxisol.

	Total dry matter at silking		
Treatments	**1986**	**1987**	**Mean**
N rates (kg/ha)	Dry matter at harvest (%)		
0	75	98	87
40	59	74	67
80	56	76	66
120	51	78	65
0–1–0	52	73	62
1–0–0	66	82	74
1/2–1/2–0	61	83	72
0–1/2–1/2	48	67	57
1/3–1/3–1/3	51	75	63
LSD:0.05			
N Rates	—	—	10
Timing	—	—	13
Rate x Timing	—	—	30

Potential Productivity and Nitrogen-Use Efficiency of Corn and Rice in Várzeas: M-910C

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Alluvial soils along the white water rivers, locally known as *várzeas*, are a major land resource in the Amazon basin. The state of Amazonas in Brazil has about 25 million hectares of such soils. Their high base status, adequate water supply, and eight-month flood-free period provide appropriate conditions for intensive food production in a region dominated by low fertility Oxisols and Ultisols. Total soil N is low in many of these soils, suggesting a potential nutrient deficiency. Yield response to N has been noted to increase during successive corn crops in *várzea* soils. This response would be magnified with the use of improved, high yielding varieties.

Despite the high native fertility and adequate water supply in this environment, yields for locally selected corn have seldom exceeded 5.0 t/ha when N was applied. These yields are similar to yields reported in the Peruvian Amazon but 1 to 2 t/ha less than yield maxima reported in the humid tropical lowlands of Sumatra, Indonesia, and Kenya.

Rice is also grown extensivly in the Amazon. Because of the soil's high water-holding capacity and the absence of severe drought stress periods, the *várzea* ecosystem is a favored upland rice condition. In the top 30 cm of soil, approximately 120 mm of available water are retained in the 0.01 to 1.0 MPa tension range. Although a limited number of rice trials in the Amazon have included N fertilization, results showed a relatively high grain yield potential, on the order of 6 to 7 t/ha for improved varieties. Results from irrigated rice in the Peruvian Amazon also showed grain yields in the same range.

Yield differences between corn (C4) and rice (C3) may be related to differences in N-use efficiency by their photosynthetic pathways and could result in contrasting N responses.

Objective

The purpose of this study was to assess the potential nitrogen-use efficiency of corn and rice in *várzeas*.

Procedures

Two experiments were conducted at the Caldeirao research field of the EMBRAPA/UEPAE Experiment Station, located 50 km west of Manaus, Amazonas, Brazil. The site is an alluvial cuaternary terrace on the Amazonas River, which is occasionally flooded during the periods of May to August. The soil in the corn experiment is a fine-loamy, mixed, nonacid, isohyperthermic Typic Tropofluvent. The soil in the rice experiment is a coarse-loamy, mixed, nonacid, isohyperthermic Aquic Tropofluvent. The two experiments were 200 m apart but the same distance from the river bank. Although the site for the rice experiment had more mottles in the subsoil, both sites were otherwise morphologically similar.

Initial soil (0 to 20 cm) characteristics for the corn experiment were as follows: 118 mg/kg of P (Mehlich 1); 1.7 and 14.1 g/kg of organic N and C; and 14.9, 2.9, 0.3, and 0.2 cmol$_c$/kg of exchangeable Ca, Mg, and Al, respectively. The nitrogen availability index, as evaluated by net anaerobic incubation during one week, gave 3 and 9 mg/kg of NH_4 production for soil samples of the corn and rice experiments, respectively. These soil test values determined that no fertilizer, other than N, was applied to the experiment. Weather data are shown in Figure 1.

Grain Yields

Grain yield responses to applied N in the two corn crops and rice varieties are shown in Figure 2. Grain yields for both corn crops were increased by fertilizer N up to the 60 kg/ha rate. This N rate produced yield maxima of 4.4 t/ha, in the first crop, and 3.9 t/ha in the second crop. Differences among years may have resulted from weather or N contribution from mineralized organic matter.

Yield plateaus for both rice varieties were achieved with 20 kg N/ha, but maximum yields of CICA 8 exceeded that of BR-1 by 0.9 t/ha. Differences in grain yield between varieties were attributed to differences in grain weight for CICA 8, although there was no N-rate effect on grain weight in either variety (Table 1).

Maximum grain yield for the first corn crop was representative of the potential yield for this species at this location. Yield maxima of CICA 8 rice variety approached the potential yield of this species under favored upland conditions. Crops were grown under near-average weather conditions with no nutrient limitations. Nitrogen uptake continued to increase beyond N rates that resulted in maximum grain yields. The N rates associated with maximum grain yields were low and suggested other limitations for grain production.

Low solar radiation may account for the lack of response to applied N above the lowest rate in rice. In the absence of a water deficit, solar radiation received during the 45-day period before harvest is the foremost climatic variable affecting rice response to N. IRRI scientists related grain N responses at several planting dates to four categories of solar energy. The category with the highest solar energy (> 489 mWh/cm^2/day) contained linear yield responses up to 120 kg N/ha with progressive declines of optimum N rates with lower solar energy levels. Our solar radiation values averaged 330 mWh/cm^2/day during the 45 days prior to harvest. Low solar-energy levels, maximum

yields, and N responses for improved rice varieties grown under favored upland conditions in the Peruvian Amazon are similar to those reported herein.

Glucose-equivalent yield for the two rice varieties and the corn corps are presented in Table 2. To compare yields of crops grown under different years, we assumed that weather effect was constant across years. Corn yields simulated with the CERES-Maize program under no water or N limitations averaged 4 t/ha using several planting dates of the 1986 weather data. Differences in maximum grain yield between corn and rice remained when glucose equivalent yields were considered. Equivalent yields from unfertilized treatments appeared higher for rice than for both corn corps even with a lower soil-N availability index. Maximum equivalent yields did not differ between corn and BR-1 rice, but corn required three times as much N as rice to produce the maximum equivalent yield.

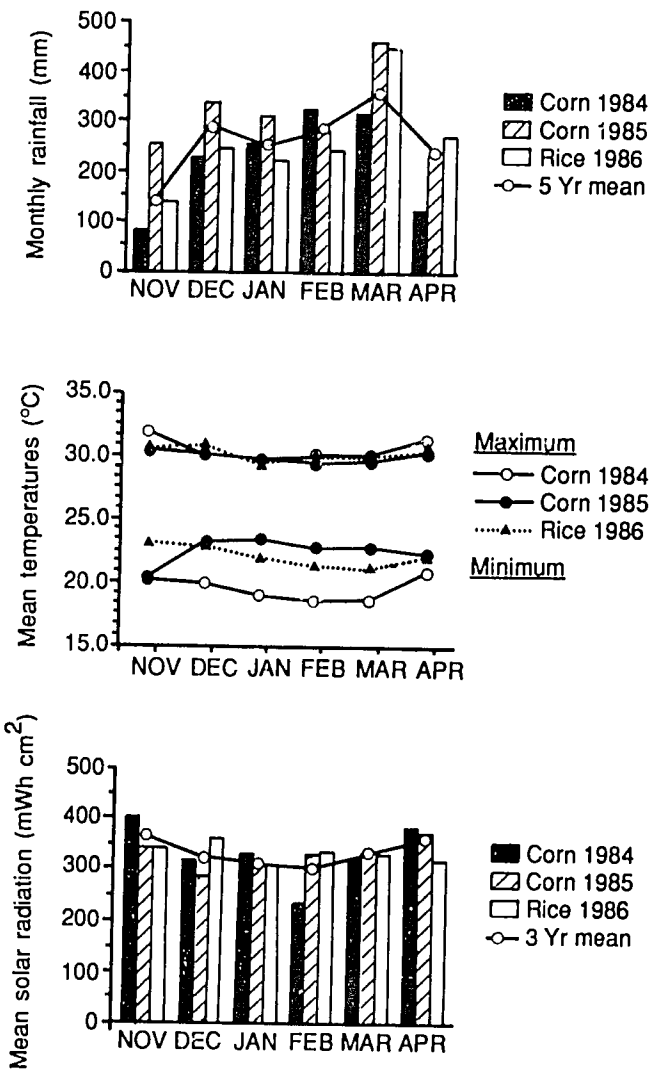

Figure 1. Monthly rainfall, maximum and minimum air temperatures, and solar radiation during the crop-growth cycles.

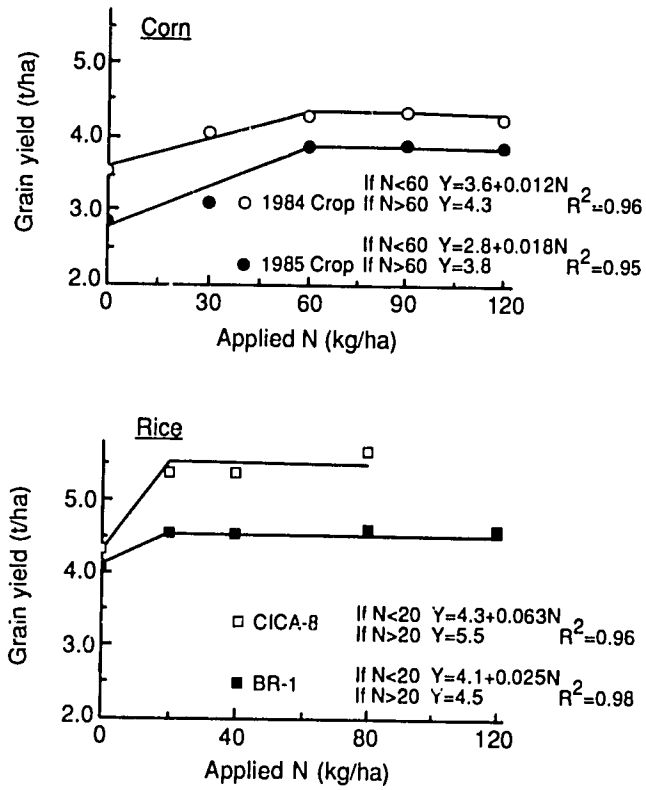

Figure 2. Grain yield response to N fertilization in two consecutive corn crops and two rice varieties.

Table 1. Nitrogen effect on grain yield components of two rice varieties.

		Yield components		
Rice variety	**N rate**	**Panicle density**	**Panicle size**	**Grain wt x 1000**
	kg/ha	pan/m	grn/pan	— g —
BR-1	0	307	57	23.3
	20	305	63	23.8
	40	310	62	23.9
	80	317	63	23.3
	120	324	60	23.7
CICA 8	0	284	54	27.5
	20	291	65	28.6
	40	308	61	28.8
	80	324	62	28.5
	120	339	51	28.3
LSD 0.05				
Variety	—	NS	NS	0.6
Rate x Variety	—	NS	NS	NS
SE N Rate BR-1	—	29	5	0.2
CICA 8	—	34	10	0.5
CV %	—	22	28	3

Table 2. Nitrogen effect on glucose-equivalent yield and harvest index of the corn and rice experiments.

	Equivalent yield				Harvest index			
	Corn crop		Rice variety		Corn crop		Rice variety	
N Rate§	1984	1985	BR-1	CICA 8	1984	1985	BR-1	CICA 8
	t/ha				Gw/TDM			
N-0	5.0	4.0	5.6	5.8	0.46	0.35	0.52	0.57
N-1	5.7	4.4	6.2	7.3	0.43	0.32	0.50	0.59
N-2	6.1	5.5	6.2	7.3	0.48	0.38	0.48	0.56
N-3	6.2	5.5	6.2	7.7	0.47	0.36	0.50	0.53
N-4	6.1	5.5	6.2	6.6	0.44	0.38	0.47	0.49
SE	0.2**	0.4	0.2*	0.4**	0.02	0.02	0.01	0.02*
CV %	7.6	16.0	9.9	9.9	7.5	11.2	8.5	8.5

*, ** = Significant treatment effect at the 0.05 and 0.01 probability levels.

§ Nitrogen rates for the corn experiment are: 0, 30, 60, 90, and 120 kg/ha; and 0, 20, 40, 80, and 120 kg/ha for the rice experiment.

Maximum yield for CICA 8 rice was higher than for BR-1. Variations in HI's accounted for grain yield difference between species, because maximum TDM was coincident for both species. Grain equivalent yield of rice varieties and corn crops correlated (= 0.77**) with their harvest indices.

N-Use Efficiency

Lack of differences in TDM between corn and either rice variety was paralleled by a lack of differences in either N-use (Figure 3) or uptake efficiencies (Figure 4) for biomass production, indicating no differences in the amount of either absorbed N or TDM produced per unit of applied N. However, differences were observed among mean utilization efficiencies for both TDM or grain in corn and rice (Table 3). No differences were observed between corn crops or rice varieties. Overall mean efficiency of plant N in biomass and grain production for rice was 20 and 50% superior to corn, respectively. Unfertilized treatments produced 41 kg of corn grain and 65 kg of rice grain per kg of absorbed N. This relationship decreased progressively with N fertilization in rice because further uptake and accumulation of N brought no concomitant grain yield increase (Figure 2). These N-use efficiency values were lower than the average 70 kg of rice per kg of accumulated N suggested by Mori and co-workers (1986) and significantly lower than the efficiency values greater than 85 reported under irrigated conditions in the high-yielding environments of Peru and California. Fertilizer N did not affect the use efficiency for corn grain.

Part of the differences in N-use efficiency may be because rice has a lower internal N requirement than corn. Rice grain yields reached a plateau at concentrations in TDM of 8.0 and 9.5 g/kg, respectively, for BR-1 and CICA 8. These values were in close agreement with the internal requirement suggested by studies in Peru. Internal N requirements reported for corn average 12.0 g/kg, with little deviation across environments or between genotypes. Plots with maximum yields in this experiment averaged 11

Table 3. Mean nitrogen effect on N-use efficiencies (plant biomass/unit of plant N) for total dry matter and grain production of corn and rice.

	Nitrogen-use efficiency			
	Total dry matter		Grain	
N Rate§	Corn	Rice	Corn	Rice
	TDM/Nt		Gw/Nt	
N-0	100	120	41	65
N-1	100	115	37	62
N-2	85	114	37	59
N-3	95	102	40	53
N-4	91	102	38	49
Mean	94	111	39	57
SE	6 *	8 *	2	4 **
CV %	16	19	14	21

*, ** = Significant treatment effect at the 0.05 and 0.01 probability levels.

§ Nitrogen levels for the corn experiments were 0, 30, 60, 90 and 120 kg/ha; and 0, 20, 40, 80, and 120 kg/ha for the rice experiment.

g N/kg, which approaches the internal requirement recommended by Stanford and Legg.

Since climatic factors impose a limit to obtaining higher biomass in annual crops, breeding programs should emphasize both N-use efficiency and harvest index to improve cereal productivity. The harvest index is an easy field determination, and it provides a quick estimate of the relative photosynthate partitioning potential among genotypes. Selecting efficient genotypes for N use would also contribute to a higher productivity on low-N environments or higher fertilizer-use efficiency.

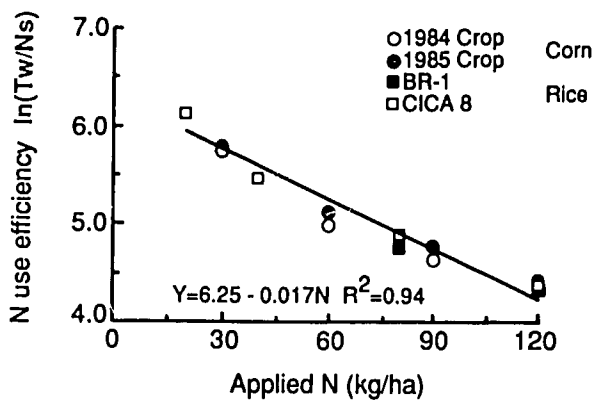

Figure 3. Effect of applied N on N-use efficiency for dry-matter production. Tw/Ns indicates total dry weight per unit of soil N.

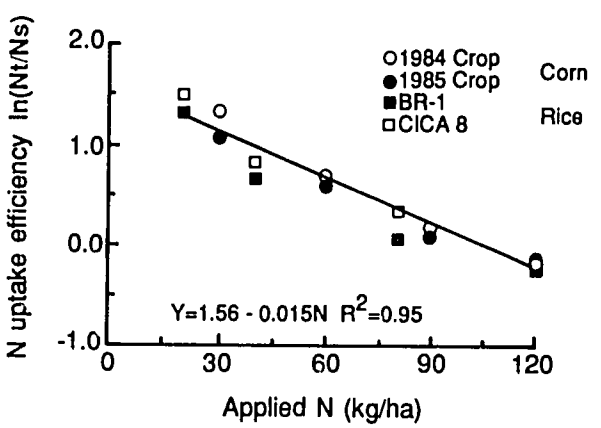

Figure 4. Effect of applied N on N-uptake efficiency for dry-matter production. Nt/Ns indicates the proportion of soil N taken up by the plant.

Lime and P Requirements for Peanut in a Clayey Oxisol: M-905

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Although there is little tradition of peanut production in the Central Amazon, data from Yurimaguas suggest that it would be a suitable crop for continuous production systems in these ustic or near-ustic soil-moisture regimes. Because of potential harvest problems in these clayey Oxisols, preliminary peanut trials compared different land preparation methods (plant beds, hilling vs. no-hilling). Results showed little seed loss when peanuts were planted toward the end of the rainy season for harvesting during the driest months (<100 mm) of the year. Planting on raised beds brought no yield advantage, but hilling near the pegging stage did.

Objective

The objective of this study was to assess soil Ca and P requirements for peanut production in these Oxisols through residual lime and P fertilization trials.

Procedures

The lime experiment contained five rates of calcitic lime (0, 0.5, 1, 2, and 4 t/ha; 83% $CaCO_3$ equivalency) applied once in 1983. Three additional treatments with 0, 1, and 2 t lime/ha also received 1 t gypsum/ha in 1983 and 1986. There were four replications arranged in a randomized complete-block design. Two peanut varieties were compared in both 1987 and 1988 in subplots of the eight lime treatments. Varieties were *Blanco Tarapoto*, selected from trials in the Yurimaguas Ultisols, and *Tatu Vermelho*, which is used in Southern Brazil. In both crops, gypsum was applied at planting to the three designated treatments, as in previous years of this study. Blanket applications were also made of P and K fertilizers.

Results

Chemical properties of the surface soil layer (0 to 15 cm) were measured at the flowering stage of both peanut crops (Table 1). Between the two years, exchangeable bases decreased and acidity increased in all plots. Aluminum saturation ranged from 17 to 79% in 1987 and from 83 to 32% in 1988. Gypsum applications caused significant increases in exchangeable Ca and small reductions in exchangeable Al. The net result was to decrease Al saturation by as much as 25% relative to comparable lime rates without gypsum.

In both years, shelled peanut yields, shelling percentage, and leaf Ca content at flowering were increased significantly by lime treatments (Table 2). Mean yields for *Blanco Tarapoto* were significantly higher than for *Tatu*

Table 1. Surface soil (0 to 15 cm) chemical properties at flowering stage of both peanut crops in the clayey Oxisol of Manaus

Lime rate	Year	pH	Exchangeable Ca	Mg	K	Al	Al sat.	Avail. P
t/ha		cmol/L					%	mg/kg
0	1987	4.3	0.26	0.04	0.16	1.7	79	19
	1988	4.4	9.19	0.07	0.14	2.0	83	13
0.5	1987	4.4	0.37	0.10	0.18	1.4	68	24
	1988	4.4	0.28	0.09	0.13	1.8	78	14
1	1987	4.6	0.62	0.15	0.19	1.2	56	24
	1988	4.6	0.44	0.11	0.19	1.6	68	12
2	1987	4.6	0.71	0.16	0.21	1.0	48	20
	1988	4.6	0.55	0.11	0.13	1.5	66	10
4	1987	5.0	1.49	0.29	0.21	0.4	17	17
	1988	4.9	1.23	0.15	0.14	0.7	32	9
0 + G[§]	1987	4.2	0.71	0.02	0.16	1.4	61	24
	1988	4.3	0.61	0.06	0.10	1.8	70	19
1 + G	1987	4.3	1.13	0.13	0.19	1.1	43	22
	1988	4.5	0.86	0.09	0.12	1.3	55	12
2 + G	1987	4.6	1.60	0.19	0.17	0.6	23	22
	1988	4.5	1.08	0.09	0.10	1.3	51	12

[§] G denotes the application of 1 t gypsum/ha to each crop.

Table 2. Seed yield, shelling percentage, and leaf Ca levels for two peanut varieties as a function of lime treatments during two crops in the Manaus Oxisol.

Lime rate	Year	*Blanco Tarapoto* Yield	Shelling	Leaf Ca	*Tatu Vermelho* Yield	Shelling	Leaf Ca
t/ha		t/ha	%		t/ha	%	
0	1987	0.8	27	0.58	1.3	64	0.68
	1988	0.1	34	0.67	0.2	56	0.50
0.5	1987	1.1	42	0.68	1.0	62	1.16
	1988	0.4	41	0.73	0.2	54	0.53
1	1987	2.1	56	0.88	1.5	69	1.10
	1988	0.7	52	1.03	0.7	68	1.00
2	1987	2.3	60	0.93	2.0	73	1.15
	1988	1.0	59	1.28	0.7	68	1.06
4	1987	3.0	71	1.16	2.1	73	1.36
	1988	1.5	69	1.46	1.0	74	1.58
0 + G[§]	1987	3.3	71	1.00	2.0	74	1.33
	1988	1.3	70	1.30	1.1	74	1.34
1 + G	1987	3.2	69	1.03	2.0	74	1.23
	1988	1.4	69	1.39	1.2	74	1.56
2 + G	1987	3.5	72	1.23	2.4	74	1.20
	1988	1.4	71	1.62	1.3	74	1.75

[§] G denotes the application of 1 t gypsum/ha to each crop.

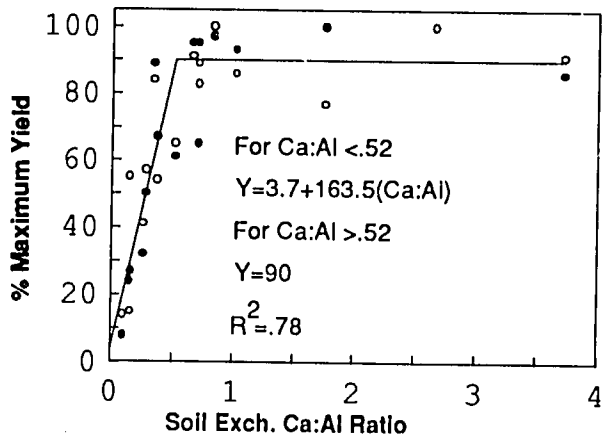

Figure 1. Relative yield of shelled peanut varieties *Blanco Tarapoto* (solid symbols) and *Tatu Vermelho* (open symbols) as a function of the exchangeable Ca:Al ratio in lime and lime plus gypsum treatments in a clayey Oxisol of the Brazilian Amazon.

Vermelho. Blanco Tarapoto also showed a greater response in both yield and shelling percentage to lime treatments than did *Tatu Vermelho*. At their maximum yields, both varieties had similar shelling percentages and leaf Ca contents. Among the chemical soil properties measured, the ratio between exchangeable Ca and Al gave the best agreement with relative peanut yields (Figure 1). There was a linear increase in yields up to an exchangeable Ca:Al ratio of 0.52. Above this value, there was no response in yield. There were no differences between varieties or years in this relationship. Similar relationships were also found with percentage Ca and Al saturation, with critical levels of 20 and 60%, respectively. The exchangeable Ca:Al ratio, however, accounted for more of the variability in yield among varieties and years than either of the cation-saturation indices. That finding is consistent with those treatments that attain maximum yields by using lime to reduce Al toxicity and gypsum to provide supplementary Ca (Table 2).

Soil P requirements for peanuts were assessed in 1987 by planting *Tatu Vermelho* in a long-term P fertilizer rates-and-placement study. The experiment consisted of a split-plot arrangement of broadcast and banded P placement with four replications in a randomized complete-block design. Main plots are broadcast P rates (0, 22, 44, 88, and 176 kg P/ha) applied once before planting the initial crop in 1981. Subplots are banded P rates (0, 11, 22, and 44 kg P/ha) applied with variable frequency to the 11 crops preceding peanuts. Whereas a rate of 11 kg P/ha was applied to all former crops, rates of 22 and 44 kg P/ha were band-applied only to the first eight and four crops, respectively. Total band-applied P in the previous crops was, therefore, 121, 176, and 176 kg/ha, respectively. The experiment was planted in an annual corn-cowpea rotation each year. Peanuts were planted in May 1987 after harvesting corn without additional P inputs.

The relationship between Mehlich 1 extractable soil P (1:10 soil to solution ratio, 5 minutes shaking) and relative yield of shelled peanut in all P treatments is shown in Figure 2. P fertilization increased yields from 0.5 t/ha without applied P to a maximum of 2.0 t/ha. The Mehlich 1 critical value of 9 mg/kg is superior to the levels of 6 and 8 mg/kg established for corn and cowpea, respectively, during preceding crops in this study. There were significant linear correlations between Mehlich 1 soil P and both the Bray 1 (r=0.96) and Modified Olsen (r=0.80) extractants. Based on linear relationships between extractants, the respective critical soil-P levels for corn, cowpea, and peanut were estimated to be 9, 13, and 15 mg/kg with the Bray 1 method and 8, 9, and 10 mg/kg with the Modified Olsen method. Higher soil P requirements for the legumes relative to corn were associated with a significant increase in foliar N concentration for cowpea and peanut with increasing P applications. These data suggested a higher soil-P requirement for plants, depending on symbiotic N_2 fixation as their primary source of N.

The soil test calibration data provide guidelines for managing acidity and P constraints for peanuts in mechanized continuous crop rotations on clayey Oxisols of the Central Amazon. Although the variety *Blanco Tarapoto* has a higher yield potential than *Tatu Vermelho*, the latter provided higher yields under extreme soil conditions of low Ca and high acidity.

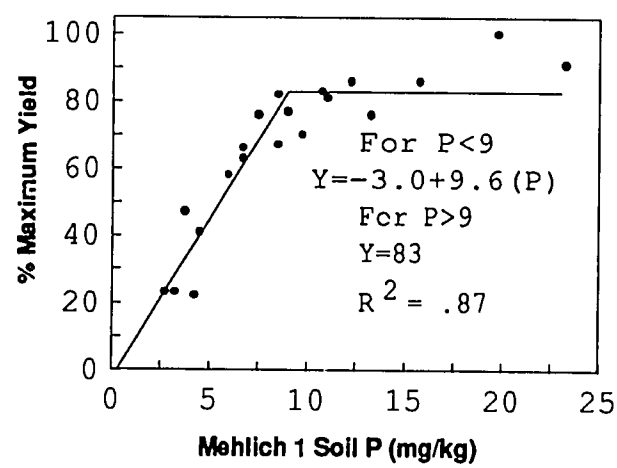

Figure 2. Relative peanut yields as a function of Mehlich 1 extractable soil P treatments containing variable rates of broadcast and/or banded P.

Decomposition Rates of Green Manures in an Acid Ultisol: Y-117A

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Soil acidity is a major problem in those Ultisols of the Amazon jungle subjected to continuous rotations of aluminum-sensitive crops such as corn. Reports from Alabama and TropSoils research conducted in Brazil and Hawaii suggest that green-manure incorporations may alleviate aluminum toxicity in Oxisols and Ultisols.

Work conducted elsewhere suggests that organic acids and other components of the metabolic carbon pool temporarily complex exchangeable aluminum until these compounds decompose and enter the microbial carbon pool. Aluminum levels are believed to increase again when this next step of organic-matter decomposition takes place. Previous observations at Yurimaguas show that leguminous plant materials left on the surface as mulch decompose at different rates in spite of having almost identical C/N ratios.

Objectives

Since we hypothesized that the rate of green-manure decomposition would be directly related to the degree of soil-acidity amelioration, our first objective in this study was to characterize the decay-rates of green manure materials that grow well in the Amazon.

Procedure

Five potential green-manure sources were selected: kudzu *(Pueraria phaseoloides)*, *Desmodium ovalifolium*, cowpea *(Vigna unguiculata* cv Vita 7), *Inga eaulis*, and rice straw (Oryza sativa). In the laboratory, leaves of the leguminous materials plus rice straw were incubated in an Ultisol of Yurimaguas (pH 4.2, exchangeable Al 4.9 cmol$_c$/L, Al saturation 86%, ECEC 5.7 cmol$_c$/L) at 80% of field capacity and 26°C. Three rates of application were used: 1.7, 3.3, and 6.7 t/ha of dry matter, giving a range of agronomically relevant rates.

The nitrogen, lignin, and polyphenolics contents of the green-manure ratios are shown in Table 1. The materials varied widely in lignin, polyphenolic contents, and C/N ratios. It has been hypothesized that green-manure quality can be measured by ratios such as C/N, lignin/N, or polyphenolics/N. High quality indicates fast rates of nitrogen release and is estimated by low values of C/N and the other ratios. The green-manure sources showed similar patterns of decomposition, with significant differences from the control during the 9-week incubation time (Figure 1).

All green manures presented with a peak rate of CO_2-C during the first week of incubation evolved and reached the plateau between 4 to 9 weeks, depending upon the source and the rate of application. The highest peak was for the highest rate of all green manures applied, following this order: kudzu > rice > cowpea > desmodium > inga.

The decomposition rate of green manures is related to the quality of green-manure leaves, expressed through their lignin or polyphenolics content. The decomposition rate of green manures is controlled by the rate applied and the lignin and total soluble polyphenolics contents. The higher the amount of green manure applied and the lower the lignin and polyphenolics contents, the higher will be the rate of decomposition of green manure or the total amount of CO_2-C evolved per amount of soil and per unit of time.

A general model describing the above relationships and the data in Figure 1 is as follows:

$$Y = 60.5 + 4.8\,R - 0.9\,L - 2.3\,PP$$

$$R^2 = 0.72$$

$$p < 0.0001$$

$$n = 45$$

Where

Y = CO_2 evolved (mg CO_2-C 100g soil/9 weeks)
R = Rate of green manure
L = % lignin
PP = % total soluble polyphenolics

No relationship was found between the rate of decomposition and C/N ratios. Rice straw, with a C/N ratio of 56, decomposed faster than legumes such as inga or kudzu with C/N ratios of 19 and 16, respectively (Figure 1). Even among legumes, C/N ratios were not indicative of decay rates. Kudzu and inga, with similar C/N ratios, produced the highest and lowest decay rates among the legumes, while desmodium and cowpea, with C/N ratios of 33 and 23, respectively (Table 1), occupied intermediate positions in CO_2-C evolution (Figure 1).

These data suggest that low lignin and polyphenolic contents of potential green manure sources indicate fast rates of decomposition when incorporated in an acid Ultisol.

Table 1. Chemical characteristics of plant materials.[§]

Green manures	N	Lignin (LIG)	Phenolics (PP)	Ratios C/N	LIG/N	PP/N
		%				
Rice	0.80	5.40	0.69	56	6.8	0.9
Kudzu	2.39	8.77	1.07	19	3.7	0.5
Desmodium	1.38	6.17	3.60	33	4.5	2.6
Cowpea	1.95	13.80	1.87	23	7.1	1.0
Inga	2.75	16.47	3.43	16	6.0	1.3

[§] Assuming 45% C content in all plant materials.

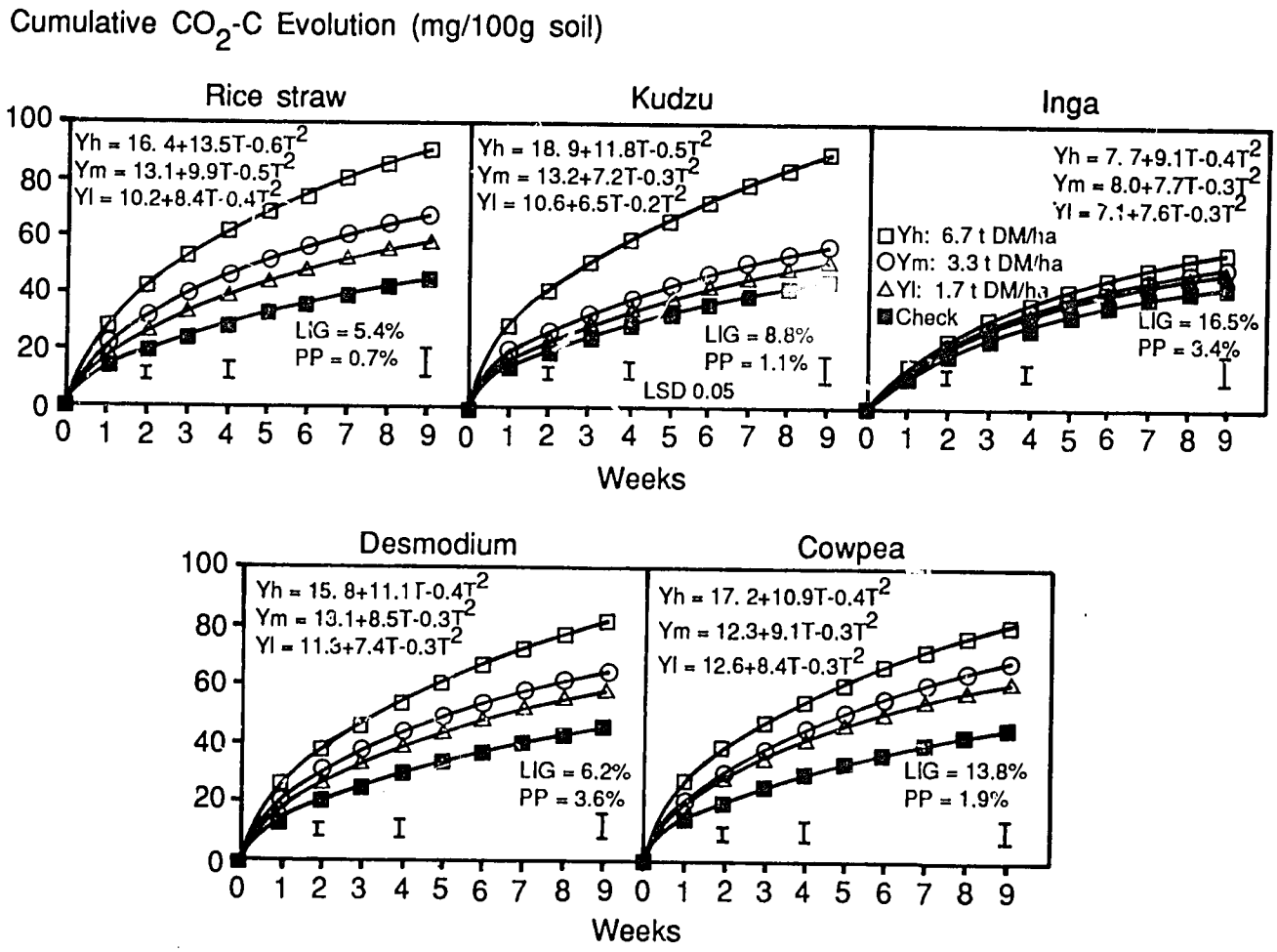

Figure 1. Cumulative CO_2 evolution with time from various rates of green manures incubated in an Ultisol of Yurimaguas, Peru. All general model F tests are significant at 0.0001 level. Letters *H, M,* and, *L* refer to high, medium, and low rates of dry-matter application (Lig. = lignin; PP = polyphnolic contents).

Green-Manure Incorporation and Soil Acidity Amelioration: Y117-B

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Objectives

The objective of the second phase of this study was to measure the effects of green-manure incorporation on soil-acidity parameters, including residual or cumulative effects.

Procedures

The previously described green manures were applied to the field, and five consecutive corn corps were grown. The experiment was conducted on a loamy Ultisol of an upland terrace at Yurimaguas. The top 20 cm had a clay content of 21%. Kaolinite was the predominant mineral (55%) in the clay fraction, the rest being partially interlayered smectite, probably hydroxy interlayer polymers (15% of the clay fraction). The chemical properties (0 to 20 cm) of the soil were among the most acid encountered at Yurimaguas: pH 4.2, exchangeable Al 4.9 cmol$_c$/L, soil-solution Al 0.6 cmol$_c$/L (Table 1), and 86% Al saturation.

Kudzu, desmodium, cowpea, inga, and rice straw were applied at 1.7, 3.3, and 6.7 t DM/ha/crop during five corn crops and incorporated into the soil with a rototiller to a depth of 20 cm. Inga was incorporated as leaves, whereas other green manures were incorporated as aboveground biomass. Two checks were included, one limed to pH 5.5 and one not limed. To eliminate a possible confounding effect between nutrient inputs and acidity effects, 160 N, 44 P, and 83 K in kg/ha were applied from the second to the fifth corn crop.

The five corn crops were grown during the period of June 11, 1987, to June 5, 1989. Total precipitation for each crop was 477, 619, 388, 667, and 767 mm respectively. Aluminum in the soil solution was determined by periodically leaching one pore volume of water from undisturbed upland cores sampled from the field.

Results

Little changes in soil acidity parameters were observed at the low rate of application (1.3 and 3.3 t DM/ha/crop). With 6.6 t DM/ha/crop, green manures decreased soil acidity in the following order: rice straw > kudzu > desmodium > cowpea > inga. Lower lignin or polyphenolics contents had four effects: (1) lower soil-solution Al (Table 2), (2) higher exchangeable Ca + Mg (Table 3), (3) lower exchangeable Al and Al saturation (Table 4), and (4) higher corn-grain yield (Table 5). No significant effect on the soil pH value was obtained compared to the check without lime.

A transient effect of green manures on the Al in the soil solution (Figure 1) and on exchangeable Al (Figure 2) during the field experiment was observed for the first four corn crops. Green manures applied at the high rate showed a residual effect through the build-up of exchangeable Ca+Mg. At the high rate during the first four corn crops, the amounts of Ca+Mg added to the soil via green manures were 255 kg/ha for rice straw, 433 kg/ha for desmodium, 434 kg/ha for kudzu, 463 kg/ha for cowpea, and 393 kg/ha for inga. Rice straw, a harvest residue with low lignin (5.4%) and low polyphenolic (0.7%) contents,

Table 1. Initial and final topsoil properties (0 to 20 cm) in the green manure and soil acidity experiment (Yurimaguas 1987 to 1989).

		Final (June 1989)										
		Green manures									Checks	
	Initial	Rice			Kudzu			Inga				
	June 1987	L§	M	H	L	M	H	L	M	H	Limed	Not limed
Al sol. m/mol/L	0.6	1.6	0.9	0.7	2.2	1.6	1.2	2.6	1.7	1.8	0.1	1.4
Exch Al cmol/L	4.9	4.1	4	3.5	4.4	4.1	3.8	4.6	4.2	3.9	0.9	0.1
Ex. Ca+Mg cmol/L	0.7	0.6	0.7	1.0	0.5	0.7	0.9	0.5	0.6	0.8	5.3	0.6
Al sat. %	86	84	81	73	86	82	76	88	83	79	13	84
pH	4.2	3.9	3.9	4.0	3.9	3.9	4.0	3.9	3.9	3.9	4.9	4.0

§ L, M, and H refer to low, medium, and high fertilization levels.

Table 2. Average Al in the soil-solution content (4 crops). Mean of 135 determinations per treatment combination.

Treatment	Lignin	phenolics	GM rate: DM/ha/crop 0	3.3	6.7
	— % —		— Soluble Al (mmol$_c$/L) —		
Rice	5.4	0.7	—	0.51	0.36
Kudzu	8.8	1.1	—	0.63	0.66
Inga	16.5	3.4	—	0.75	0.81
Check without lime	—	—	0.72	—	—
Check with lime	—	—	0.17	—	—

Table 3. Average exchangeable calcium + magnesium content (4 crops). Mean of 135 determinations per treatment combination. 100% is 0.72 cmol/L (check without lime).

Treatment	Lignin	phenolics	GM rate DM/ha/crop 0	1.7	3.3	6.7	Mean effect
	— % —		Exchangeable Ca + Mg (cmol/L)				
Rice	5.4	0.7	—	0.59	0.68	0.93	0.73
Desmodium	6.2	3.6	—	0.60	0.77	0.89	0.75
Kudzu	8.8	1.1	—	0.55	0.63	0.83	0.67
Cowpea	13.8	1.7	—	0.69	0.81	0.70	0.73
Inga	16.5	3.4	—	0.51	0.66	0.71	0.63
Check without lime	—	—	0.72	—	—	—	—
Check with lime	—	—	4.30	—	—	—	—
Rate mean effect				0.59	0.71	0.81	

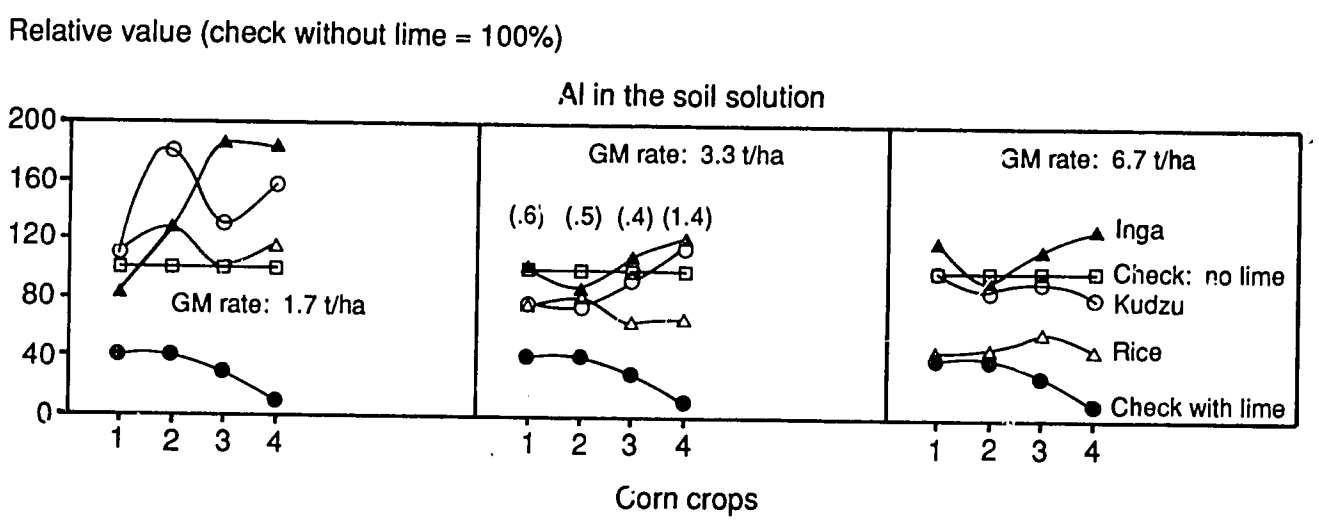

Figure 1. Effect of rice straw, kudzu, and inga green manures on aluminum in the soil solution. Numbers in parenthesis are absolute values for 100% relative yields expressed in mmol/L, mean of three or four samplings per crop.

Table 4. Average effect on aluminum saturation (4 crops).

Green-manure source	L	PP	GM rate t/ha/crop 1.7	3.3	6.7
	—— % ——		Al saturation (%)		
Rice Straw	5.4	0.7	86	84	78
Kudzu	8.8	1.1	87	85	80
Inga	16.5	3.4	88	86	84

Check without lime = 84%.
Check limed = 24%.

applied as green manure at the high rate during four consecutive corn crops decreased Al in the soil solution by half, increased exchangeable Ca+Mg by 29%, lowered exchangeable Al by 12%, and lowered Al saturation by 6% (Table 4). This green manure produced 2.7 t/ha of corn grain as an average of 4 crops in Yurimaguas, or 88% of the yield produced by liming (Table 5).

Kudzu is a leguminous species containing 8.8% lignin and 1.1% polyphenolic. Growing in Yurimaguas as a weed, kudzu increased exchangeable Ca+Mg by 15%, decreased Al in the soil solution by 8%, and decreased exchangeable Al and Al saturation by 4%. These effects were produced when kudzu was applied at the high rate.

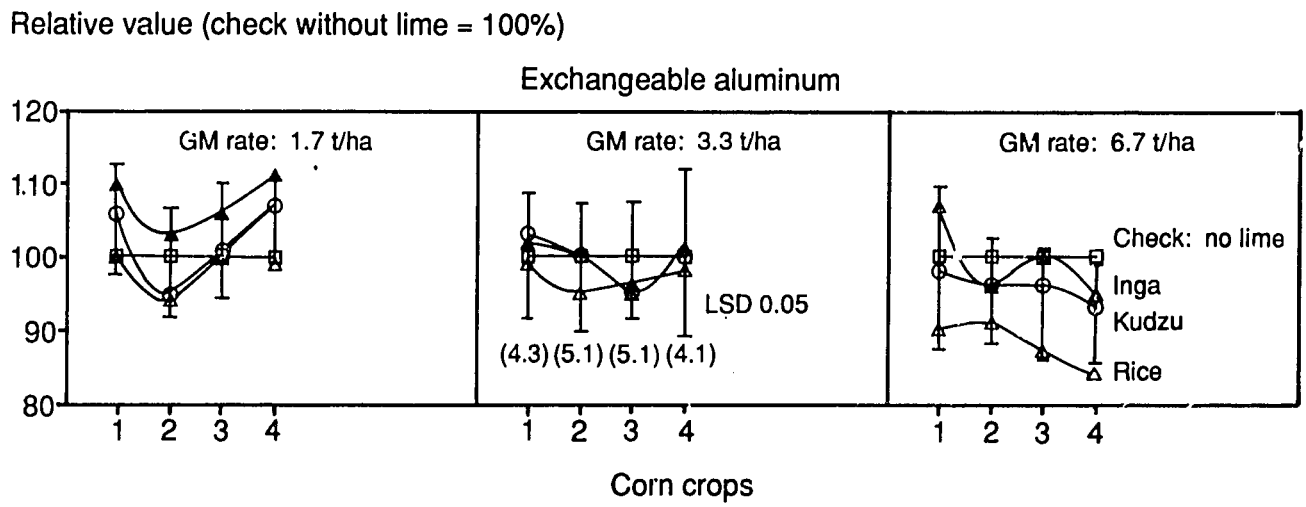

Figure 2. Effect of rice straw, kudzu, and Inga green manures on exchangeable aluminum. Numbers in parenthesis are absolute values for 100% relative yields expressed in $cmol_c$ Al/L, mean of three or four samplings per crop.

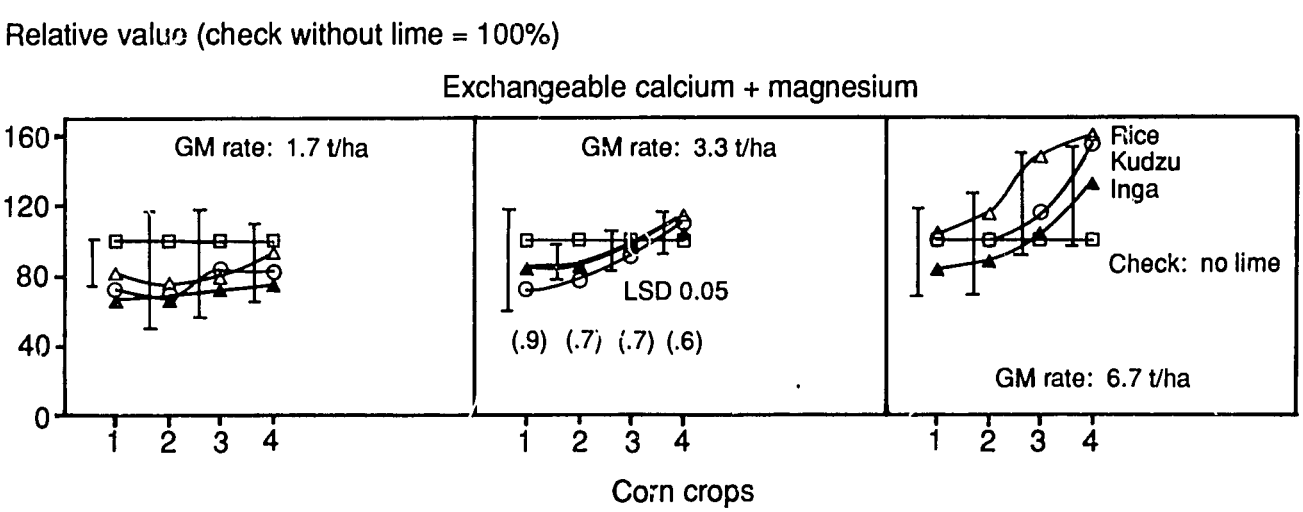

Figure 3. Effect of rice straw, kudzu, and Inga green manures on exchangeable calcium + magnesium. Numbers in parenthesis are absolute values for 100% relative yields expressed in $cmol_c$ Ca + Mg/L, mean of three or four samplings per crop.

This source produced 2.3 t/ha of corn grain as an average of 4 crops (74% of limed check plots).

Desmodium ovalifolium contains 6.2% lignin and 3.6% polyphenolics. Applied at the high rate, it decreased soil-solution Al by 32%, increased exchangeable Ca+Mg by 23%, decreased Al saturation by 3%, and had no effect on exchangeable Al. It produced 2 t/ha of corn grain as an average of 4 crops (65% of limed check plots).

Cowpea contains 13.8% lignin and 1.7% polyphenolics. Incorporated at the high rate, it decreased soluble Al by 13%, lowered exchangeable Al by 2%, and had no effect on exchangeable Ca + Mg. This green manure produced 1.7 t/ha of corn grain as an average of 4 crops (56% of limed check plots).

Inga edulis (16.5% lignin, 3.4% polyphenolics) leaves applied at the high rate produced the least effect. *Inga* actually increased Al concentration in the soil solution by 12%. Plots with this green manure produced 1.6 t/ha of corn grain as an average of 4 crops, or 51% of limed check plots.

Green manures varied in their effect on soil acidity. High-quality green manures of low lignin or total soluble polyphenolics reduced the soil acidity more than did low-quality green manures. The overall effect, however, varied with time. Corn roots growing in low-quality green-manure plots seemed affected by Al toxicity and Ca deficiency in the same way as those growing in the no-lime check plots. These effects observed during the first crops, diminished with the successive applications of green manures, producing more favorable conditions for corn-root initiation and growth in the latter crops. The build-up of exchangeable Ca and Mg with time as a result of successive green-manure applications may be largely responsible for this effect. Yields of the third and four crops given high-quality green manures were similar to or exceeded yields obtained with liming to pH 5.5. This effect, however, disappeared in the fifth crop, for reasons not presently understood.

Green manures of high quality (low lignin and polyphenolic contents) applied at agronomically relevant rates are not as effective in decreasing soil acidity as liming, but they provide definitive temporary benefits.

Table 5. Corn-grain yield obtained during four consecutive corn crops, by source* and rate.

Green-manure source	Rate	Corn crops			
		Second	Third	Fourth	Fifth
		Corn grain (t/ha)			
Rice	Low	0.36 *	1.25 *	0.89 *	1.25 *
	Medium	1.36 *	1.47	1.76	2.22 *
	High	1.93	2.44	2.85	3.52 *
Kudzu	Low	0.50 *	1.05 *	0.59 *	0.83 *
	Medium	0.91 *	1.62	0.94 *	1.60 *
	High	1.75 *	2.11	2.43	2.76 *
Desmodium	Low	0.31 *	0.72 *	0.57 *	0.55 *
	Medium	1.02 *	1.75	1.53	1.56 *
	High	1.19 *	2.15	2.44	2.13 *
Cowpea	Low	0.65 *	1.41 *	1.20 *	1.64 *
	Medium	1.04 *	1.31 *	2.09	1.46 *
	High	0.99 *	1.86	1.75	2.29 *
Inga	Low	0.18 *	0.44 *	0.35 *	1.02 *
	Medium	0.53 *	1.19 *	0.98 *	1.47 *
	High	0.98 *	1.37 *	1.94	1.93 *
Check w/o lime		0.59 *	1.01 *	1.09 *	0.86 *
Check w/lime		2.96	2.37	2.07	4.82

* Values are significantly different from the control with lime. Dunnett LSD, p = 0.05, one-tailed t test.

Limited Effects of a Green-Manure Crop in Weed Control: Y-116

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Although it is possible to grow three crops per year in udic isohyperthermic environments like Yurimaguas, we have experienced considerable practical difficulties in preparing land and planting and managing a crop during the wettest trimester of the year, January to April. Because the land is often not used during these months, weeds take over.

Objective

The objective of this study was to determine if growing a green-manure crop during the wettest trimeseter of the year might provide ground cover, smother weeds, and provide fixed nitrogen.

Procedures

A field experiment was conducted from November 1986 until December 1988 on a portion of Chacra I which had been under a high-input rotation of rice, corn, and soybeans since October 1972. A total of 33 crops were harvested in that period. *Centrosema macrocarpum* CIAT 5065 was the species selected as a green manure. The five treatments used are shown in Table 1. The first four were rotations of corn (c.v. Marginal 28) with one trimester of green manure, either during the wettest (March–May) or the driest (June–August) trimester; two trimesters of green manure; and a full year of green manures followed by a corn crop. The fifth treatment was a continuous corn monoculture with chemical weed control. All corn crops received N, P, K, micronutrient fertilization, and dolomitic lime to keep aluminum saturation below 40%.

The treatments were arranged in a randomized complete-block design, with four replications. The experimental plot was 46 x 4.8 m, suitable for fully mechanized farming. The legume was inoculated with rhizobium. Then, it was sown by planting stick, at a rate of 15 kg/ha. Weeds were controlled manually in all but management-system five, where pre-emergent and post-emergent herbicides were used (Dual, Metolachlor 1.2 L/ha and Gramoxone, Paraquat 1.9 L/ha). During the first year, corn plots were weeded three times, and *C. macrocarpum* plots four times. Those plots with chemical weeding did not receive any manual weeding.

Results

Weeds were not controlled by a four-month *Centrosema macrocarpum* fallow (treatment 1, Table 2). The population of weeds by species showed the same pattern of distribution in treatment 1 and control plots of corn with manual weeding (Table 2). Both treatments showed 144% more weeds than the control plots with chemicals. *Digitaria sanguinalis* and *Eleusine indica* were the dominant species, comprising around 70% of the total weed population (Table 2).

Increasing the duration of the centrosema crop decreased weed populations in the subsequent corn crop. Total weed biomass decreased from 886 kg/ha when centrosema was grown for four months, to less than half (396 kg/ha) when it was grown for eight months, to about one-third (292 kg/ha) when grown for 12 months (Table 2). Conventional chemical weed control on corn resulted in a weed biomass of 662 kg/ha, equivalent to a centrosema fallow of about six months.

The results suggest that a short-term (four months) *Centrosema macrocarpum* crop is not an attractive weed-control alternative. Either a longer period or a more aggressive green-manure species is needed.

Table 1. Treatment description of corn and *Centrosema macrocarpum* green-manure crops of different duration (dates indicate the month a trimester began).

Systems	Nov '86	Mar '87	Jul '87	Nov '87	Mar '88	Jul '88
Corn-GM sequence	Corn	GM[§]	Corn	GM	Corn	GM
Corn-corn GM	Corn	Corn	GM	Corn	Corn	GM
Corn-two trimesters of green manures per year	Corn	—— GM ——		Corn	—— GM ——	
One full year green manures	——— GM ———			Corn	—— GM ——	
Continuous corn, inorganic N + chemical weeding	Corn	Corn		Corn	Corn	

[§] GM: *Centrosema macrocarpum* CIAT 5063 fallow, incorporated to the soil (green manure) before corn crops.

Table 2. Weed dry matter 108 days after planting the corn crop during the third semester (July to October 1987).

Weeds	Corn after centrosema G. manure (tmt 1)	Centrosema fallow growing			Corn w/chemical weeding (tmt 5)
		4 months (tmt 2)	8 months (tmt 3)	12 months (tmt 4)	
	kg/ha				
Paspalum conjugatum	42	155	246	42	101
Digitaria sanguinalis	365	375	7	0	58
Eleusine indica	669	41	0	0	103
Other grass species	245	97	18	0	106
Commelina sp.	58	161	10[illegible]	250	150
Other species	169	57	23	0	105
Total	1548	886	396	292	662

Development and Evaluation of Soil and Water Management and Conservation Practices for Rainfed Agriculture in Sandy Soil of Sub-Saharan Africa: TAMU-402

Rainfall in sub-Saharan Africa is scarce, but its variability is the major constraint to stable food production. Soil fertility is also a limiting factor, and water-fertility interactions should be better understood in order to make efficient use of limited water. African farmers are well aware of these constraints, and farming strategies reflect a long process of adaptation to low and variable rainfall, poor and fragile soils, and readily available land. The farmers' main goal is to avoid risks. The hypothesis of this project is that it is possible to manipulate the soil water-fertility-plant system in such a way as to increase total yields or to decrease year-to-year yield fluctuations by improving traditional strategies through the application of scientific soil- and crop-management principles.

Farmers and agronomists in Niger are also aware of the trend in ecosystem degradation. Although sandy soils usually have high infiltration rates, loss of natural vegetation, surface crusts and soil-restricting layers generate high volumes of surface runoff and soil erosion. Wind erosion is also a serious problem because soil surfaces remain dry and unprotected during extended periods of high-velocity winds.

In severely degraded areas, appropriate watershed-management systems are needed to prevent further soil losses and to restore soil fertility. Research is needed to assess the effectiveness of (1) appropriate tillage practices designed to increase water infiltration, (2) systems of water diversion or collection, (3) microclimate modification to decrease evaporative demands, (4) revegetation, and (5) supplemental irrigation. There are also several ways to remove chemical constraints and improve water-use efficiency with moderate amounts of fertilizer. Most of these practices are based on the strategy of intensifying crop production on more fertile land while alleviating the pressure on the less fertile or more fragile lands.

Conclusions from small-scale studies cannot be extrapolated to full-scale land-management problems. Consequently, for this second phase, TropSoils-SAT is devoting most of its research efforts in small agricultural watershed management and on the improvement of whole farm systems through environmentally sound soil- and water-management systems.

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Integrated Management of Agricultural Watersheds

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The Sahel has seen increased demands for cropping and grazing land in recent years. These factors threaten the sustainability of the inherently fragile environment in Niger in particular and in the Sahelian region as a whole. The TropSoils project, which has been working in the semi-arid tropics since 1983, sees the urgent need to develop sustainable agricultural and resource-management systems and practices to meet changing human needs while enhancing the region's natural-resource base.

In line with the new global trust, TropSoils decided to undertake research to develop a more productive and sustainable agriculture in this region to integrate the risk-reducing and resource-conserving components of traditional farming systems, as well as the appropriate elements of modern technology. In collaboration with INRAN, the Integrated Management of Agricultural Watersheds project was initiated.

Objectives

The objectives of this study are as follows: 1) to select an experimental watershed representative of the plateau-sand-valley system and conduct baseline studies; specific components of the baseline studies are a) inventories of soil and vegetation resources within the watershed, and b) assessment of indigenous knowledge with respect to traditional farming systems and farmers' conceptions of soil conservation and land degradation.; and 2) to integrate baseline information into a Geographic Information System (GIS) to delineate and characterize land-management units which will serve as the basis for the establishing sustainable management strategies.

Procedures

Site Selection and Description

A pilot site was selected near the village of Hamdallaye, in western Niger. This watershed occupies an area of 589 ha. It is divided into four major administrative zones: Hamdallaye, Bokotili Kaina, Falanke Beri, and Falanke Kaina (Figure 1). Farmers from the four villages have lands in the watershed.

This watershed was selected for several reasons: 1) a good reception by villagers to a previous research study undertaken by a TAMU Ph.D. student, 2) its proximity to Niamey, and 3) its proximity to a paved road for easy access.

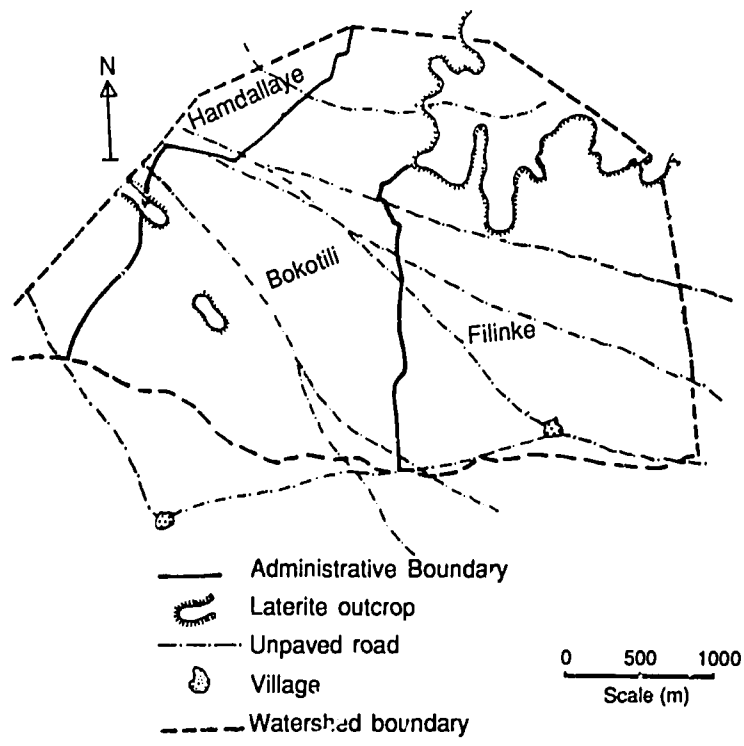

Figure 1. The four major administrative zones of the Hamdallaye watershed.

The watershed is in an area where improved varieties of millet (*Pennisetum glaucum (L.) R. Br.*) and cowpea (*Vigna unguiculata*), as well as fertilizers (urea and simple and triple superphosphates) are readily available. The available technologies, and farmers' familiarity with them, were also considerations in choosing this site.

Geomorphology

The watershed is situated in the plateau-valley geomorphic system, which consists of a laterite-capped plateau that slopes gently to a dominant depression or valley. The major distinctive geomorphic units identified in the watershed are as follows: 1) a broad, level laterite-capped plateau, which occurs on high peneplain remnants; 2) steep talus slopes (2 to 5%), which occur directly below the plateau; 3) a large region of broad, gentle slopes (0.5 to 2%); and 4) steep slopes that descend to the valley floor.

Laterite outcrops occur at two places below the plateau. One is in the northern region of the watershed, below outwash fans leading from the plateau. Laterite in this area occurs within 80 cm of the surface and, in some places, occurs at the surface. Another outcrop occurs nearer the valley floor and forms a steep slope (5 to 7%) composed entirely of ironstone concretions and a broader region of shallow soils overlying laterite.

Drainage System

Intermittent watercourses are observed throughout the watershed and are closely related to geomorphology (Figure 2). Extensive gully systems are observed on slopes greater than 2%. Water flowing in gullies from the laterite-capped plateaus loses velocity on slopes less than 1% to form depositional fans. One water course in the eastern portion of the watershed, however, does extend from plateau to valley floor. This water course is relatively shallow nearest the plateau but cuts deeply midway to the valley floor and in places forms a 2-m deep ravine. A very large depositional fan is formed by this ravine near the village of Falanké.

Activities Carried Out in the Watershed

Aerial survey

Aerial photographs of the watershed are needed for the following: 1) mapping of soils, geology, and vegetation; 2) locating spatially the information obtained in both vegetation and farmer surveys; and 3) estimating the size of farmers' fields.

Three flights were made to photograph the watershed. A preliminary flight was made in late September 1989, during which black-and-white film was used with standard 35 mm Nikon and Canon cameras mounted with 50 mm lenses. Elevations varied between 2,000 and 14,000 feet above ground level to obtain photographs of 1:5,000 and 1:10,000 scale. Transects were run to obtain 60% overlap between photos.

A second flight was made in early October 1989, and both color and black-and-white photographs were taken at elevations varying from 4,000 to 12,000 feet.

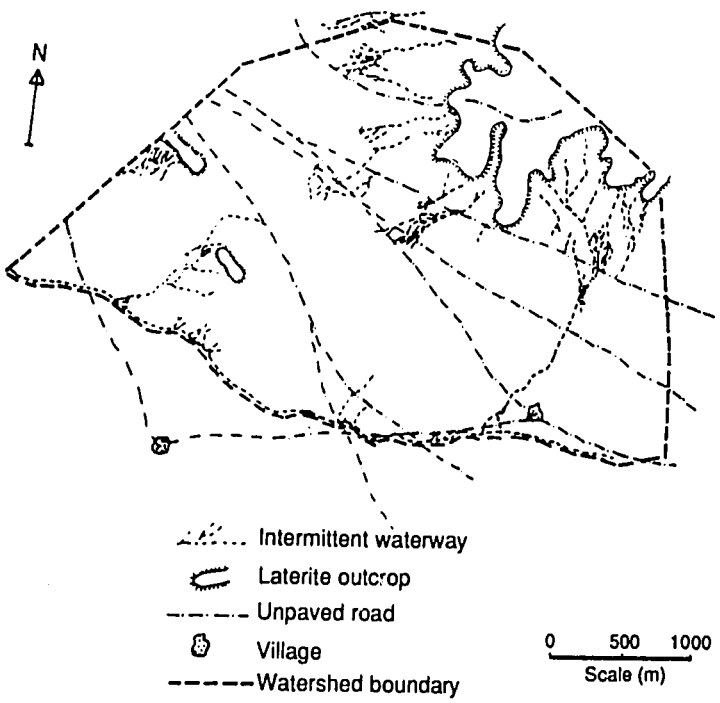

Figure 2. Intermittent watercourses and geomorphology.

A third aerial survey was conducted in mid-October. Black-and-white stereo photos were taken at 3,700 feet with a 500 EL/M 70 mm Hasselblad camera. Due to some technical problems, good photos were not obtained with this camera. Additional aerial coverage was collected with a Biovision color infrared video camera, which will be used to determine what percentages of farmers' fields are productive, nonproductive, or in fallow.

Topography

A team was engaged to conduct a topographic survey of the watershed. Traditional field survey methods were used to make elevation measurements every 50 m on a grid pattern. A contour map with a minimum contour interval of 1 m was produced from this survey.

Pedologic Survey

Soils were examined along five transects running from the plateau to the valley floor. Sampling sites were chosen along each transect, based primarily on landscape position. Field determination of soil texture, pH, structure, and color were made at the selected sites, and samples were taken with a bucket auger to a depth of 3.2 m or to the depth at which laterite was impenetrable. Based on this preliminary survey, six distinct map units were identified within the project's watershed boundaries below the plateau.

Two pedons from each map unit were described from a pit wall, using standard procedures, to a depth of 2 meters or to a lithic contact, whichever was shallower. Samples were taken to the laboratory for analysis. Based on both the field and laboratory observations, a large-scale (1:5,000) soil map of the watershed was prepared. Below is a brief description of map units identified.

I. Tondo Kakasia series (T0) 3 to 8% slope

This deep, severely eroded soil occurs on undulating slopes adjacent to the laterite plateau. The surface soil is typically 30 cm of dark-red sandy clay loam with cryptogamic crusts. The Bt horizon is a red sandy clay loam to sandy loam that extends below 2 m. Soil structure below the surface 6 cm is a strongly developed subangular blocky. No lateritic gravels were observed within the profile, and lateritic contact was not observed within 340 cm. Eroded and stony phases of this map unit were identified.

II. Dantiandou series (Da)

This deep, gently sloping soil lies downslope of the Tondo Kakasia series The surface horizon of this soil is yellowish-red 2 to 3 cm of loose, structureless sand over 7 to 8 cm of thin sand lamellae. The pH ranges from slightly to strongly acid. The Bt horizon is a yellowish-red to red sandy loam that extends below 2 m and has pH values between 5.0 and 5.2. Available P values range from 1.1 to 3.7 ppm in the surface horizon and 0.8 to 1.0 ppm in the subsoil. Organic-matter content ranges from 0.2% in the surface to less than 0.1% in the subsoil.

An eroded phase with intermittent streams which form gullies ranging in depth from 15 to 100 cm was identified.

III. Hamdallaye series (Ha)

This is a very deep, gently sloping soil in the middle backslope region of the toposequence. The surface (50 cm thick) is yellowish red sand that has a pH between 5.0 and 5.2. It has 7 cm of platy top horizon. The Bt horizon is a red sand that extends to a lateritic contact at 160 cm. Available P values range from 0.8 to 1.9, and from 0.4 to 0.8 ppm in the topsoil and subsoil, respectively.

A depositional phase where intermittent streams have formed outwash fans was also identified.

IV. Gangani Kirey series (Ga) 0 to .5% slope

This nearly level, shallow soil occurs in the northern portion of the watershed. The surface is 8 cm of stratified red loamy sand (pH 5.6), which contains a lot of vesicular pores. A dark-brown loamy sand (25 cm thick) is buried below this layer.

The Bt horizon is a red sandy loam that extends to an indurated laterite. This Bt horizon is composed of 2 to 10% ironstone gravels. Depth to laterite varies between 30 and 80 cm. Available P levels range from 2.2 ppm in the surface to 0.8 ppm in the subsoil. Organic-matter content is 0.2%. In approximately 40% of the area in which this soil occurs, the surface horizons are eroded.

V. Bokotchili series .5 to 2% slopes

This is a very deep, gently sloping soil located in the lower backslope region of the toposequence, just upslope of the valley bottom soils. The surface is a strong brown sand up to 32 cm thick, the upper 15 cm of which is composed of 2 to 3 cm of loose sand underlain by 7 to 8 cm of thin lamellae. The Bt horizon is a yellowish red sand that extends to a depth of about 1 m, below which occurs a C horizon that extends below 2 meters. This soil has the highest level of available P within the watershed. The values range from 8.5 ppm in the surface to 0.9 ppm in the subsoil. Soil pH ranges from 5.0 at the surface of the Bt horizon to 6.0 at the surface.

An eroded phase was identified in two places where intermittent streams have cut deep gullies.

VI. Falanke series 5 to 7% slopes

This very deep, moderately sloping soil is on the valley walls of the main drainage way. The surface soil is 15 cm of strong brown sand, the upper 4 cm of which is com-

posed of thin lamellae. The Bt is yellowish red loamy sand that extends below a depth of 2 m. Soil pH values range from 5.3 in the surface horizon to 5.8 in the subsurface. Available P values range from 2.2 ppm at the surface to 1.0 ppm in the subsoil. In the western portion of this map unit, a lithic phase of indurated laterite occurs at 140 cm below the soil surface. A depositional phase of this soil was also identified at the base of each of the gullies, where there are extensive outwash fans.

Survey on Vegetation and Indigenous Knowledge

In the attempt to develop a reference data base against which the effects of further interventions can be compared, a vegetation survey was carried out in the watershed between October and December, 1989. The survey recorded the abundance and diversity of trees, shrubs, and herbaceous species on plateaus, cultivated land, and fallow areas. The survey was carried out along one of the transects established during the soil survey. Results of this survey are presented under project TAMU-404.

Another significant component of the baseline studies is the assessment and documentation of indigenous knowledge, traditional farming systems, and related social and cultural factors. A survey involving all cultivators in the watershed was carried out by a social scientist. The major findings of this survey are reported in project TAMU-405.

Development of a Geographic Information System (GIS)

Information gathered on geomorphology, topography, pedology, vegetation, indigenous knowledge and any other spatially related information will be used in the development of a GIS. This will permit identification or definition of land-management units on which research will be carried out.

Conclusions

1) In line with TropSoils' new global thrust, a project has been identified which takes an integrated approach in addressing issues of land management for agricultural sustainability in Niger and in the Sahel in general.

2) A 589-ha pilot watershed was identified in western Niger for activities of the first phase of the project.

3) Baseline information on geology, geomorphology, topography, pedology, vegetation, and indigenous knowledge has been gathered. Land-management units will be identified based on above information through the development of a geographic information system.

Deep Placement of Phosphorus Fertilizer

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Water is generally not the only limitation to crop growth in the Sahel. Natural soil fertility is low, with phosphorus (P) probably being the most limiting nutrient. The use of P amendments is generally necessary to appreciably augment yields. Research has shown that there is no effective difference in yield if these are applied broadcast, banded, or hill-placed.

Phosphorus is very immobile due to reduced diffusion through the soil matrix. Thus, surface-applied P requires that a good root distribution occurs at the soil surface to enable uptake of this element. However, soil surfaces within the Sahel are very dry, as temperatures can exceed 60°C in the top few centimeters. These high temperatures, combined with low relative humidity and sandy soil textures, result in vaporization of soil water, most likely to a depth of at least 30 cm, so that actual soil water contents above 30 cm might not be adequate for plant growth. This implies that millet roots must be distributed in such a way that they can take advantage of the P (and other) fertilizers at the soil surface, and also water stored within the subsoil.

It has been shown that deep placement of P fertilizers in semiarid cropping systems resulted in improved grain yield. This was due to a deeper distribution of roots within the soil profile, as P was placed nearer to the water supply. One study placed phosphorus fertilizers at different depths around seeds of winter wheat and found that they could predict a best placement strategy for conditions in which wheat was grown. Another showed that soybean root and shoot growth was affected by the placement of P within pots. As the same amount of P was localized in smaller areas of the pot, growth decreased. The investigators concluded that placement strategies are important for optimum utilization of applied fertilizer phosphorus.

When the surface of the soil dries, roots in this zone will die. As soil-water contents are increased from precipitation, there will be a drain of photosynthates to regrow these roots for uptake of water and surface-applied nutrients. If the rain was not heavy enough to result in soil-water recharge, by the time new root growth appears the soil surface will again be dry, and reduced P uptake will then recur.

Objectives

The objectives of this research were to study the effects of surface and subsurface placement of P fertilizer on millet growth in the semiarid environment of the Sahel.

Procedures

Each experiment was replicated in three rainfall zones of Niger. Seven treatments were used:

1) P hill-placed
2) P broadcast
3) P banded
4) P point-placed at a depth of 15 cm
5) P point-placed at a depth of 30 cm
6) P hill-placed + P point-placed at a depth of 15 cm
7) P hill-placed + P point-placed at a depth of 30 cm

Nitrogen was applied as urea in a split application at the rate of 45.0 kg N/ha. Phosphorus was applied as triple superphosphate (TSP) at the rate of 22.5 kg P_2O_5/ha. In the combination treatments (6 and 7), half this amount of P was surface-applied in each hill and half was deep-placed to the appropriate depth. Phosphorus was applied to the soil prior to planting millet. A soil auger was used to remove either 15 or 30 cm of soil to deep-place the P, and the soil was replaced on top of the fertilizer.

Plot size was 8 x 9 m, and millet (variety HKP) was planted at 1 x 1 m intervals, with each hill thinned to 3 plants/hill. Three repetitions were used for this experiment.

Results

Millet grain and biomass yield are presented in Figure 3. A significant difference in yields existed among treatments. However, no consistent trend in yields was observed among the three research sites. Crop growth was much higher at the intermediate rainfall site (Tyeleda). Table 1 shows statistics for the relative biomass yield at each site.

The following trends were observed for this study: 1) At Malgorou, highest yields were obtained with surface applications of P. Generally, deep placement of P did not augment yield. In this climatic zone, broadcast or banded surface applications were more efficient than pocket placement.

2) At Tyeleda, the highest yield was obtained when P was deeply placed (30 cm). Yields with surface placement were generally lower, with placement at the intermediate depth (15 cm) lying roughly between these two extremes. For surface applications, pocket and broadcast applications were more efficient than banding.

3) At Ounditan, the intermediate P placement gave the highest yield, while deeper placement generally produced the lowest yield. For surface applications, the same trend was observed as for Tyeleda: pocket and broadcast applications were more efficient than banding.

Conclusions

An experiment employed different methods of applying P fertilizer in three rainfall zones of Niger. General trends indicate a greater efficiency of deep placement with lower rainfall, but the deepest placement (30 cm) yielded highest at the intermediate-rainfall site, while the intermediate placement (15 cm) yielded highest in the low-rainfall zone.

Since 1988 was a wet year for the Sahel, the experiment will be continued in 1989 to observe the effects of residual P on millet yield and also the effects of placement when water stress might be more limiting. Field observations at the start of the 1989 growing season showed that P fertilizer granules were still identifiable within the soil.

Table 1. Relative millet biomass yield as a result of P placement strategy in three rainfall zones of Niger.

Malgorou		Tyeleda		Ounditan	
Treatment	Yield %	Treatment	Yield %	Treatment	Yield %
7	74 A	3	64 A	5	72 A
6	81 A	6	76 AB	3	85 B
4	81 A	2	88 BC	2	89 BC
1	82 A	4	90 BC	7	91 BC
7	85 AB	1	92 BC	1	91 BC
3	99 BC	5	97 C	4	95 BC
2	100 C	7	100 C	6	100 C

The same letter within a column indicates no significant difference at the 0.05 level according to the LSD test.

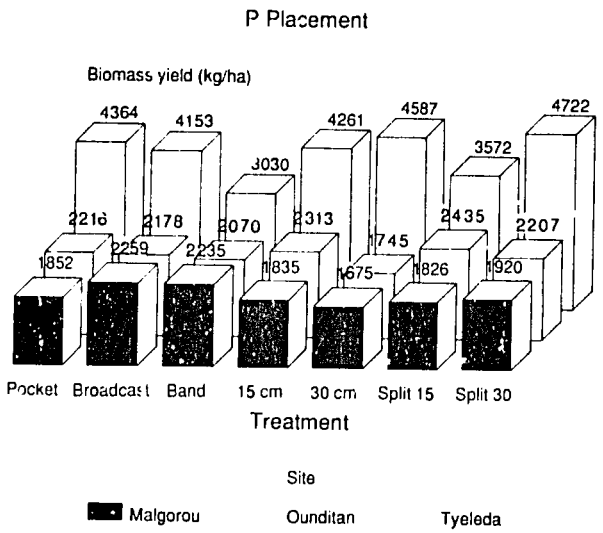

Figure 3. Millet biomass yield as a function of P placement.

Millet Production with the Use of Surface Mulches, Phosphorus, and Nitrogen Fertilizers in Three Agroclimatic Zones of Niger

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Crop residues are used sparingly by farmers in the Sahel as a surface mulch. This mulch has been shown to augment soil fertility while at the same time stabilizing the soil surface against the erosive action of strong winds. Phosphorus fertilizer use results in large yield responses of millet in the sandy soils of western Niger. The use of nitrogen fertilizer also produces yield response, but generally not as effectively as phosphorus.

Since millet residues are prized for purposes other than agriculture (i.e., construction of houses and walls, animal feed) their use as soil amendments may be limited. It is therefore necessary to obtain an idea of the effects of residue and fertilizer additions on millet yield in different rainfall zones, so as to devise a recommendation for their use that will conform to village economies.

Objective

The objective of this experiment was to compare the effect of millet residue as a surface mulch with the direct effects and interactions of N and P fertilizers within different agroecological zones of Niger.

Procedure

Experiment 1

For both the 1988 and 1989 growing seasons, an experiment was conducted to compare the effects of residue addition as a surface mulch with the use of P and N fertilizer. These experiments were conducted in three different rainfall zones of Niger. The sites and their long-term average rainfalls (mm) are as follows: Malgorou (700), Tyeleda (500), and Ounditan (350). Residue applied consisted of the millet biomass produced on each plot in the previous year. Phosphorus was applied at the rate of 22.5 kg P_2O_5/ha as TSP, and N was applied at the rate of 45 kg N/ha as urea. The millet variety HKP was used at all three sites. In the 1989 cropping season, plots were split to allow for different P-fertilizer application rates. Rates applied were 0, 12.25, 22.5, and 45.0 kg P_2O_5/ha as TSP.

Experiment 2

A second experiment was initiated in 1988 to quantify the effect on millet yield of different amounts of millet residue as a surface mulch. The field trials were installed at the same experimental sites as in experiment 1. Treatments were 0, 1.5, 3.0, and 6 t/ha of millet residue. No

fertilizer was added; however, these trials were located on land that had been evenly fertilized with N and P in 1987.

Results

1988 Cropping Season

There was considerable variability in millet grain yields at Malgorou and Tyeleda in 1988, due to crickets and bird damage, respectively. For these reasons, millet biomass (stalks and leaves as dry matter) is presented as an indicator of treatment effects on millet yield.

Generally, there was no response to residue application in the first year of the study (Table 2). The strongest P response was at the high-rainfall site, which is also the most acidic. Little P response occurred at the low-rainfall site. There was N response at all three sites in 1988.

Yield values with differential residue application were generally not significantly different among treatments in Malgorou and Tyeleda in 1988 (Table 3). However, there was a significant difference between the control and residue addition at Ounditan. This difference was apparent at all rates of residue application, and there was no change in yield with an increase in the quantity of residue added.

1989 Cropping Season

There was a slight yield response with the use of millet residue at the high-rainfall site in 1989, when no additional inputs were used. However, in experiment 1 in the other sites, and in all sites for experiment 2, there was no significant effect of residue use (Figures 4a, b, c). Phosphorus response was strongest at the highest rainfall site, which corresponds with the low acidity and low amounts of extractable P found at the soils of this site. There was little P response at either of the other two research sites, due to adequate levels of soil P. Nitrogen response was strongest at the low-rainfall site but was generally not very significant at the other two sites.

Table 2. Millet biomass yield at Malgorou, Tyeleda, and Ounditan with respect to P, N, and residue application in 1988.

Treatment		Site		
		Malgorou	Tyeleda	Ounditan
		kg/ha		
P level:	–P	977 A	2282 A	2124 A
	+P	1790 C	2722 B	2221 AB
N level:	–N	1364 A	2375 A	2132 A
	+N	1607 B	3079 B	2337 B
Residue:	–residue	1474 A	2666 A	2259 A
	+residue	1498 A	2788 A	2211 A

Treatment means within each level followed by the same letter are not significantly different according to the Duncan's multiple range test at the 0.05 level.

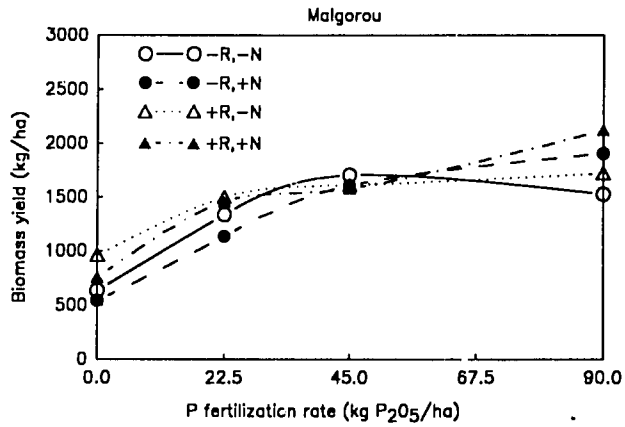

Figure 4a. Millet biomass yield at Malgorou in 1989 as a function of P, N, and residue additions.

Conclusions

First-year results of the effects of residue additions on millet yields were generally not significant. The fact that residue application as a surface mulch resulted in a slight yield increase in the most northern site (Ounditan) indicated that one benefit of residue use might be a short-term reduction in soil water evaporation. However, neither soil temperature (measured at depths of 10, 20, and 50 cm) nor soil water contents (data not reported) differed with the use of residues in the first year of the study.

Generally, the use of P fertilizer increased yields, while the use of N fertilizer increased yields only when P was also applied.

The second year of application of millet residue as a surface mulch resulted in a yield increase only at the high-rainfall site. However, since this response occurred in only one of the two experiments, it may be anomalous. Phosphorus response was greatest where low levels of extractable P are found in the soil, which generally corresponds with high soil acidity and exchangeable Al contents. Nitrogen effects were variable.

Overall conclusions of this research indicate that the use of residues as surface mulches does not have an immediate effect on soils that are generally productive. Since there is a competition for use of the millet residue by the local populace, it is suggested that efforts to use this residue for soil-productivity enhancement be restricted to marginally productive soils and that the productive soils on the landscape be managed with the use of fertilizers. It is generally believed that P fertilization results in the best yield responses in Niger. However, the research presented within this report suggests that not all soils in the Sahel are P deficient and that selection of a fertility program will need to be closely tied to the fertility conditions of the soil to be managed.

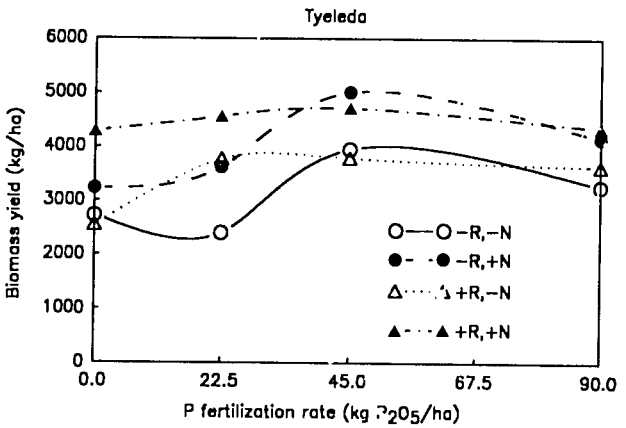

Figure 4b. Millet biomass yield at Tyeleda in 1989 as a function of P, N, and residue additions.

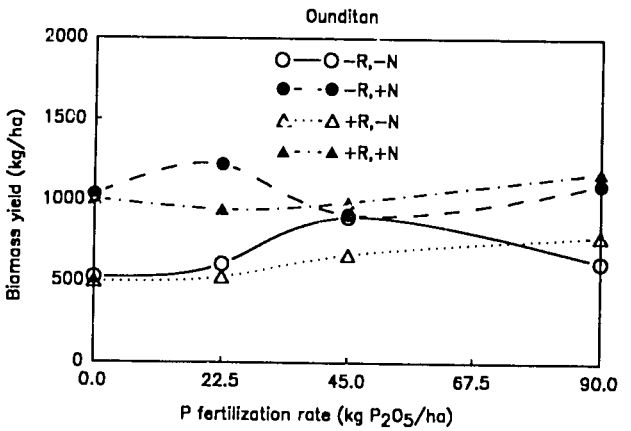

Figure 4c. Millet biomass yield at Ounditan in 1989 as a function of P, N, and residue additions.

Table 3. Millet biomass yield with additions of crop residue.

Residue added	Malgorou 1988	Malgorou 1989	Tyeleda 1988	Tyeleda 1989	Ounditan 1988	Ounditan 1989
	kg/ha					
0.0	1247 A	1207 A	2875 B	2425 A	1581 A	317 A
1.5	1278 A	1136 A	2437 A	2577 A	1964 B	376 A
3.0	1212 A	1430 A	2929 B	2605 A	1917 B	417 A
6.0	1308 A	1258 A	2536 AB	2761 A	2004 B	398 A

The same letter following treatment means for each site within a year indicates no significant difference according to Duncan's multiple range test at the 0.05 level.

The Long-Term Effects of Millet Residue as a Surface Mulch and P Fertilizer on the Chemistry of a Sandy Soil in the Sahelian Zone of West Africa

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Technologies to improve the fertility status of sandy soils found within the semiarid uplands of West Africa include the use of inorganic fertilizers and organic amendments (manure and crop residues). The use of manure as a soil amendment is limited to fields in which herders are paid by local farmers to graze their cattle (and thus leave the manure on the field) during the dry season, and in the areas immediately surrounding villages where local animals (goats, sheep) are kept. Millet residue is a readily available form of organic material, although it is extensively used for village industries and animal feed during the dry season.

A long-term experiment to observe the effects of millet residue and/or phosphorus fertilizer on millet growth was established in 1983 at the ICRISAT Sahelian Center. After five years, the addition of millet residue resulted in a three-fold increase in millet grain yield over the control. Yield increases with P fertilizer were slightly greater than those obtained with the additions of millet residue. When residues were added in combination with phosphorus fertilizer, yields were increased by three-fold over those found with the fertilizer or residue additions alone.

Objectives

The primary objective of this study was to examine the differences in soil chemical parameters after long-term additions of residue and/or phosphorus fertilizer in the above-mentioned experiment. A secondary objective was to deduce the mechanisms responsible for the increase in millet yields with the addition of millet residue as a surface mulch.

Procedure

Soils

The experiment was conducted at the ICRISAT Sahelian Center, approximately 30 km south of Niamey, in Niger, West Africa. The geomorphology of this area consists of sand plains (terraces) sloping towards the Niger river valley, which are composed of eolian sands deposited over a layer of cemented gravel (Continental terminus). The field plot was located on a Labucheri soil (Psammentic Paleustalfs; sandy, siliceous, isohyperthermic).

Soil sampling

Soils were sampled from three of the four replications of the field trial during the dry season of 1987, prior to preparation for planting for the 1988 growing season. Soil samples were taken at 10-cm increments to a depth of 120 cm at two locations within each plot and were pooled into one sample. Soils were then air-dried and sieved (< 2 mm) prior to analysis.

A topographic survey of the research site was made on a 3-m x 3-m grid pattern, using standard survey equipment. The lowest grid mark on the field was used as the reference soil height, and was adjusted to zero meters. Values for grid points falling within each plot were averaged, and were again averaged over the 4 repetitions of each treatment of the field trial. All soil analyses were made using standard procedures at the INRAN soils laboratory.

Results

Soil Acidity Parameters

Native soil pH was low in the control plots (Figure 5). The pH increased slightly with depth to approximately 30 cm and remained relatively constant until the 60-cm depth, where pH again increased down the profile. There was a large treatment effect on soil acidity parameters. Soil pH was significantly higher in the two treatments receiving residue application. However, this effect only occurred in the top 0 to 10 cm of the soil profile, and below that depth, pH values were similar to those of the control plots.

Aluminum saturation in the control plots followed a trend opposite to that of pH (i.e., % Al saturation increased to the 30- to 40-cm depth and then decreased thereafter) (Figure 6). In plots that received crop residues, there was a complete absence of exchangeable Al in the surface 10 cm. There was also a significant decrease in Al saturation, relative to the control, after the long-term addition of P fertilizer.

It is worth noting that differences in soil acidity parameters were operative only within the first 20-cm depth of the soil profile.

Exchangeable Bases (Ca, Mg, K, and Na)

Calcium was the dominant basic cation on the exchange complex, which was followed by Mg, K, and Na. Total exchangeable bases reflect the distribution of Ca within each profile (Figure 7). Exchangeable Ca in the control plots ranged from 0.01 cmol (+)/kg at the surface to 0.38 cmol (+)/kg at the 120-cm depth. The addition of residue resulted in increased Ca levels in the surface 10 cm. The addition of P fertilizer resulted in an increase in Ca intermediate between those of the control and the residue treatments. The residue plus P fertilizer treatment contained an amount of Ca at the surface equal to the additive effect of residue alone plus P fertilizer alone. Magnesium

and K were significantly higher in the surface 10 cm of only the plus-residue plots, since there was no extraneous addition of either of these elements from the superphosphate. Sodium was not a significant factor.

Available Phosphorus

The Bray 1 extractant is widely used in the Sahel and throughout West Africa to measure available soil P. Phosphorus in the surface of the control plots was low (<4.0 mg P/kg) and decreased to approximately 2 mg P/kg within 20 cm of the surface. There was no variation in Bray 1 P beyond this depth (i.e., Bray 1 P levels were similar throughout the rest of the profile; Figure 8). Upon the addition of millet residue, available P levels increased slightly, but significantly, in the first 10 cm. The addition of P fertilizer resulted in a large increase in available P in the surface 20 cm of the soil. The combination of residue plus P fertilizer produced an additive effect approximately equal to the amounts of P extracted when residue was added alone, plus the P from the treatment receiving additions of fertilizer alone. As with the acidity components of these systems, changes in available P occurred only within the surface 10 to 20 cm of the soil profile.

Organic Carbon

Organic carbon was measured in the top 30 cm of each plot (Table 4). Levels were low, ranging between 0.17 and 0.22%. As expected in this temperature regime, there were no significant differences in organic carbon levels between treatments.

The result of these analyses indicated that organic-matter levels most probably cannot be increased over the long term in the Sahel with the application of moderate rates of organic material, as an equilibrium level appears to be reached at a relatively rapid rate. Both microbial and termite activity are high in this environment, and field observations indicate that residues applied as a surface mulch can disappear within one year.

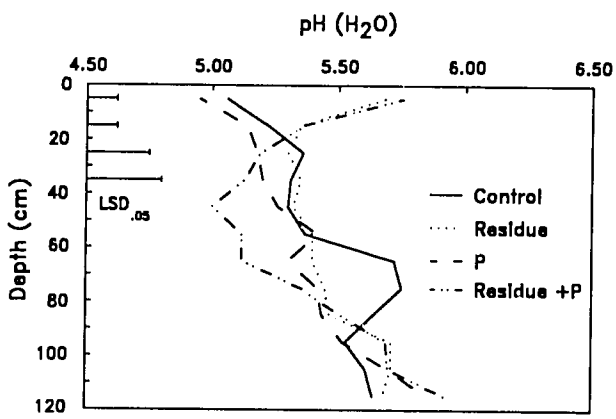

Figure 5. Soil pH in 1:1 (soil:water) throughout the profile.

Deposition of wind-blown material

The surfaces of the plots receiving residues were higher in elevation than the plots not receiving residue. Results of

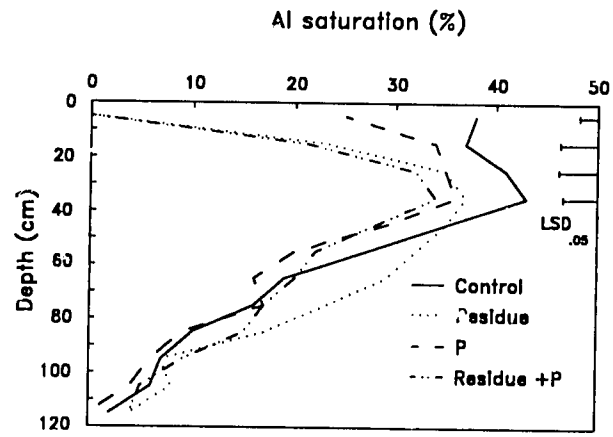

Figure 6. Al saturation throughout the soil profile.

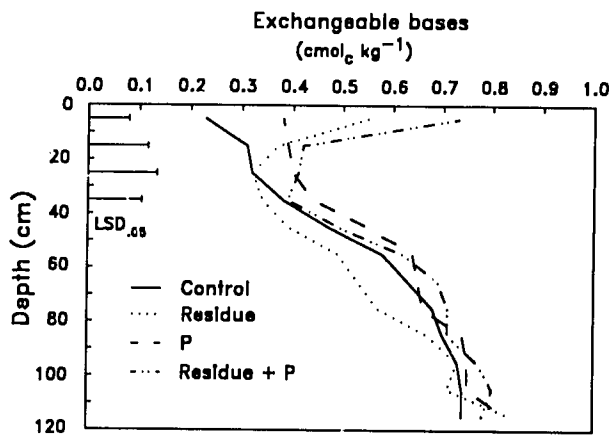

Figure 7. Exchangeable bases throughout the soil profile.

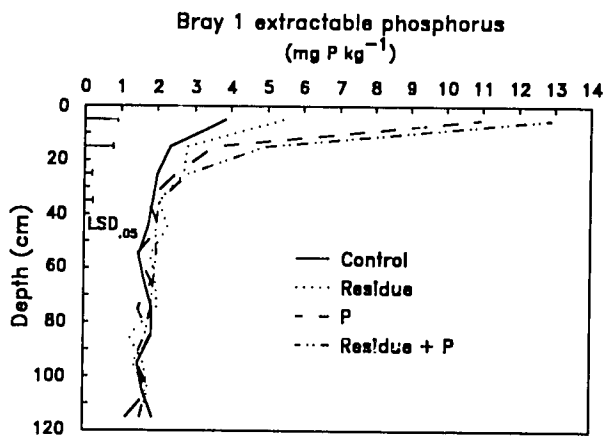

Figure 8. Bray 1 extractable P throughout the soil profile.

Table 4. Organic carbon in the top 30 cm of each treatment.

Depth	Control	Residue	Fertilizer	+ P
(cm)		%		
0–10	.21	.22	.19	.21
10–20	.20	.21	.19	.20
20–30	.17	.19	.20	.21

There were no significant differences between treatments within a depth, or at different depths within a treatment, at the 0.05 level according to the Duncan's multiple range test.

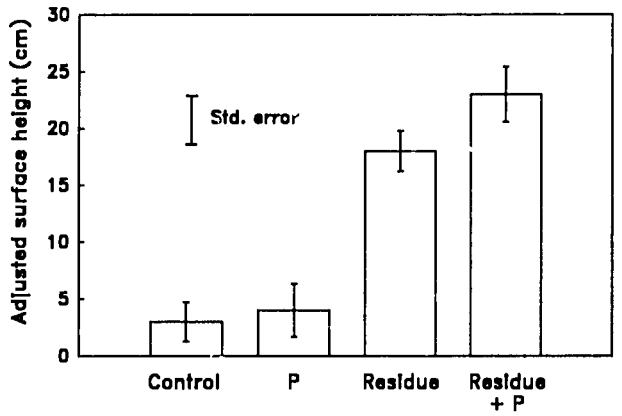

Figure 9. Average relative surface heights of the four treatments.

the topographic survey are shown in Figure 9. There was no significant difference in surface elevations between the control and the P fertilizer plots. However, the addition of residue for five years resulted in a difference in soil surface elevation approximately 15 cm higher than that of the control. The use of residue plus P fertilizer resulted in a slightly higher surface (approximately 20 cm) when compared to the control.

Mechanisms of Soil-fertility Enhancement

Two mechanisms could operate to increase soil fertility within the system described in this document—recycling of nutrient elements from the millet residue and stabilization of the soil surface. Beneficial elements can be returned to the soil through microbial decomposition of the millet residue. This process could account, in part, for the elevated base saturation and elevated P contents found in the plus-residue plots.

Short-range variability in plant growth and in soil physical and chemical properties is common in this area of the Sahel. It has been observed that wind-blown material has chemical properties similar to those on the surface of productive soils found in the same area. The surface of nearby nonproductive soils had a more deficient nutrient balance and higher exchangeable Al contents, indicating that the wind-blown material most likely arose from productive areas of the landscape.

The research presented in this report implies that the eroded material trapped by the residue was most likely local in origin, being the coarser-textured fraction that was displaced by either saltation or surface creep. The relatively low nutrient contents found in the control plot were probably due to the removal of part of the surface horizon by erosion.

Conclusions

The long-term effect of millet residue and/or P fertilizer applications on the chemical properties of a sandy soil in the West African Sahel were studied. Residue systems had higher exchangeable bases and extractable P, and lower percent Al saturation and pH than the control plots. The addition of P fertilizer resulted in an increase in P and a slight increase in exchangeable Ca. The combination of residue + P fertilizer resulted in an additive effect of additions of residue and P fertilizer alone.

Changes in soil chemistry after five years of continuous experimentation were found only in the top 10 to 20 cm from the soil surface, indicating no downward movement of nutrients and no long-term effects of treatments on subsurface chemical properties.

A model for the effect of residue can be explained as follows: wind-blown materials are trapped by residue on the soil surface. These trapped soils are more fertile (or less infertile) than the underlying soil. Adding to the process is the recycling of nutrients from decomposing residue, which tends to make the deposited soil an even more suitable substrate for plant growth. Areas from which the wind-blown materials originate, however, may be severely degraded with respect to soil fertility.

The implications of this research are that stabilization of the soil surface against high winds and erosive water flow can lead either to a regeneration or to preservation of native soil fertility in fragile soils of the Sahel.

The Use of Liming Materials and Millet Residues as Surface Mulches in a High-Rainfall Zone of Niger

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A. Foumakoye, TropSoils/INRAN

Soils of the Sudanian zone of southern Niger often exhibit high levels of exchangeable acidity. While total amounts of Al are not large, Al saturation of the exchange complex can exceed 50%. It has been observed that Al saturation above 30% can result in reduced millet dry-matter yield in pot studies.

The use of lime ($CaCO_3$) to neutralize Al has not been thoroughly investigated in Niger. Crop residues applied as a surface mulch have had a beneficial effect on millet yield. If the effect of residue is due to nutrient and organic-matter recycling, there might be a complementary effect of $CaCO_3$ and residue additions, through the neutralization of exchangeable Al by reaction with $CaCO_3$ reaction products or complexation with functional groups of organic-matter decomposition products.

Objectives

The objective of this study was to observe the effect of liming and/or millet residue additions on millet response in an acid soil of the Sudanian ecological zone of Niger.

Procedure

The experiment was conducted in Malgorou, a village in southern Niger where long-term average annual rainfall exceeds 700 mm. The soil at the site is a Typic Kanhaplustult, loamy, siliceous, and isohyperthermic.

The experiment was conducted for two years and consisted of the following treatments: 1) control, 2) liming material to neutralize one-half the exchangeable Al, 3) liming material to neutralize all exchangeable Al, 4) millet residue added as a surface mulch at the rate of 3 T/ha, 5) treatment #2 plus treatment #4, and 6) treatment #3 plus treatment #4.

The lime source in the first year was reagent grade $CaCO_3$, as lime was unavailable in Niger. Agricultural-grade dolomite was used for the second year of the study. A bulk sample of the soil at this site was analyzed for exchangeable Al prior to the first and second year field preparations. Liming materials were added at the rate of 135 and 270 kg $CaCO_3$/ha to neutralize one-half and all exchangeable Al in the first year, and 370 and 740 kg/ha dolomite to neutralize one-half and all of the exchangeable Al in the second year.

Plot size was 9 x 8 m, with a plant density of 30,000 plants/ ha. The millet variety HKP was used. Phosphorus was broadcast at the rate of 22.5 kg P_2O_5/ha over each plot. Lime was also broadcast at the same time, and both P and lime were incorporated by raking. Nitrogen was applied as urea at the rate of 45 kg N/ha in two applications—one after the first weeding and the other after the second weeding.

Soils were sampled from each plot prior to treatment application. All soil analyses were performed at the INRAN Soils Laboratory.

Results

Soil Variability

Soil chemistry was variable at this site. As Figure 10 indicates, the exchangeable Al calculated from the bulk sample did not give a true representation of actual field conditions. Similar variability was found for other soil-fertility parameters (Table 5).

Lime Effect on Millet Yield

Millet grain and biomass (stalk and leaves) yields for both years are shown in Table 6. Differences in biomass yield occurred only with additions of residue (treatments 4

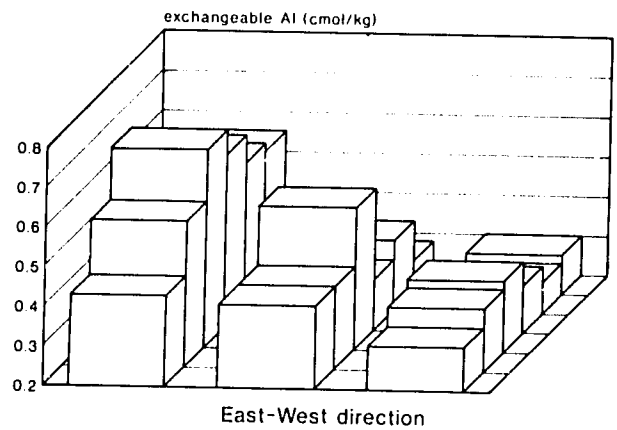

Figure 10. Variability in exchangeable Al within the experimental site. Each value represents a plot.

Table 5. Variability in soil chemical parameters between plots prior to the 1988 field preparation (n=18).

Parameter		Mean	Range	Standard deviation
Exchangeable:				
Ca	(cmol/kg)	.30	.14 – .63	.12
Mg	"	.13	.07 – .20	.04
K	"	.10	.07 – .15	.03
bases	"	.53	.29 – .95	.17
Al	"	.43	.28 – .70	.13
acidity	"	.80	.64 –1.07	.15
ECEC		1.34	1.18 –1.59	.08
Al Saturation (%)		.32	.18 – .50	.10
Bray 1 P (mg/kg)		2.19	1.37 –3.02	.55

through 6) and not with addition of liming material in the first year. In a separate pot study utilizing the same soil and treatments, it was determined that the fine mesh size of the reagent grade $CaCO_3$ most likely resulted in rapid dissolution and neutralization or leaching of the material out of the soil.

The use of dolomite in the second year of the experiment resulted in an increased biomass yield (cricket attack resulted in variable grain yield within plots). Soil analyses of each plot prior to field preparation in the second year indicated that the $CaCO_3$ applied in the first year had no effect on exchangeable Al or acidity.

Effect of Residues on Millet Yield

The use of millet residue as a surface mulch resulted in a 38% grain yield increase in the first year. During the second year, at all levels of dolomite application (where there was an increase in yield due to dolomite) there was a significant increase in yield with the addition of millet residue as a surface mulch compared to the nonresidue plots.

Conclusions

In spite of the problems encountered with the availability of suitable liming materials in Niger, the following conclusions can be drawn.

1) In the acidic soil systems found in the higher-rainfall zone of Niger, the use of liming materials can result in an increase in millet yield.

2) Millet residue as a surface mulch resulted in a yield increase. However, it must be cautioned that variable results have been found with mulches used in other experiments within the area of this experiment, and further research will be required to assess the relative effect of surface mulches on farmers' fields.

3) Soil variability, especially of the acid-producing components, will make field-plot research difficult in this agroecological zone.

Table 6. Millet grain and biomass yield with additions of liming materials and/or millet residue as a surface mulch.

	1988		1989	
Treatment	Grain	Biomass	Grain	Biomass
	kg/ha			
Control	819 A	2316 A	369 A	1663 A
0.5 exch. Al	899 AB	2168 A	512 AB	1756 A
Exch. Al	911 AB	2261 A	587 AB	2233 AB
Residue	1131 C	3143 B	702 B	2096 AB
Residue + 0.5 exch. Al	1108 C	2991 B	434 AB	2192 AB
Residue + exch. Al	1044 BC	2949 B	657 AB	2544 B

Similar letters following treatment means within each column indicate no significant difference by Duncan's multiple range test at the 0.05 level.

Correlation of the Soil Chemical Properties with the Incidence of Striga in Millet

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S. C. Geiger, Texas A&M University
J. Werder, ISC

A collaborative effort was undertaken with the millet pathologist at ICRISAT to ascertain the effect of native soil fertility on the incidence of Striga on millet growth. This section reports the results of the collaboration.

Striga (*Striga hermonthica*) is a noxious weed (parasite) that commonly infects the roots of millet (*Pennisetum glacum (L.) R. Br.*). Field observations generally indicate a decrease in Striga populations when N fertilizers are applied. This observation suggests that the alleviation of stress factors to the host plant might enable either a stronger resistance to Striga attack or a decreased ability of the Striga to infect the plant.

Variability in soil physical and chemical properties over small distances is common in the Sahel. Striga occurrence has also been observed to occur irregularly within a field. However, interactions between short-range soil spatial variability and occurrence of Striga within a field have not been investigated.

Objective

The objective of this study was to correlate Striga occurrence with differences in native soil fertility within a field in which Striga infestation was not uniform.

Procedures

Site Description

The research was conducted at the ICRISAT Sahelian Center (ISC), approximately 45 km southeast of Niamey. The plot has been under continual observation since 1985, with millet grain yield and occurrence of Striga being measured each of those years. Plot size was 25 x 60 m. Millet (cv. CIVT) was planted on a 1- x 1-m spacing with three plants per pocket, for a final plant density of 30,000 plants/ha. Striga plants were counted on a 1- x 1-m spacing on a two-week interval from first emergence, and millet grain yield (kg/ha) was taken in 5- x 5-m subplots. Striga occurrence was reported as number of plants per 5- x 5-m subplot. The field trial and measurement of yield and Striga occurrence were conducted by J. Werder, millet pathologist/ICRISAT.

Soil Sampling and Analysis

Soils were sampled in April 1988 in the same 5- x 5-m subplots as used for yield determination. Each subplot was randomly sampled at 10 different spots to a depth of 20 cm and pooled into one sample. There were 60 samples for analysis.

Soils were air-dried and ground to pass a 2-mm sieve prior to analysis. Soil pH was measured in a 2:1 H_2O:soil paste and in N KCl. Exchangeable Al and total acidity were measured. Exchangeable bases were displaced with N NH_4OAc and determined by AAS (Ca and Mg) or flame emission photospectroscopy (K and Na). Effective cation-exchange capacity (ECEC) was calculated as the sum of total acidity and exchangeable bases. Labile P was extracted with the Bray 1 extractant and measured spectrometrically, using the molybdate blue method.

Statistical Design

A cross-correlation matrix was composed to elucidate the relationships between Striga occurrence, soil chemical parameters, and millet grain yield.

Results

Soil Properties

The means and ranges of the soil chemical parameters measured are presented in Table 7, as are those of the Striga occurrence and millet grain yield. Exchangeable Al levels were low to nonexistent. Only six subplots had measurable amounts of exchangeable Al. This was reflected in the pH, which averaged 5.7 (in H_2O) with little variability (%CV 3.6).

Total exchangeable base contents were low, as was the variability between subplots (%CV 8.1). Exchangeable Na was very low.

Labile P, as measured by the Bray 1 extraction, was highly variable throughout the subplots (%CV 26.9).

Table 7. Means and ranges of selected soil chemical properties, Striga counts, and millet grain yield.

Parameter	Mean	Range
pH (H_2O)	5.71	5.11 – 5.99
ph (N KCl)	4.66	4.05 – 5.09
Exch. Al cmol (+)/kg	0.008	0.00 – 0.25
Exch acidity cmol (+)/7kg	0.149	0.08 – 0.35
Exch: [cmol (+)/kg]		
Ca	0.73	0.63 – 0.86
Mg	0.04	0.03 – 0.05
K	0.10	0.07 – 0.13
Na	0.01	0.01 – 0.02
Bases	0.88	0.75 – 1.04
ECEC cmol (+)/kg	1.02	0.85 – 1.18
Bray 1 P mg/kg	5.56	2.85 – 9.38
Striga #	102	8 –655
Millet grain kg/ha	257	105 –441

Values were low to optimum for millet growth, with an average that was much higher than that found in other soils of the ISC (5.56 mg/kg).

In summary, the surface soil at this site had a low-to-nonexistent exchangeable Al content, and low base availability. However, labile P levels appeared on the average to be higher with respect to the other fertility parameters (Ca, Mg, and K).

Striga and Millet Yield

Striga infestation was highly variable (%CV 104) between all subplots. The mean value was fairly high (102). For all soil and grain parameters measured, the mean, median, and modal values were similar, suggesting a normal distribution throughout the field. However, for Striga these values varied extensively: mean 102; median 77; mode 19 with a standard deviation of 106.

Grain yields were low, with a mean of 257 kg/ha and a high of 441 kg/ha, suggesting that native soil fertility was limiting crop growth, especially with respect to the "wet" growing season that occurred in 1988.

Relation between Soil and Plant Yield Parameters

A correlation matrix relating soil chemical parameters with Striga occurrence and millet grain yield is presented in Table 8. In all cases, correlation coefficients (r) were low. The highest correlations found between soil fertility parameters were between the exchangeable bases (Ca, Mg, K, and total) and ECEC. There was little correlation of labile P with any other soil parameter.

While millet grain yield was positively correlated with the base status of the soil, the correlation was weak. The largest correlation with millet grain yield was with Striga occurrence. Surprisingly, this correlation was positive, and greater than those obtained with the bases. This fact indicates that Striga occurrence might be linked to the general health of the host plant and that a healthy host plant is able to support a higher level of Striga infection without serious yield loss.

Striga occurrence was positively correlated with millet grain yield and exchangeable bases (Ca, Mg, and K). There was no correlation between labile P and Striga occurrence.

Conclusions

Native soil fertility at this site was low and variable. However, the variability was not expressed as strongly as in other sites at the ISC and elsewhere in the Sahel where soil variability is a constraint to crop production.

There was a weak correlation between soil chemical properties and either Striga occurrence or millet grain yield. Striga occurrence was most highly correlated with millet grain yield.

The results of this study indicate that areas of relatively high native soil fertility might be able to support both higher infestations of Striga and higher grain yields. The ability of a plant to grow under more favorable conditions also appears to enable it to withstand the stress imposed by the parasitic attack by Striga. However, water stress was probably not a large factor influencing millet yield in 1988. The conclusions of this report might not be valid during a dry year, when water stress will have more of an influence on crop growth and possibly the Striga/millet interaction.

Table 8. Correlation matrix relating soil chemical parameters, Striga occurrence, and millet grain yield (n = 60).

		Exchangeable								
	Al	Bases	Ca	Mg	K	Na	ECEC	P	Striga	Yield
pH	–.30	.46	.51	.17	.35	–.08	.25	–.07	.20	.33
Acidity		–.22	–.22	–.08	–.17	.07	.54	–.10	–.15	–.18
Bases			.93	.61	.80	–.25	.70	.11	.32	.53
Ca				.53	.65	–.29	.64	.07	.27	.48
Mg					.5	–.26	.46	–.25	.32	.35
K						–.20	.56	.10	.39	.46
ECEC								.02	.17	.33
P									.14	.17
Striga										.47

Significance levels found at the corresponding r values:

level	r
.05	.15–.18
.005	.18–.20
.0005	> .20

Tillage, Cultural Practices, and Fertilization Effects on Infiltration, Soil Erosion, Soil Water Storage, and Crop Yield: TAMU-403

Inefficient use of rainfall is a major factor in the deterioration of the Sahelian ecosystem. Declining soil physical properties are caused by low organic matter, high soil temperatures, raindrop impact on exposed soils, and poor tillage practices. These combine to destroy soil structure, resulting in compaction, reduced infiltration, increased runoff, decreased soil water storage, and soil erosion. Other factors in the deteriorating ecosystem of the Sahel are problems of soil fertility (low N and P) and soil chemistry (low pH, Al toxicity). In some cases, these problems are so severe that crops and rangelands cannot efficiently use the limited precipitation.

Both qualitative and quantitative information on the factors behind the degradation of the ecosystem are lacking. In developed countries, tillage techniques, engineering structures, and cropping systems have been developed to increase soil water storage and crop yields and to reduce soil erosion. In Sahelian countries, farmers have developed adaptive strategies over the centuries. Concepts derived from these techniques have value for further adaptation and development. Additionally, the deteriorated fertility and chemical properties of the soil should be amended so that crops can use stored water more efficiently.

The hypothesis of this study is that tillage, cultural, and fertilization techniques can be developed so that soil erosion can be minimized and rainfall can be used more efficiently in the Sahel.

Tillage and Fertilization Effects on Grain Sorghum and Cowpea Yields and Water-Use Efficiencies in Mali

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Z. Kouyate, IER
A. B. Onken, Texas Agricultural Experiment Station

Mali is typical of the Sahelian countries, with an increasing population and decreasing agricultural production. Techniques to stabilize or increase cereal grain production are needed.

Objectives

The objective of this study was to compare several techniques of soil preparation alone and in combination with fertilizer application and to evaluate their effect on water-use efficiency and yield of sorghum.

Procedures

This study was initiated in 1986 at the Agronomic Research Station at Cinzana, Mali, on a previously fallow loam soil. This study involved the influence of tillage and fertilization on sorghum growth and yield. After the first year, the sorghum was rotated with cowpeas. Appropriate measurements of the soil physical and chemical properties were made. Tillage treatments were no tillage (ST), subsoiling (SS), ridging (B), subsoiling + ridging (SSB), tied ridging (Bcl) and subsoiling + tied ridging (SSBcl). Fertilization treatments were no fertilizer (F_0) and fertilizer (F_1). Fertilization consisted of 100 kg/ha of 17-46-0 at seeding and 50 kg/ha of 46-0-0 at jointing or stem elongation.

Results

Sorghum grain yields for 1988 and 1989 are presented in Table 1. The most surprising result was that the subsoiling (SS) treatment produced lower yields than the no-till treatment both years. All treatments that included ridging produced higher yields than did the no-till treatment. There were no significant differences between the yields of ridging and tied-ridging treatments. Fertilization significantly increased the yield of all tillage treatments. The fertilized treatments had lower yields in 1989 (1807 kg/ha) than in 1988 (2133 kg/ha). This was probably due to rainfall which was higher in 1988 (701 mm) than in 1989 (626 mm).

The differences in cowpea yields (Table 2) between years were not as significant as those of sorghum (Table 1). The cowpea yields were slightly higher in the dry year, 1989, than in the wet year, 1988, which was the reverse of sorghum. The unfertilized (F_0) subsoiled treatment (SS) had lower yields than the untilled treatment (ST) while the reverse was true for the fertilized treatment (F_1). Ridging increased cowpea yields both years. The effect was larger in 1989, the year of lower rainfall. Yields of the tied-ridge treatment (Bcl) were not different from the ridge treatment (B).

Percentage increases due to fertilization and tillage are presented in Table 3. In 1988, percentage increases for both grain sorghum and cowpeas were higher in the fertilizer treatment than in the tillage treatment. The

Table 1. Grain sorghum (cv. CSM 219) yields (kg/ha) of different tillage treatments with and without fertilizer at Cinzana, Mali, in 1988 and 1989.

1988 Treatments				1989 Treatment			
	Fertility				Fertility		
Tillage	F_0	F_1	Mean	Tillage	F_0	F_1	Mean
ST	1023	1941	1482 bc	ST	863	1170	1017 c
SS	742	1861	1302 c	SS	311	903	607 d
B	1479	2370	1925 a	B	1790	1922	1856 ab
SSB	1527	2258	1893 ab	SSB	1507	2247	1877 ab
Bcl	1682	2164	1923 a	Bcl	1457	1998	1728 b
SSBcl	1320	2132	1760 ab	SSBcl	1722	2606	2164 a
Mean	1296	2132	1714		1275	1807	1541
Test of significance	HS				HS		

reverse was true in 1989. The tillage treatments, especially ridging, had higher percentage increases than did the fertilization treatment.

Water-use efficiency data for selected treatments for 1989 are presented in Table 4. More water was available for use in grain sorghum in the tilled than in the untilled treatment. The most intense treatment, subsoiling + tied ridges (SSBcl) had the highest water-use efficiency. Fertilization had little effect on the water-use efficiency of ridged treatment (BF_0 vs. BF_1). The overall water-use efficiency was less in cowpeas than grain sorghum. Water-use efficiency due to treatment was affected the same way in both grain sorghum and cowpeas.

Conclusions

Conclusions based on the two years of data are as follows:

1) Subsoiling (SS) is not a worthwhile practice on loam soils such as those on the Cinzana station.

2) Ridging (B) appears to be the best tillage treatment for increasing yields.

3) From this study, there does not appear to be any advantage to tied beds (Bcl). However, it should be pointed out that the site of this study is very level.

4) Since fertilization (F_1) was effective in increasing yields both years, the practice can be recommended, assuming it is economically sound.

5) Fertilization is more effective in increasing yields in wet years, although tillage is more effective in dry years. Since the weather cannot as yet be predicted, it will be necessary to use both practices to get maximum yields.

6) In 1989, tillage was more effective than fertilization in the data obtained. However, it should be pointed out that all treatments were not evaluated for water-use efficiency.

Table 3. Tillage and fertilization effects on grain sorghum (cv. CSM 219) and cowpea (cv. KN1) yields at Cinzana, Mali, in 1988 and 1989.

		Grain yield increase (%)		
Crop	Year	Fertilization (F)	All tillage	Ridging only
Sorghum	1988	65	19	27
	1989	42	62	83
Mean		53	40	55
Cowpea	1988	68	10	16
	1989	58	59	70
Mean		63	34	43

Table 2. Cowpea (cv. KN1) yields (kg/ha) of different tillage treatments with and without fertilizer at Cinzana, Mali, in 1988 and 1989.

1988 Treatments				1989 Treatment			
	Fertility				Fertility		
Tillage	F_0	F_1	Mean	Tillage	F_0	F_1	Mean
ST	449	874	662 ab	ST	410	593	502 b
SS	216	942	579 b	SS	323	627	475 b
B	737	841	789 a	B	796	911	854 a
SSB	596	927	762 a	SSB	732	1181	957 a
Bcl	645	963	804 a	Bcl	682	993	838 a
SSBcl	570	841	706 ab	SSBcl	542	1215	879 a
Mean	536	898	717	581	920	750	
Test of significance	HS				HS		

Table 4. Estimated water-use efficiency in selected treatments of grain sorghum (cv. CSM 219) and cowpeas (cv. KN1) at Cinzana, Mali, in 1988 and 1989.

	Grain Sorghum			Cowpeas		
Treatments	Water use	Grain yield	Water-use efficiency	Water use	Grain yield	Water-use efficiency
	mm	kg/ha	kg/mm	mm	kg/ha	kg/mm
STF_0	307 b	863 c	2,81	261	410 c	1,57
BF_0	356 a	1790 b	5,03	292	796 b	2,73
BF_1	359 a	1922 b	5,36	285	911 b	3,20
SSBcl F_1	371 a	2606 a	7,02	324	1215 a	3,75
Test of significance	HS	HS	—	NS	HS	—

Tillage Effects on Infiltration and Millet Yield

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R. L. Baumhardt, Texas Agricultural Experiment Station
D. McCool, ARS-USDA

The rainfall in the Sahel is irregular in amount and distribution. Much of it is lost to runoff because of the high intensity of many rainstorms. Techniques that would decrease runoff and increase soil water storage would improve crop yields.

Objective

The objective of this study was to compare the effects of different tillage techniques on infiltration and millet yield.

Procedures

In 1988, a rotating-disk rainfall simulator was used on a loamy sand soil with three different tillage treatments.

In 1989, the study was expanded to include simulation on both loamy sand and loam soils with three different tillage treatments in both the rainy and dry seasons. Water was applied with the simulator at the rate of 50 mm/hr for 1 hr. Periodic measurements of runoff were made to determine infiltration. The data were fitted to the Philips equation. Yield data were obtained from the plots at the end of the season.

Results

The infiltration data obtained in the preliminary study are presented in Figure 1. The data were obtained during the dry season and are what would be expected—with the highest final infiltration rate in the plowed treatment, followed by the scraped and no-till plots.

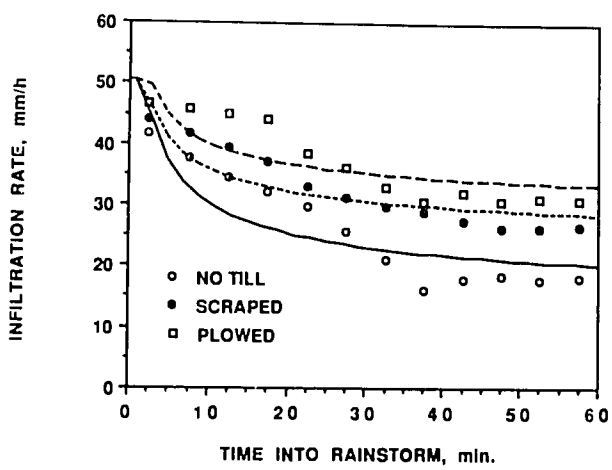

Figure 1. Effect of tillage on infiltration in a loamy sand soil, Cinzana, Mali, 1988.

During the rainy season in 1989, the no-till treatment had the highest final infiltration rate (Figure 2). However, during the dry season, the plowed treatment had the highest infiltration rate (Figure 3).

Infiltration rates on the loam soil were lower in the rainy season (Figure 4) than the dry season (Figure 5). There was no difference due to tillage treatments in either the wet or dry season.

Millet yield data are presented in Table 5. Although differences in yield were obtained on the loamy sand soil due to tillage, the differences were not significant due to variation (C.V. = 30%). Tillage treatments affected the yields on the loam soil even less than on the sandy soil.

Conclusions

1) Plowing will increase infiltration during the dry season on loamy sand soils. However, the effect does not hold through the rainy season. It appears that it will be

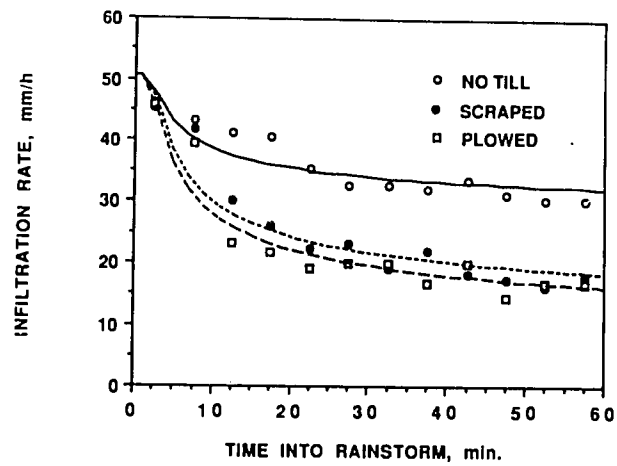

Figure 2. Effect of tillage on infiltration in a loamy sand soil during the rainy season, Cinzana, Mali 1989.

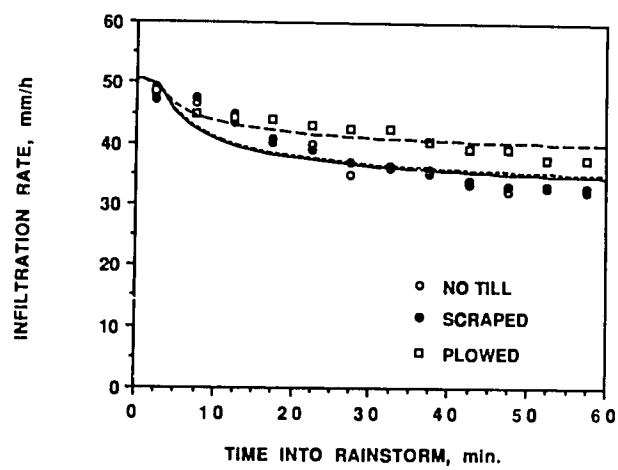

Figure 3. Effect of tillage on infiltration in a loamy sand soil during the dry season, Cinzana, Mali, 1989.

necessary to use some form of plowing after each rainfall to maintain increases in infiltration. Although tillage did increase millet yields on the loamy sand soil, the increases were not statistically significant.

2) Neither infiltration nor millet yields were affected by tillage on the loam soil.

3) Tillage will probably have to be a part of a system including the management of fertility and/or organic matter if it is to have a major impact on infiltration and millet production.

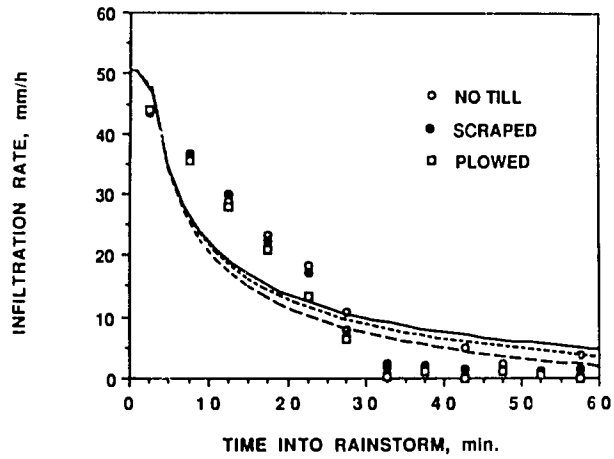

Figure 4. Effect of tillage on infiltration in a loam soil during the rainy season, Cinzana, Mali, 1989.

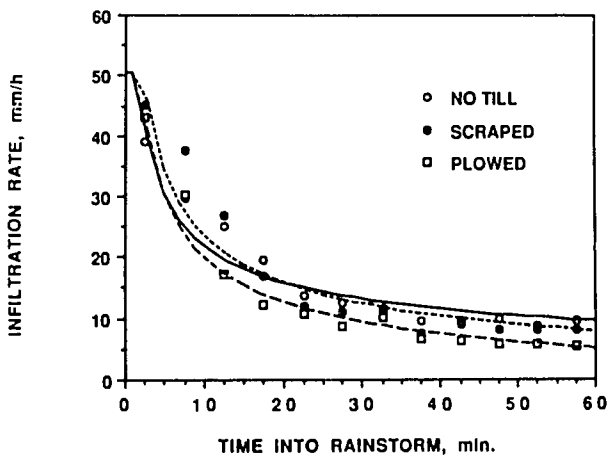

Figure 5. Effect of tillage on infiltration in loam soil during the rainy season, Cinzana, Mali, 1989.

Table 5. Millet yields (kg/ha) of different tillage treatments on different soil types at Cinzana, Mali, 1989.

	Soil Types	
Treatments	**Loamy sand soil**	**Loam soil**
No till	778	1109
Scraped	1025	1126
Plowed	1030	1253
Test of significance	NS	NS

Water Requirements and Low-Cost Water Management Technologies for Sorghum and Millet Production: TAMU-408

Rainfall in the Sahel is extremely variable in yearly amount, distribution, and intensity. Over the long term, the rainy season can fail for several years in succession. Such failures occurred in 1909–1916, in 1940–1948 and, most recently, in 1968–1973. The rainfall patterns of multiple locations in Niger, including overall trends and probabilities, have been summarized already (see *Trop-Soils Technical Report, 1986–1987*). Physical and hydrological properties of major cropped soils in Niger have been reported in the same publication.

The potential of water-harvesting techniques, the effects of a modification of the microclimate between windbreaks, and different soil- and crop-management practices such as tiller removal in millet have been explored by the TropSoils-SAT, and research results have been reported (see *Tropsoils Technical Report, 1986–1987*). A strategy to improve and sustain food production is to intensify crop production on better soils along the river valleys, where a supplemental water supply is readily available. Before crop yield on more productive soils is increased, basic information is needed on the water requirements of the crops grown in the area. Information is also needed on the water requirements when different levels of soil chemical amendments (lime and fertilizer) are added. Once the water requirements are known, it should be possible to design low-input, water-management systems to stabilize crop yield.

The overall hypothesis of this study is that low-input, water-management systems and fertilization techniques can be developed to overcome the variability in water and soil resources after the water and soil requirements for the crops are known.

Interactive Effects of Water and Nutrients on Sorghum Growth in a Sahelian Soil-Plant-Atmosphere Continuum (proposal)

C. Zaongo, Texas A&M University
C.W. Wendt, Texas A &M University
M. Gandah, INRAN
A.S.R. Juo, Texas A&M University

The Sahel is characterized by rainfall which is extremely variable in yearly amount, distribution, and intensity. Over the long term, the rainy season can fail for several years in succession. Such failures occurred in 1909–1916, 1940–1948, and most recently 1968–1973. A strategy to improve and sustain food production is to intensify crop production on better soils along the river valleys, where a supplemental water supply is readily available.

Before crop yield on more productive soils can be increased, basic information is needed on the water requirements of the crops grown in the area. Information is also needed on the water requirements when different levels of soil chemical amendments (lime and fertilizer) are added. Once the water requirements are known, it should be possible to design low-input water-management systems to stabilize crop yield.

The overall hypothesis of this project is that low-input water-management systems and fertilization techniques can be developed to overcome the variability in water and soil resources after the water and soil requirements for the crops are known.

Objectives

The objectives of this study are 1) to determine the yield of West African food crops grown at different water and fertility levels and 2) to increase or stabilize crop yields through supplemental irrigation and optimum fertilization.

Methods

No research was conducted on this project during the past two years. C. Zaongo has written a dissertation proposal entitled *Interactive Effects of Water and Nutrients on Sorghum Growth in a Sahelian Soil-Plant-Atmosphere-Continuum.* The proposal has been approved both by his committee at Texas A&M University and INRAN. He will begin his research in May 1990 at the INRAN national irrigation research station at Tarna, Maradi, Niger.

Water-Use Efficiency and Soil Fertility Relationships: TAMU-409

In many arid and semiarid regions, rainfall is the primary or the only source of water and must be used to the fullest extent to increase food production. Cultural practices that reduce runoff and evaporation and enhance infiltration are important in making the maximum amount of water available to a crop. However, such practices are economical only if the crop uses water efficiently.

Water-use efficiency (WUE) is defined as either yield (Y) per unit of transpired water (T) or yield per unit of evapotranspiration (ET) and is expressed as follows:

$$WUE_T = Y/T \text{ or } WUE_{ET} = Y/ET$$

Yield can be total biomass or useable product such as grain. WUE_T is known as the transpiration efficiency while WUE_{ET} is known as the evapotranspiration efficiency. WUE_T is important in basic studies of crops while WUE_{ET} is the common parameter evaluated under field conditions.

Research shows that the water requirement of crops grown on poor soil may be reduced one-half to two-thirds by the addition of fertilizers. Many studies have shown that fertilizers increase yield, but there has been little emphasis on using fertilizers to increase water-use efficiency. Management practices can increase the efficient use of water, but the influence of nutrients on WUE_T is hard to assess under field conditions because of the variation in water loss to soil evaporation among treatments.

In preliminary studies (see *TropSoils Technical Report, 1986-1987*), we investigated the relationship between yield and ET and yield and Y/ET for grain sorghum genotypes differing in nutrient-use efficiency (kg grain/kg nutrient available) on nutrient-deficient soils. Results showed a significant, positive, linear relationship between grain produced and ET. This relationship, however, was not as pronounced as the one we found between grain yield and WUE_{ET}, for which we found a highly significant positive linear correlation. Thus, factors that affect grain yield for sorghum will also affect ET and WUE_{ET}.

The hypotheses for this project are 1) that crop utilization of available soil moisture in the Sahelian environment is closely linked with fertility level and 2) that increased crop production and introduction of new cereal germplasm can be facilitated by minimizing soil physical and chemical constraints.

Effects of Soil Fertility, Crop Genotypes, and Available Soil Water on Water-Use Efficiency of Sorghum

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Z. Kouyate, IER

One factor that significantly affects efficient water use by crops is the chemical nature of the soil, including, but not limited to, soil fertility. In West Africa, soil fertility is a major consideration because most soils of the region are deficient in one or more nutrients. A second factor influencing efficient water use is crop genotype. Drought tolerance, water-use efficiency, nutrient-use efficiency, and responses to applied fertilizer have been found to differ among crop genotypes. Most countries in arid and semiarid West Africa have major breeding programs directed at sorghum improvement. Such programs will be more productive if they include an understanding of the various factors influencing water use and how those factors interact to affect crop production.

Objectives

Two studies were conducted in cooperation with INTSORMIL at Lubbock, Texas, with the following objectives: 1) to delineate the interaction effects among sorghum genotypes, nitrogen nutrition, and available soil water on evapotranspirational and transpirational water-use efficiencies under field conditions; and 2) to determine the effects of the interaction among sorghum genotype, phosphorus nutrition, and available soil water on transpirational water-use efficiency.

Procedures

The first objective was addressed in a field study conducted at the Texas A&M University Agricultural Research and Extension Center at Lubbock on an Amarillo loam (fine-loamy, mixed thermic) Aridic Paleustalfs. This study consisted of two sorghum breeding lines grown in factorial combinations of three water levels and three N levels arranged in a randomized block with three replications.

Water levels were as follows:

W1—a preplant application of 10.2 cm ha/ha plus 5.6 cm ha/ha on June 10;

W2—a preplant application of 10.2 cm ha/ha plus 5.6 cm ha/ha on June 10, then weekly irrigation to replace approximately 50% of evapotranspiration (ET) beginning July 25 (20.8 cm ha/ha after planting);

W3—a preplant application of 10.2 cm ha/ha plus 5.6 cm ha/ha on June 10, and then weekly irrigation to replace approximately 95% of ET beginning July 18 (40.6 cm ha/ha after planting). Water was applied through a trickle-irrigation system with orifices on a grid 30 x 30 cm. Evapotranspiration was calculated as the sum of rainfall, irrigation, and soil-water depletion. Water-use efficiency based upon ET (WUE_{ET}) was calculated as grain yield/unit of ET.

In order to determine the effect of N fertilizer on transpirational water-use efficiency (WUE_T) under field conditions, data were obtained for use in a model. These included data on soil water content, soil temperature, soil evaporation using microlysimeters, and leaf area index (LA) for the high-water, low-N, and high-N plots of MB9. These data, along with daily weather data, were used to calibrate the model. Leaf area index and soil water content were collected periodically on all plots and daily weather data for the entire season.

The sorghum breeding lines were MB9 and B35. They are of similar maturity but differ in drought and nutrient responses. The line B35 has the stay-green characteristic (post-flowering drought resistance), which MB9 does not, and MB9 yields well under low fertility and available-water conditions. Nitrogen levels were 0, 22, and 90 kg/ha, broadcast as urea before bedding.

The second study addressed Objective 2 and was conducted in minilysimeters in a rainout shelter at the TAMU Agricultural Research and Extension Center at Lubbock. The 75-liter minilysimeters were filled with a P-deficient Amarillo loamy fine sand. Treatments consisted of two sorghum genotypes of similar maturity grown on a factorial combination of four P levels and two water levels. The sorghum genotypes were the Malian sorghum CSM-63 and the improved TX 7078. The four P levels were 0, 20, 40, and 80 mg/kg of soil. The water levels were sufficient to bring the lysimeters to 50% and 100% of field capacity when 75% and 50% of the available water had been used, respectively. Water use was determined by periodic weighing. After two plants per lysimeterwere established, the soil surface was sealed to prevent evaporation. Plants, including roots, were harvested at black layer.

Results

Grain yields, evapotranspiration, water-use efficiency and nitrogen-use efficiency as affected by treatment and sorghum genotype are given in Table 1. Grain yields ranged from 2778 kg/ha to 7179 kg/ha for MB9 and from 1456 kg/ha to 5085 kg/ha for B35. Both sorghum lines produced their lowest yield at the lowest level of water and N, while highest yields were produced at the highest level of water and N. MB9 yield increased with increased water supply for each N rate; however, B35 responded to increased water only at the highest N level. The highest grain yield at the lowest water and N levels was produced by MB9, which did not respond to applied N at this water

level (W1). In contrast, B35 responded to applied N at the W1 water level and produced a statistically similar yield to MB9 at the 90 kg/ha rate. Grain yield of MB9 increased significantly with each increase in N application at the W2 and W3 water levels. Grain yield of B35 increased significantly with each increase in N rate at the W2 water level, as it did at the W1 water level, but produced a significant yield increase only at the 90 kg/ha N rate at the W3 water level. Thus, the grain-yield response between these two genotypes as related to N and water levels is very different. Evapotranspiration was generally independent of N rate and yield for MB9; however, at the low and moderate water levels, N applications increased ET for B35. Increased grain yields (and therefore N levels) resulted in increased WUE_{ET} with MB9 having much greater WUE_{ET} than B35 for any given treatment combination. However, the highest WUE_{ET} was not obtained at the highest grain yield but rather at the highest N rate at the moderate water level.

Calculations using a crop-growth model to determine the effects of N of WUE_T under field conditions are not complete. Preliminary results indicate a 31% decrease in evaporation due to a 62% increase in LAI with the application of 90 kg of N/ha at the high water level. This finding, coupled with a 100% increase in yield, indicates a potential increase in WUE_T due to N application.

Results from the minilysimeter study indicate that WUE_T was greatest for CSM-63 when total biomass produced was used as the basis for calculation, but was greatest for Tx 7078 when grain yield was used as the basis for calculation.

Total dry-matter production was positively and linearly related to transpiration ($R^2 = 0.95$) when data for all P levels and water levels were combined for both genotypes.

Table 1. The effect of nitrogen fertilizer and irrigation level on grain yield, evapotranspiration, and water-use efficiency of two grain sorghum breeding lines at the Texas Agricultural Experiment Station, Lubbock, Texas, 1988.

Irrigation Level	Sorghum Line	Fertilizer rate	Grain yield	ET	WUE Grain yield/ water used
		kg/ha	kg/ha	cm	(kg/ha cm)
W1	MB9	0-22-0	2778 ghi*	37.3 f	74.5 d
		22-22-0	3136 efg	37.6 f	83.4 d
		90-22-0	3058 fgh	37.8 f	80.9 d
	B35	0-22-0	1456 k	37.1 f	39.2 f
		22-22-0	2374 ij	40.6 e	58.5 e
		90-22-0	3158 efg	40.4 e	78.2 d
W2	MB9	0-22-0	3696 e	47.0 cd	78.6 d
		22-22-0	4469 d	48.3 c	92.5 c
		90-22-0	6608 b	49.0 c	134.8 a
	B35	0-22-0	1714 k	45.7 d	37.5 f
		22-22-0	2352 ij	47.0 cd	50.0 e
		90-22-0	4670 cd	48.5 c	96.3 c
W3	MB9	0-22-0	3573 ef	63.5 ab	56.3 e
		22-22-0	4659 cd	62.5 b	74.5 d
		90-22-0	7179 a	65.3 a	109.9 b
	B35	0-22-0	1949 jk	62.7 b	31.1 f
		22-22-0	2509 hij	63.2 b	39.7 f
		90-22-0	5085 c	63.8 ab	79.7 d

*Values followed by the same letter are not significantly different (0.05 Duncan's Multiple Range Test).

Phosphorus application increased WUE_T for both genotypes. Highest WUE_T was obtained at the lowest water level. A positive and linear relationship ($R^2 = 0.94$) was found between WUE_T and harvest index.

Conclusions

1) Grain sorghum genotypes vary in their responsiveness to applications of N and P fertilizer.

2) A three-way interaction exists among genotype, water level, and nutrient level for grain production of sorghum.

3) Evapotranspirational and transpirational water-use efficiencies of grain sorghum are affected by a three-way interaction among genotype, water level, and nutrient level.

Implications

1) Responsive sorghum types will be required to increase efficient use of limited supplies of avail able water by fertilizer application to nutrient de ficient soils.

2) Appropriate sorghum genotypes should be coupled with appropriate fertilizer applications to derive the maximum economic benefit from cultural practices designed to increase available soil water.

3) The relationship between WUE_T and harvest index should be investigated further for its potential to provide useful information to plant breeders.

Effects of Soil Phosphorus and Water Supply on Growth Analysis and Transpirational Water-Use Efficiency of Pearl Millet

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Arthur B. Onken, Texas Agricultural Experiment Station
Charles W. Wendt, Texas Agricultural Experiment Station
Robert J. Lascano, Texas Agricultural Experiment Station

It has been well-documented that nutrient deficiency and low, erratic water supply strongly influence pearl millet production in the Sahel. The interaction of soil nutrients, plant growth, and water-use efficiency is therefore of paramount importance. In Niger, scientists have observed a lack of millet response to nitrogen when no phosphorus is added. The interaction of soil phosphorus and water supply in this agronomic system must therefore be understood to stabilize and increase millet production.

Objectives

The objectives of this experiment were to observe the effects of water and phosphorus supply on 1) growth analysis of pearl millet under Sahelien-like conditions; and 2) transpirational water-use efficiency, defined gravimetrically and in terms of gas exchange.

Procedures

A field experiment using minilysimeters was conducted in Lubbock, Texas, which has a semiarid environment. Lysimeters were filled with 85 kg of Betis sand (Psammentic Paleustalf, sandy, silicious, thermic), which has physical, chemical, and mineralogical characteristics similar to those of sandy millet fields of Niger, Mali, and Senegal. Lysimeters received a blanket treatment of potassium (5.6 g of K_2SO_4) and nitrogen (a total of 31.1 g of NH_4NO_3 in three applications). An African variety of millet (ICTP 8203, provided by D. J. Andrews of Nebraska) was planted and thinned to two plants per container at seven days after emergence (DAE). Treatments consisted of four phosphorus doses (0.00, 0.16, 0.47, and 1.08 g P per container) and two water treatments (approximately 0.06 m^3/m^3 and 0.16 m^3/m^3 water content, i.e. stressed and nonstressed). Lysimeters were sealed so that water loss, which was determined using a load cell balance, was restricted to transpiration. Five pots from each treatment were harvested at two-week intervals beginning at 14 DAE for dry-matter analysis, for a total of six harvests. At each harvest, plants were separated into components for dry-matter analyses.

In a second experiment, pots containing 6.00 kg of Betis sand were treated with seven phosphorus doses (four replicates) ranging from 0.00 g to 0.931 g P/pot. After the seedlings were six days old, they were transferred to a

growth chamber with photosynthetically active radiation (PAR) set at 500 W/m³, temperature at 35°C day/25°C night, and relative humidity at about 40%. All pots were watered to a volumetric water content of 0.17 m³/m³ and covered to restrict water loss to evaporation. Transpiration was measured gravimetrically every two or three days. After weighing, pots were watered so as to achieve a soil-water content of 0.17 m³/m³. At 28 days after sowing (DAS), photosynthesis and transpiration rates were measured on the youngest/fully-expanded leaf using a calibrated infrared gas analyzer. Plants were harvested at 29 DAS, at which time dry-matter production and partitioning were determined.

Results

Total plant dry-matter accumulation (Figure 1) responded positively to P supply, with differences becoming most pronounced during the exponential growth phase. A substantial difference in dry-matter accumulation was also apparent between water treatments. For storage organs or heads (Figure 2), dry-matter accumulation appeared to be linear with time. Slope magnitude, however, differed with water and phosphorus treatments. Significant differences were also noted between water and phosphorus treatments for the other individual organs and dead material.

In the field experiment, transpirational water-use efficiency, defined as kg dry matter produced/L water transpired, responded to both phosphorus and water supply and also changed with time (Figure 3). Water stress increased transpirational water-use efficiency, whereas decreasing phosphorus supply decreased water-use efficiency.

In the growth-chamber experiment, decreasing phosphorus supply again was associated with decreased transpirational water-use efficiency on a gravimetric basis (date not shown). Gas-exchange measurements offer at least a partial physiological explanation for this observed phenomenon (Figure 4). As phosphorus supply decreases, specific transpiration remains relatively constant until deficiency is severe, at which point transpiration apparently increases. Photosynthesis, on the other hand, decreases rapidly as phosphorus deficiency becomes severe. The ratio of photosynthesis to transpiration provides another measure of water-use efficiency on a leaf gas exchange basis. Data in Figure 5 indicate that water-use efficiency, defined now in terms of gas exchange, decreases dramatically as phosphorus supply becomes low.

Conclusions

Gas-exchange data, along with leaf-mass data from the field experiment (data not shown), suggest that water will

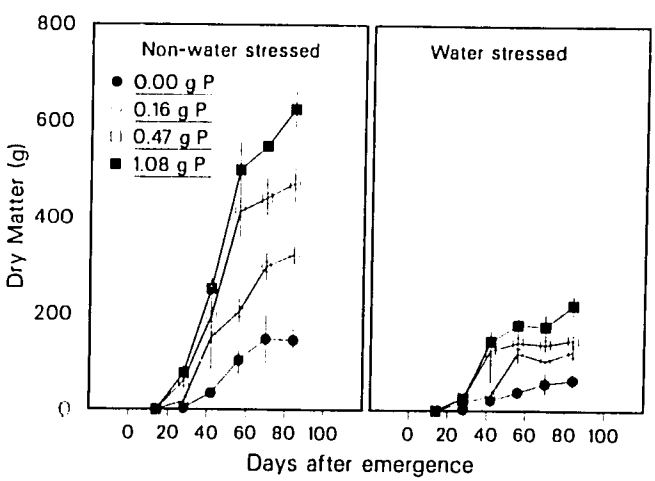

Figure 1. Total plant dry-matter accumulation of millet, Lubbock, Texas, 1988. Source: Payne, Wendt, Onken, and Lascano, 1990.

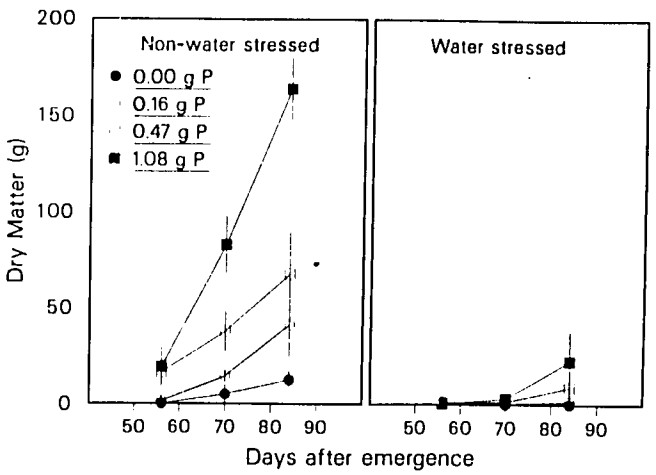

Figure 2. Head dry-matter accumulation of millet, Lubbock, Texas, 1988. Source: Payne, Wendt, Onken, and Lascano, 1990.

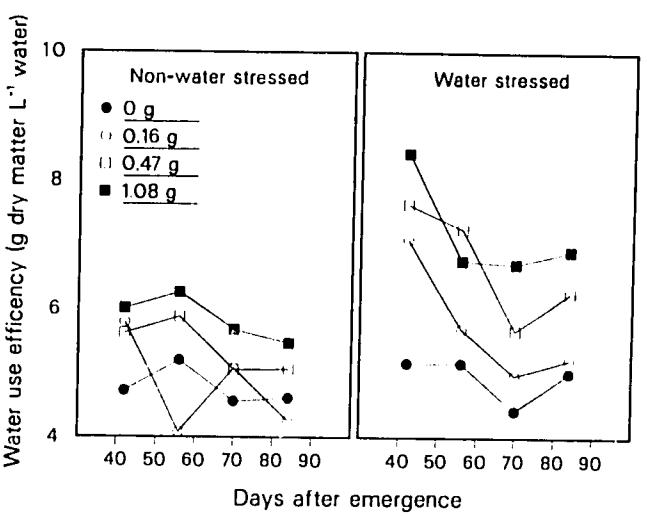

Figure 3. Transpirational water-use efficiency of millet as a function of time, Lubbock, Texas, 1988. Source: Payne, Wendt, Onken, and Lascano, 1990.

be used very inefficiently for growth in severely nutrient-deficient millet fields for two important reasons: 1) on a field basis, low leaf area will result from low fertility, resulting in greater evaporative loss from the soil; 2) on a plant basis, very little carbon is fixed per unit amount of water transpired under nutrient-deficient conditions. As a result, water-conservation measures that do not take into account fertility needs in phosphorus-deficient millet fields will not effectively raise millet production. Further, although data in this study reaffirm the importance of good water supply to millet growth and production, it is noted that relatively small phosphorus doses significantly increased total and head dry-matter accumulation even under water-stressed conditions.

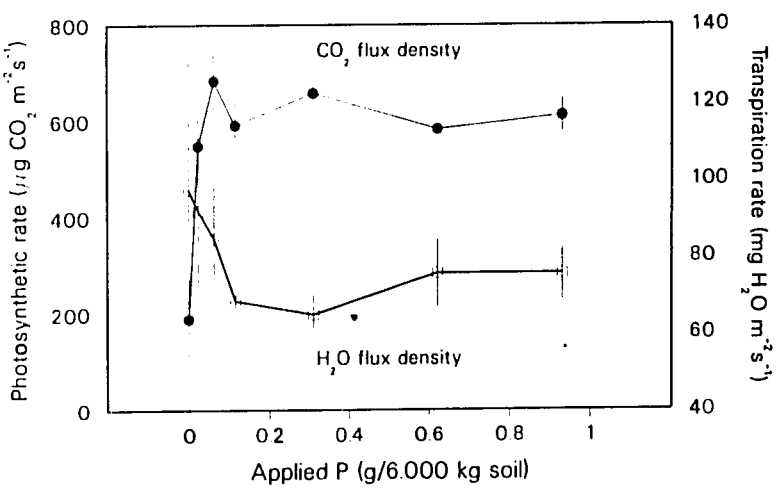

Figure 4. Leaf CO_2 and H_2O flux density in millet as a function of applied phosphorus, College Station, Texas, 1989. Source: Payne, Wendt, Onken, and Lascano, 1990.

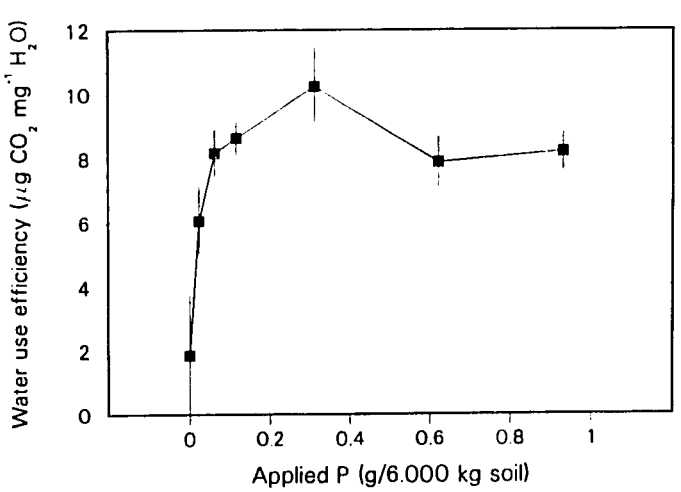

Figure 5. Leaf water-use efficiency in millet as a function of applied phosphorus, College Station, Texas, 1989. Source: Payne, Wendt, Onken, and Lascano, 1990.

3.
Outreach

Decision Support Systems: UH-4

The soil management knowledge base is large, but not effectively used by resource-poor farmers. Existing knowledge needs to be organized in a way that enables extension agents and policy makers to diagnose problems and prescribe solutions. Organizing what we know into a problem-solving product may also expose gaps in our knowledge and thus guide research priorities. Information organized in decision support systems also becomes our institutional memory. It helps us to avoid doing what has already been done and discovering what is already known.

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Decision Support Systems for Diagnosing and Recommending Economically Feasible, Farmer-Acceptable, and Environmentally Safe Soil-Management Practices: UH-4A

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Objectives

The objectives of this study are as follows: 1) to translate the exisiting ACID4 soil acidity expert system into Prolog with extensions of improved user interface, multiple-objective consultation, and preliminary natural language; 2) to test expert systems for managing soil acidity and soil phosphorus and evaluate performance and integrity relative to requirements and expectations; 3) to expand the interface between the soil data base and the expert system by increasing the soil information accessible to the expert system; 4) to incorporate learning capability into Prolog version of the expert system; and 5) to add output from TropSoils research into an expert system and provide feedback to researchers on critical information gaps.

Procedure

What are the Soil-Acidity Decision Support System (ADSS) and the Phosphorus Decision Support Systems (PDSS)?

The Soil-Acidity Decision Support System (formerly ACID4) and the Phosphorus Decision Support System are computer programs designed to turn knowledge about crops and soils into tools for diagnosing and evaluating the impact of soil acidity or phosphorus deficiency in a farmer's field or site. They enable the user to determine what corrective measures are needed and what economic consequences those measures will impose.

ADSS was initially developed for Center for Soils Research in Bogor, Indonesia, a collaborating partner of the TROPSOILS/Indonesia project. ADSS implements the Cochrane equation (Cochrane et al. 1980) as a way of determining how much aluminum (Al) in the soil needs to be neutralized with limestone in order to reduce Al toxicity so that the selected crop can produce its maximum yield. The amount of lime needed to neutralize the Al is, therefore, influenced by the crop tolerance to Al, the depth of incorporation, the quality of the limestone being used, and the amount of organic material added. An economic analysis is also performed; it compares the benefits of the probable yield increase from the lime application to the costs of the lime, its transport, distribution, and incorporation. ADSS is available in English and will soon be translated into Spanish.

The Phosphorus Decision Support System is designed to determine whether a phosphorus deficiency is likely and, if so, to estimate how much fertilizer P should be added to correct the deficiency. The diagnosis is made by comparing the levels of extractable soil P in field samples with estimated critical values for soils with similar texture and mineralogy. PDSS is in an early stage of development.

How do Soil ADSS and PDSS work?

ADDS and PDSS are a type of computer program formerly called "expert systems." This term was often misunderstood as an ambitious claim to excellence. Knowledge-based systems, to use more current terminology, are intended to emulate expert behaviour in diagnosing problems, suggesting solutions, and evaluating alternatives. Decision-support systems are typically more general aids that may be as simple as a small spreadsheet or as complex as a combined knowledge-based system and a mathematical simulation model.

Although knowledge-based systems can never be quite as expert as human experts, they can excel at certain kinds of tasks. For example, such systems can carry out mathematical calculations with speed, accuracy, and near perfect repeatability. The ability to recalculate complex calculations quickly and reliably helps users evaluate many management alternatives. Evaluating alternatives is one of the most important functions of the systems and has led to the term "decision-support," which indicates that decisions can now be made by choosing the most desirable of many possible consequences predicted by the computer system. It should be emphasized that the human must make the decision, and that the computer is the tool, not vice versa.

How are ADSS and PDSS structured?

ADSS is composed of the following modules: Soil database, Crop requirements, Management alternatives, and Economic analysis.

The Soil-Acidity Decision Support System structure is primarily a set of rules that are linked together in a manner similar to that used when reasoning logically. The rules are sequences of IF and THEN phrases, which operate by attempting to satisfy the IF conditions. If the

phrases in the IF part of the rule can be satisfied, then the conclusions and actions listed in the THEN part of the rule are considered true, and they are either shown to the user as conclusions, or they cause another computer program to run or other actions to occur.

The program looks at all possible conclusions and employs four methods to determine whether rules are true or false: 1) it uses already entered facts; 2) it uses already inferred conclusions; 3) it uses linked rules (e.g. IF a THEN b, IF b THEN c, IF c THEN d, IF d THEN e) to infer from facts already entered or conclusions already made; or 4) as a last resort, it directly asks the user. To use linked rules, the software attempts to determine whether the conditions of the IF part of the rules are true or false. After the program examines all rules and determines which are true and which are false, the conclusions are gathered and displayed to the user. More details on rule-based systems, semantic nets, frames, and object-oriented systems are available in the following texts: Waterman, 1986; Barrett and Jones, 1990.

Newer methods of inference are being intensely studied and are available in some systems (semantic nets, object-oriented structures, logic programming languages, and neural nets). Other methods are being explored to develop rules from a given s examples. This effort focuses on Objective 1-4 of the overall UH-4 project.

What criteria are used by ADSS?

As suggested earlier, the Cochrane equation provides a way to estimate the amount of lime needed to neutralize the extractable Al and thus reduce toxicity to a level tolerated by the specified plant. The equation is originally written as follows:

$$LR = 1.5*(Extral - (CAS/100 * ECEC)) \quad (1)$$

where LR is the lime requirement, Extral is the extractable Al (determined using *1N* KCl), CAS is the critical aluminum saturation (aluminum saturation in the soil at about 95% relative yield), and ECEC is effective cation-exchange capacity.

We have added to the equation several terms that express other variables used by the ADSS in modifying the lime requirement:

1) *Depth of incorporation:* If the lime is to be incorporated to a depth other than 15 cm, there should be a term such as (Depth/15), where "Depth" is the intended depth of incorporation.

2) *Bulk density:* Because there is a conversion from weight (cmol Al/kg or meq/100g) to volume (t/ha), the weight-to-volume conversion is needed. Where soil analyses are already so converted, this factor need not be considered.

3) *Lime quality:* The basic lime recommendation assumes high-quality limestone, both from a physical (100 percent smaller than 60 mesh) and chemical (100 percent calcium carbonate equivalent). The final recommendation is modified to reflect the quality of the limestone actually used. Currently, we are considering how the Ca and Mg content of the limestone could be used to estimate the level of Ca and Mg that would result in the soil after the applied limestone has reacted with the soil.

What sort of economic analysis will be employed?

The economic consequences of lime application are estimated by performing a partial budget analysis. This analysis compares the costs of lime and its application to the expected benefits. The cost of purchase, transportation, application, incorporation, and labor are considered in the anaysis. Benefits are those associated with the increase in yield predicted from the neutralization of aluminum and the reduction in aluminum saturation. Yield increases occurring from other benefits of liming are not currently included.

One of the more useful features of the economic analysis has been the inclusion of the residual effects of lime. This information helps researchers evaluate the economic consequences of lime applications (Gonzalez, 1979; Salinas and Sanchez, 1971). Until now, however, procedures for including residual effects in economic analyses have not been readily available to agronomists. In attempting to describe residual effects in the mathematical form used in an economic analysis, we have adopted an algorithm in ADSS (below). The approach represented in the algorithm is preliminary; however, the residual-effect values can be changed to reflect regional differences should such data be available.

The benefits of lime may be realized for several years as the lime continues to neutralize soil Al. The *prorated* lime cost option reduces lime cost for the current year in proportion to the expected residual effect. The other option (total cost) charges all current lime costs to the present cropping season. The latter option may reflect the subsistence farmer's situation: very limited cash is available for investment in lime.

The prorated cost is calculated by summing the effectiveness of the lime during each of five successive years. The effectiveness is expressed in terms of the amount of lime that would have been needed to reduce Al+H saturation to the observed value. This value was taken from field data of the TropSoils Project, Indonesia, for ground limestone, and Yurimaguas, Peru, for burnt lime (Dr. M. Wade, personal communication). The prorated cost also considers the interest on the initial lime investment when benefits are not received as long as five years. Compute the prorated cost as follows:

$$PT = 1 / (1 + 0.67*w + 0.45*w2 + 0.30*w3 + 0.20*w4) \quad (2)$$

where PT is the ratio of prorated cost to total cost. Total cost is the total cost of lime the first year. The terms w, w2, w3, and w4 are expressions of interest calculated as follows:

$$w = 1 / (1 + \text{interest} / \text{cost}) \quad (3)$$

where interest is the amount of interest and cost is the cost of lime. The terms w2, w3, and w4 are w*w, w*w*w, and w*w*w*w, respectively.

The above expression for PT is valid for ground lime and reflects the observation that about 1/3 is lost per year (Wade, personal communication 1985). Burnt limestone appears to have a shorter residual value and is calculated as follows:

$$PT = 1 / (1 + w + w2 + 0.50*w3 + 0.25*w4) \quad (4)$$

where the w's are the same as those above. This expression reflects the estimate that lime effectiveness does not seem to decrease markedly until years four and five. The data used for this estimate are only three-year data, so we are not sure of the later approximations, which, consequently, are rather conservative.

What modifications are being considered?

The Cochrane equation assumes a straight-line relationship between the lime added and the Al neutralized. This relationship is depicted in Figure 1. Data collected in Indonesia, however, suggests that some of the extractable Al is held more tightly, particularly the last few increments on the exchange complex (Wade et al., 1988). Aluminum held in this manner probably varies with sources of negative charge and the sources of the Al + H removed in the KCl extraction. Using the compulsive and exchange approach, Gillman and Sumner (1986) have described some extractable Al portions that are harder to exchange than others.

Another assumption in our use of the Cochrane equation is that there is a straight-line response from the critical value to zero relative yield at 100% Al saturation (Figure 2). However, many types of data do not show this response. Often, yields decrease at Al saturation levels greater than the critical Al saturation; however, where there are sufficient data, relative yields decrease more slowly than assumed in the initial equation (also shown in Figure 2 from Wade et al., 1988). As indicated in Figure 2, an extrapolation of the curve for relative yield of mungbean will reach 0% slightly before 60% aluminum saturation. Consequently, the straight-line estimate would underestimate mungbean response to lime. For rice, however, the straight-line interpolation between critical aluminum saturation and the point of 0% relative yield and 100% aluminum saturation will tend to overestimate the response to lime. A more accurate representation of these responses is needed, particularly because the slope of the response curve at Al saturatation levels above the

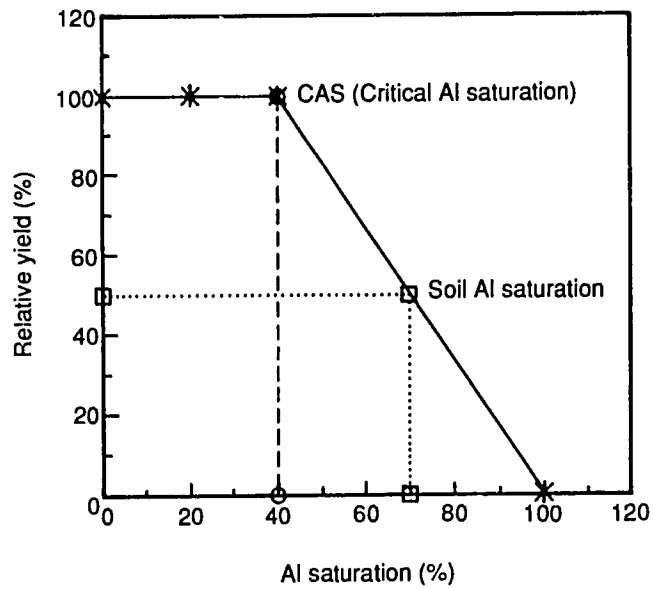

Figure 1. Adjusting soil Al saturation to crop needs.

critical level is crucial in estimating yield increases due to liming. One way to include such information would be to obtain the Al saturation at both 95% relative yield and at 50% relative yield (Figure 2). The additional point on the curve would permit substantially more accurate predictions of yield increases.

Eventually we would like to see more fundamental Al processes included, such as direct assessment of Ca availability in the soil solution and the interaction with phosphorus, and water availability due to restricted rooting as well as reduced access to subsoil nitrogen (Souza and Ritchey, 1985).

Using extractable Al to estimate the lime requirement has been extended to soils with less than 20% clay and those with more than 60% clay. Results of this approach have been compared with those of the "base saturation approach" (Quaggio, 1983). According to the latter, one seeks to determine the amount of bases that should be added to provide about 50% saturation (based on a CEC measured at pH 7.0), (Sousa et al., 1989). This approach gives lower lime requirement estimates than the extractable Al approach on soils with less than about 20% clay; it gives higher estimates of lime requirement than the extractable Al approach on soils with greater than 60% clay. Field studies show that lime requirement estimated from crop-response curves compares more favorably with the base-saturation approach than the extractable-Al approach for the extremes in texture. For intermediate textures, the two approaches give similar lime requirements (Sousa et al., 1989). These results need to be compared over a wider group of soil textures and mineralogies.

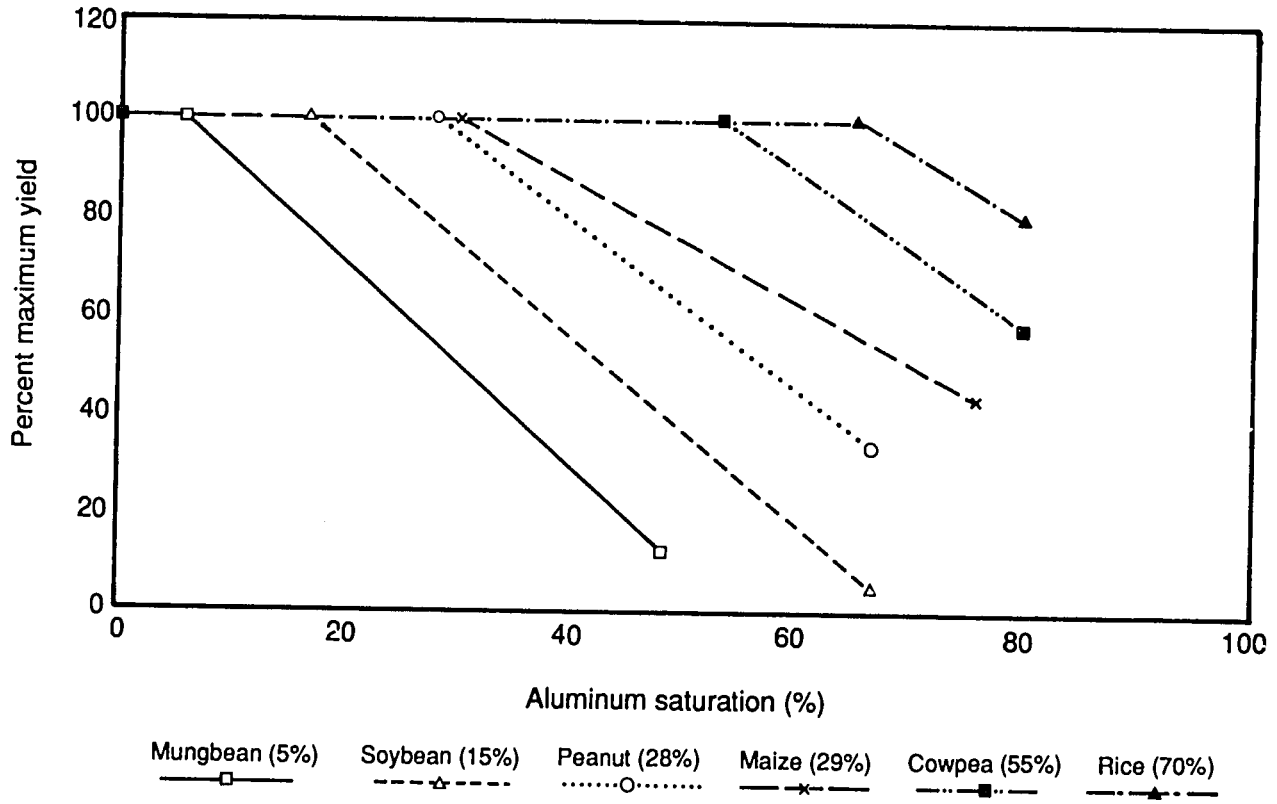

Figure 2. Acidity tolerance of crop plants.

We speculate that with soils of textures less than 20% clay, the ratio of KCl to extractable Al is far higher than that occurring with intermediate-textured soils, and thus relatively more Al is extracted. At clay percentages greater than 60%, we would similarly speculate that the ratio of KCl to Al surface would be less than that at intermediate texture and, hence, the procedure may not extract all the Al that might eventually react with added limestone. Again, this influence is highly speculative and needs closer examination.

Nonetheless, researchers need to consider more directly the Ca needed by the plant root to counteract the effects of Al toxicity, as well as the pH-increasing effect of the carbonate anion in the liming material. More accurate, process-reflecting approaches are needed for use in new decision-support software for the management of acid soils.

What criteria are used in PDSS?

PDSS, in contrast, is less well defined, conceptually. The approach being considered at this stage of development is a combination of diagnosis and recommendation based on soil tests.

The diagnosis step primarily compares critical soil-test values for various crops with values measured from a specific farmer's field. Another less reliable but often more available source of diagnostic information is the regional information, i.e., the likelihood of having deficiency in the region, soils, or under-cropping patterns in the region. For example, in Niger, if the field had not been previously cropped, we would predict a phosphorus deficiency, although with less confidence than with soil tests (Manu et al., 1989).

Critical levels are taken from Souza's tabulated values, which have been determined for soils of the Brazilian Cerrado. At present, the estimated critical levels for Mehlich 1, as influenced by % clay, are given in Table 1.

Similar values from Kang and Osiname (1979), for Mali and Niger, and Widjaja-adhi (1988), for Indoensia, are also included in the prototype PEX4.

Table 1. Interpretation of soil analysis results of the Mehlich 1 method: lime and fertilizer recommendations for soybean in the Cerrado (Portuguese).

Clay content	Soil P Level (Mehlich) Very low	Low	Medium	Good
%	ppm			
61–80	0–1.0	1.1–2.0	2.1–3.0	>3.0
41–60	0–3.0	3.1–6.0	6.1–8.1	>8.0
21–40	5.0	5.1–10.0	10.1–14.0	>14.0
0–20	0–6.0	6.1–12.0	12.1–18.0	>18.0

Source: Sousa D. M. G. 1989.

Estimates of critical levels are also given for the Bray 1 extractant. Attempts have been made to determine the equivalence among various extractants. Unfortunately, most studies that compare extractants do not provide sufficient characterization data to establish the range of surface area and surface reactivity necessary to group the soils with respect to sorption properties. In addition most comparisons of methods do not include field studies or field results. Data that provide estimates of critical levels for a range of soil textures and mineralogies are clearly needed for the development of the appropriate regression relationships so that critical levels can be interpolated to soils for which no field-determined critical levels are available. Such a tabulation of critical level with % clay on one axis and CEC/% clay (where CEC is determined by ammonium acetate pH 7) on the other axis would greatly assist efforts to extrapolate and generalize results from one field to another (Figure 3).

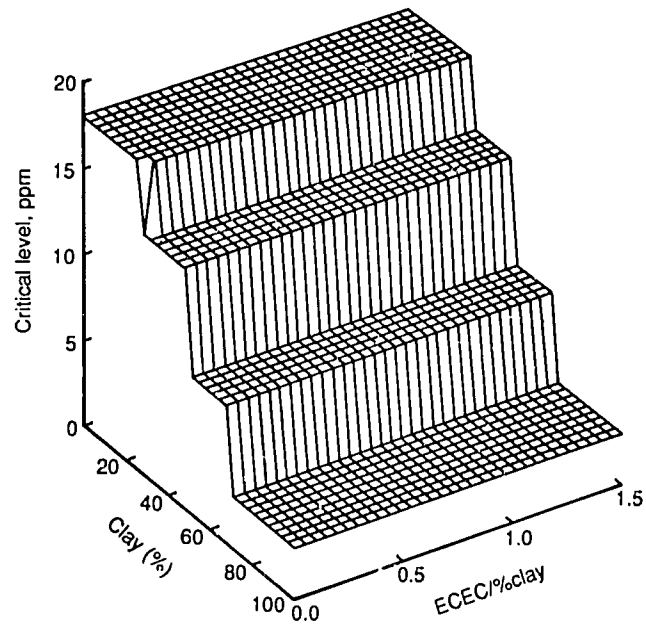

Figure 3. A tabulation of critical level with % clay on one axis and cation-exchange capacity/ % clay on the other.

Conclusion and Recommendation

If PDSS concludes that a phosphorus deficiency exists, then it will request soil texture as represented by % clay and either Mehlich 1 or 3 or Bray 1 extractants. This choice of extractant reflects the choices made by Lins and Cox (1989). The equation predicting the phosphorus requirement based on % clay and soil-test value is then used to estimate the basic phosphorus requirement. We will soon be adding the option whereby the user specifies the type of phosphate material available in the region so that the recommendation will be given in convenient units. Many other details remain to be organized and logically linked in this ongoing effort.

One of the major problems in assembling the P knowledge base has been that while estimates of critical values are similar for the same crop and the same extractant, the next step is difficult: one must use both the soil-test P values and the relation between P added and the critical value to predict the quantity of P needed to restore or increase soil test levels to the critical level. This problem is clearly reflected in diagnostic approaches that interpret soil-test data. In the Cate-Nelson approach, for example, the intent is primarily to provide a yes/no answer: is there or is there not a deficiency? Soil sorption of fertilizer P is a crucial issue, and predicting how P will react with the soil is central to successfully estimating the P requirement. We are considering P sorption as composed of two processes: (1) a factor related to the surface available for sorption and 2) the reactivity of the surface with the added phosphorus:

$$\text{P sorption (P reactivity)} = \text{area } (m^2) \times \text{reactivity } (mg\ P/m^2) \quad (5)$$

The most commonly available data that relate to surface area is % clay.

The second factor, surface reactivity, should reflect mineralogy. To estimate this factor, we are considering an index widely used in Soil Taxomony, clay activity (cation-exchange capacity per unit % clay), as represented by CEC/% clay (Soil Taxonomy, 1975). Other measures such as pH in NaF or oxalate extractable Al and Fe also need to be considered in order to indicate the quantity of short-range order minerals. In some cases, P's buffering capacity might be a more direct and more useful measure. The choice and possible use of this index is markedly influenced by the likely availability of data or by the cost of acquisition. Considering the former, we emphasize that data for such an index needs to be available for the field experiments where P responses are being measured as well as for new locations for which we seek to make recommendations. It is also clear that organic compounds modify surface reactivity; consequently, a readily available measure of that reactivity is needed. As useful measures are discovered for such phenomena, we hope to improve diagnosis and recommendations.

This brief description of the two decision support systems makes it clear that the conceptual framework for the phosphorus system is less well-developed mathematically than that of the nitrogen system. This is probably because the phosphorus fertilizer requirements, at least initially, reflect variations in the soil's sorption of P. Adequately describing P sorption by soils for site-specific recommendations requires detailed data.

Implications

Knowledge-based or decision support systems can be used in the following scenarios.

Diagnosis and Recommendation

The systems can be used (1) where the user is unfamiliar with the factors involved in making a diagnosis of a growth- or production-limiting condition, (2) where the user does not know how much amendment is needed to resolve a problem, (3) where the user is unaware of limitations or special precautions that should be exercised in intervening with applications or control measures, (4) where the user is not aware of the major cautions that should be exercised in interpreting field observations or data, and (5) in the case of the ADSS, when the user wishes to evaluate the profit of liming acid soil, the relationship between profit and liming materials of various quality, the impact of residual effects on profitability, the impact of crop selection on profit, or the impact of different soil types on profit.

Planning

Decision support systems can be useful for planning soil and crop management because they permit site-specific recommendations to be made. These recommendations require not only the decision support system but the on-site observations and local data needed to drive the decision aids.

As indicated above, in order to plan well, one needs to identify alternatives and describe their probable consequences. Decision support systems are one way to provide this information.

Evaluating Alternatives

A recent study at Purdue University indicated that users of expert systems evaluated more alternatives when using computer-based decision aids than when consulting with a human expert. Producers considered the decision aids more accessible than the human expert. Also, producers sometimes reported more confidence in the decision aid because they felt that the expert's personal bias had been taken out of the decision process (Smith, 1988).

The increased evaluation of alternatives emphasizes one of the major benefits of decision support systems: they explore the implications of different soil-management, cropping-management, and economic conditions so that farmers and planners can be prepared to act quickly when certain events occur—rather than missing opportunities or not being prepared for rapid action. Farming has always been fraught with risk. Being able to work through the consequences of various management scenarios with expert advice and doing so ahead of time can turn farming from a major gamble to a choice among thoroughly examined alternatives.

Improving the Quality of Soil Research

Well-designed decision aids can also improve the research process (Rauscher, 1987). If one assembles the information needed for the best possible diagnosis and recommendation, weak links in the rationale will often become apparent. The weak links may include (1) inadequate knowledge of which factors reduce yield, (2) an inadequate algorithm to relate the identified factors, (3) site-specific empirical measurements that cannot be generalized, (4) insufficient data due to the high cost of measurement or inadequate infrastructure, or (5) faulty logic in relating the information.

Ways Network Members Might Use the Decision Aids

Network members can best determine possible benefits from the use of decision aids. Certainly a comparison of diagnoses and consequent recommendations from the decision aids described herein could be compared with network trials and field results. We would encourage such comparisons and would be especially pleased to discuss the results, particularly when the decision-aid predictions do not fit or agree with the field results. We recognize that decision aids are incomplete and that additional details or changes in approach may be needed. An ideal time to discuss such changes would be during the regular network visits. Articles might also be published in the network newsletter to share with other members.

In some cases, local conditions and situations cannot be entered into the decision aid because of certain assumptions about the cropping or farming system. In such cases, we would like to discuss the problems and try to modify the software to reduce such difficulties in future releases.

Appendix

What follows are suggestions for adding your own dBASE III file into the ADSS DB. Note that in this description capital letters refer either to programs or variables in dBASE III.

1) To add your own dBASE III files into the ADSS DB without changing the linkage between the expert system and the DB files, you must use the same format on the new DB files as on the existing files. By using the COPY STRUCTURE command in dBASE III, you can easily set up a new data base file, say ABCDE.DBF, from any of the existing DB files EXCEPT the file SMAP3.DBF.

Next enter the data into ABCDE.DBF. In ADSS DB, each pedon has no more than three layers, the depths of which are 0 to 15, 15 to 30, and 30 to 45 cm, respectively. All numeric data should be depth-normalized (meaning an average value calculated for each 15 centimeters). Each pedon must have a unique name: IDPED (used as the database 'key'). SSNAME's are the Soil Series names

which will be displayed to indicate the location. You can assign your own names to this dBASE field. The TXOSGG are the taxonomy codes used by the Soil Conservation Service (SCS) USA (see TX.DAT for the list). You may fill the field with word 'blank' if you do not have the code.

For the numeric data, values of '-3' or '-3.0' indicate missing data. The naming of all fields follows exactly the convention of SCS. Among other data, the SNCFIP2, OC, N, P, PHSP, PHNAF, PSORP, IDSAM can just be blanks if there are no such data available.

2) Create an ASCII file ABCDE.CAT with the SSNAME and IDPED values already specified in the ABCDE.DBF. Use one line per pedon. This file, as all other .CAT files, serves as the catalog file.

3) Find the log file CAT.DAT. Add the following line into the file:

'3 Continent $1 New Country/Area Name $b:abcde.dbf $b:abcde.cat$'

You may use your own words or descriptions for "Continent," " New Country/Area Name," while B:abcde.dbf tells the system where the soil database file is stored and its file name. Make sure the fields are separated by $.

4) Run the whole system.

Decision Support Systems for Diagnosing and Recommending Economically Feasible, Farmer-Acceptable, and Environmentally Safe, Soil-Management Practices: UH-4B

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Objectives

The objectives of this study are as follows: 1) to translate the exisiting ACID4 soil acidity expert system into Prolog with extensions of improved user interface, multiple-objective consultation, and preliminary natural language; 2) to test expert systems for managing soil acidity and soil phosphorus and evaluate performance and integrity relative to requirements and expectations; 3) to expand the interface between the soil data base and the expert system by increasing the soil information accessible to the expert system; 4) to incorporate learning capability into Prolog version of the expert system; and 5) to add output from TropSoils research into an expert system and provide feedback to researchers on critical information gaps.

Procedure

Since 1983, TropSoils Indonesia has conducted a field research program aimed at overcoming severe soil acid and fertility constraints in Sitiung, West Sumatera, a transmigration area. The goal of the research program is to make sustained production of basic food crops possible in the transmigration area (TropSoils Bulletin No.88-01, 1988, p. 3).

In order to extend the results of the research program to the farmer and extension community, a complementary effort within TropSoils Indonesia was undertaken from March 1989 to February 1990. This effort was termed the Outreach Project.

The Outreach Project focused on twin problems: how to convert scientific knowledge and research findings into improved agricultural practices useful to resource-poor farm families and how to keep such families informed of

improved agricultural practices. The Outreach Project addressed these problems by engaging extension to build a continuum between researchers and farm families. This outreach effort focuses on Objective 5 of the overall UH-4 project.

The following outlines the overall strategy for implementation of the Outreach Project.

1) Develop an understanding of the existing research-extension-farmer continuum in West Sumatera.
2) Develop collaborative working relationships with organizations and people in the system.
3) Identify potential improved agricultural practices for dissemination through the Outreach Project.
4) Develop an understanding of farmers' current practices relative to these improved agricultural practices.
5) Center Outreach activities on on-farm "outreach plots" to be managed by farmers and by extension research personnel. These plots are to be collaboratively designed to validate improved agricultural practices and to provide training and information-dissemination opportunities for extension and farmers.
6) Initially assess the role of Decision-Support Systems in Outreach efforts.

Results

The following discussion is organized by highlighting procedures used and results obtained as a result of carrying out each of the strategies listed above.

The Research-Extension-Farmer Continuum

Information-seeking meetings were held with key actors in research, extension, and the farming community at the Central, Provincial, District, and Subdistrict levels; and appropriate documents were identified and reviewed. This resulted in a working document developed for use in the field; it identified people and organizations to involve in Outreach efforts.

Collaborative Working Relationships

After understanding who to involve, Outreach obtained very close collaboration with the extension system and with farmers in general. Outreach collaborated primarily with one local Rural Extension Center, the home-base of field-level extension agents. Other research institutions collaborated in Outreach field plots and activities.

Identification of Improved Agricultural Practices

Several working meetings were held with staff from both a local research institution and from TropSoils. The following practices were identified and provided the primary focus of Outreach efforts:

1) amount and depth of lime incorporation,
2) alternative methods for establishing lime recomendations, including decision support system Acid4, on-site scientists' expertise, field histories, and pH meters,
3) phosphorous and/or lime and phosphorous interaction,
4) improved soybean seed,
5) spacing and planting methods for soybeans.

Other practices were identified. Specific supporting data on these practices were limited. Thus, these practices were not thoroughly incorporated into Outreach efforts:

1) soil-management practices related to timing of application and depth of fertilizer incorporation, particularly TSP and animal manure;
2) amount and method of application of animal manure;
3) inclusion of grasses in the farming system for sloping areas and contouring purposes; and
4) seed growers' production of improved seed for sale.

Farmer Practices Related to Improved Agricultural Practices

Several limited studies of farmer practices and constraints to adoption of improved agricultural technologies were completed. Methods included focus-group interviews, survey questionnaires, and farmer group discussions.

Focus-group interviews

Results from Focus Group Interviews conducted with 19 contact farmers from three Rural Extension Centers showed the following respondent characteristics:

Transmigrant/indigenous farmers: 15 of 19 farmers interviewed were transmigrant farmers; the remaining 4 were born in Sumatra.

Age: The youngest respondent was 30, the oldest 59. The average age was 45; the standard deviation was 7 years.

Household size: There were between 3 and 11 people in the respondents' households. The average was 6, with a standard deviation of 2.

Land in food crops: The respondents had a mode and average of one hectare of land in food crops. The minimum was 1/16 ha and the maximum was 2.5 ha. The standard deviation was about .5 ha.

Respondents use of inputs for food crops: Of 18 farmers responding, 16 had previously applied lime to their fields; 8 had applied organic manure to their fields; 15 had applied chemical fertilizers.

Only one of the responding farmers had previously purchased lime (300 kgs). All other respondents reported having applied lime that was provided through the government program.

When queried about the relative importance of lime in increasing food-crop production, respondents generally identified it as less important than NPK, pesticides, capital, and management ability.

Survey questionnaire: farmer liming practices
To further explore liming practices in the Sitiung area, a survey questionnaire was administered to 31 farmers who attended one of our field days. Results of the survey questionnaire follow.

Of 30 farmers responding, over four-fifths indicated that they had previously applied lime to their fields. Of 21 farmers providing data, the large majority indicated they had previously applied between 3 and 3.9 t/ha of lime to their fields. The majority of these had applied lime in 1983 or 1984.

Of the 25 farmers who indicated they had previously applied lime, 80% reported that, in their opinion, they needed to apply it again.

Farmers were asked if, in their opinions, lime increased the productivity of their fields. Of 19 farmers responding, 17 (almost 90%) reported increased productivity. Two farmers reported no increase in productivity.

In order to understand farmer perception of the residual effect of lime on productivity, farmers who indicated they observed increased productivity were asked to indicate how many cropping-seasons of improved productivity they observed on land where they had applied lime: one-half of the farmers reported increased productivity for two subsequent cropping-seasons after the initial lime application. The remaining one-half were about equally split between increases seen in one and three subsequent cropping-seasons.

Informal conversations with farmers suggest that they were interested in knowing how much lime they should currently apply to those fields limed three to five years ago. Farmers also informally and in general advise that the availability of lime for purchase and ease of purchase, the purchase cost, and problems with transporting lime to fields were constraints to their future use of lime. The recurring theme was that farmers are awaiting the government's help in supplying lime.

Survey questionnaire: extension perceptions of farmer practice relative to use of TSP
Area extension agents were asked to respond to a survey questionnaire about their perceptions of farmer practices relative to the application of TSP. Earlier discussions had identified possible differences between farmer practice and recommended practice for TSP application. The recommended practice is to broadcast and incorporate TSP two to three days before planting palawija crops.

Results of the survey, based on responses from 43 extension agents, suggest that, of farmers that extension agents know, about one-half apply TSP to food crops *before* planting, and the remaining one-half apply *after* planting. Of those that apply TSP before planting, about one-half broadcast and then incorporate. The remaining one-half broadcast without incorporating. Of those that apply TSP after planting, about one-third broadcast and then incorporate. The remaining two-thirds, broadcast without incorporating.

For the group of farmers that extension agents know, about three-fourths do not seem to follow the recommended practice for applying.

Farmer group discussions: farmer-perceived constraints to adopting improved soybean production practices
The following summarizes data gathered through farmer group discussion. At a field day, farmers were asked to collectively identify, write-down, and discuss those problems and constraints they felt inhibited their use of improved agricultural practices for soybean production.

Major problems/constraints identified by farmers were the following:

A) Obtaining the recommended inputs was difficult because they were not available for purchase in their village or because producers lacked the money to purchase them or because of difficulties in purchasing from the local government-sponsored cooperative. Inputs particularly difficult to obtain were improved seed, lime, and organic manure. In the last case, farmers noted that there are few animals in their area—hence the difficulty.

B) Transportation for inputs/harvests to and from their area is too expensive.

C) Producers are uncertain about the different recommendations (e.g., amount, time of application, method of application). Specific questions were asked about method of inoculation and timing of application of TSP plus broadcasting versus incorporating TSP.

D) Too much time is required to plant in rows. Some farmers said they thought it might be easier to weed/spray the rows. They added, however, that while these activities could be completed over time (thus lessening the need for labor at one specific time), planting needed to be completed within one day and, thus, could not be spread over time.

E) Management of soybeans is time-consuming. Farmers pointed out that soybeans require a lot of attention and that they have other competing demands on their time. They also noted the lack of available labor (or the money to hire workers) as a constraint.

F) Soybeans frequently have a number of pests and diseases. Such concerns were mentioned as contributing to the time and money required for properly managing soybean production.

G) The farmers were uncertain about the best time to plant. Farmers appeared to think this was an important problem, noting that not everyone planted at the same time.

H) Farmers were concerned about whether they could make a profit. Concerns were raised about previous experiences in which good soybean harvests were followed by a drop in market prices. Additionally, when farmers were asked if they "usually" made a profit on soybeans, much good-natured laughter and discussion preceded their final, tentative, answer of "sometimes."

Outreach Plots and Related Training

Outreach plots

Three Outreach Plots were collaboratively designed, installed, maintained, and harvested by research, extension, and farmer participants. All plots were located on the collaborating farmers' fields. All plots were planted with soybeans, and included lime as a treatment variable. The Decision Support System, Acid4, was used to determine lime recommendations. Other variables (details of which are included in Appendix A) included a comparison of farmer-stored seed and improved seed; an analysis of lime and TSP interaction; a comparison of a farmer-package of production methods and a recommended-package of production methods. Farmer-perception of the treatment variables was of primary interest in all Outreach Plots. A questionnaire was developed to obtain systematic feedback from farmers about their perceptions of the improved agricultural practices shown on their fields. Additionally, there were numerous informal conversations with farmers, focusing on this aspect of Outreach Plots. A qualitative summary of participating farmers' perceptions follows.

Farmer A's perception was that applying lime together with TSP resulted in better production than applying lime or TSP alone. He also said that the improved seed resulted in better production than did the seed he previously stored.

Farmer B suggested that as the amount of lime applied to his field increased, so did his production. He also felt that the seed he stored resulted in better production than did the improved seed.

Farmer C's perception of the effect of lime on production was not clear. He viewed production from improved seed as better than production from seed he had previously stored. He observed that production from the package of recommended practices was better than production from his package of practices.

These perceptions are generally supported by production data reported in Appendix A.

Related training

To support Outreach Plots, in-service training for extension agents and field days for farmers, researchers, and extension agents were held. Area farmers and staff from TropSoils, local research institutions, and local rural extension centers presented and participated in Outreach training activities.

Eight formal one-half to one-day training workshops, each attended by about 15 extension staff from BPP Sitiung, were conducted. Workshops included in-class instruction and field visits to Outreach Plots. Individual Workshop sessions focused on technical aspects of Outreach Plots or on the educational aspects of using Outreach Plots in extension programs.

Two farmer field days were held; both field days focused on Outreach Plots. Participating farmers visited the Plots and discussed the improved agricultural practices. Extension staff were critically involved in planning and implementing these field days. A total of 133 people attended.

In order to strengthen the working relationships between research and extension, an Information Day was held to apprise area extension staff of ongoing research work at TropSoils and a local research institution. About 50 extension staff from three Rural Extension Centers in the area participated in the day's activities, touring both research stations.

Assessing Decision Support System

The Decision Support System, Acid4, was initially assessed by using Acid4 to determine lime recommendations for Outreach Plots. Validation of the lime recommendations obtained and used in Outreach Plots was not accomplished. Rather, use of Acid4 raised the following question: toward which users, located where, should the system be targeted? The infrastructure required to use Acid4—such as a good soil analysis laboratory, a dependable source of electricity, and computer-literate users—in part, defines its potential users.

Conclusions and Implications

The above demonstrates that the Outreach Project did build on the research-extension-farmer continuum and that it did increase the flow of information within the continuum. The extent to which Outreach strengthened the continuum and the effect of an increased flow of information on the behavior of people in the continuum are not known. Obtaining this knowledge requires a larger, lengthier effort.

The above report supports the tentative conclusion that the constraints faced by Sitiung farmers may override their willingness to utilize much of the available technology or improved agricultural practices. This bottleneck must be addressed.

In what ways might the technology itself be better adapted to the situation, and/or in what ways might the existing situation be altered? In the case of liming, the

data show that a majority of farmers contacted had already used lime and that they may not have perceived liming as a major overriding problem. Implications include structuring a research orientation that focuses most closely on farmer-perceived problems and that develops stronger ties to policy-makers who are willing to effect changes that will address constraints farmers face in adopting improved technologies.

Farmers are continually faced with the task of allocating time and resources to efforts that are likely to produce desired results. The results, however, often depend as much on weather and other uncontrolled factors as on the application of lime or fertilizer. Thus, to assess the true benefits of lime or fertilizer, the recommended practice should be tested over many years to expose hidden dangers and benefits which one or two years of on-farm trial cannot reveal. One way to subject recommended practice to long-term testing is to do so *ex ante* through simulation. In this way, innovations can be rapidly screened so that only the most promising options are recommended for on-farm testing.

Appendix
Outreach Plots

Field Design #1
Outreach Plot
Farmer: Pak Lardi
Location: Sitiung I, Blok C
Extension Worker: Yunida
Rural Extension Center: Sitiung
Planting Date: August 30, 1989
Harvest Date: November 27, 1989
Collaborators: Farmer/Extension/SARIF/TropSoils

8 m

#5 0 lime 100 kg/ha TSP Farmer seed: Orba	#6 0 lime 0 TSP Farmer seed: Orba	#7 200 kg/ha lime 100 kg/ha TSP Farmer seed: Orba	#8 0 lime 0 TSP Farmer seed: Orba	7.5 m
#1 Lime and TSP same as above but Improved seed: Kerinici	#2 Lime and TSP same as above but Improved seed: Kerinici	#3 Lime and TSP same as above but Improved seed: Kerinici	#4 Lime and TSP same as above but Improved seed: Kerinici	7.5 m

8 m

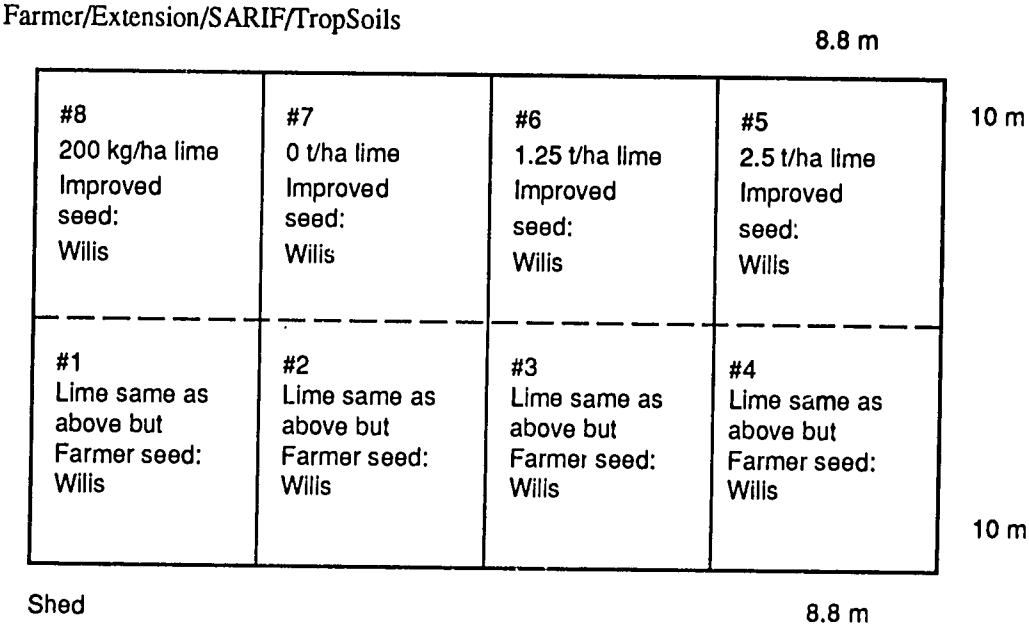
Land preparation: Farmer prepared land using cow/plow.
Other fertilizer added: Farmer added approximately 1 t/ha cow manure before planting to all treatments.
Total area of this field: 480 m^2, about 1/20 ha.
Planting distance: All planted in rows at 40 x 10 cm, 2 seeds per hole.

- In plots (1, 3, 5, 7) where TSP was applied, TSP was broadcasted and then hoed-in.
- In plots (3, 4, 7, 8) where lime was applied, furrows were opened to between 10–12 cm lime was applied. Furrows were covered up. Seeds were planted on furrow line.
- Dibble-sticks were used for planting.
- Curator was applied at planting with seed.

Yield Data: Field Design #1
Yield data should be interpreted with caution. Estimating production per hectare from harvest data taken from small plots results in per-hectare production figures that are imprecise.

Plot #	*t/ha*
1	1.025
2	0.912
3	1.313
4	1.185
5	0.576
6	0.598
7	0.551
8	0.570

Field Design #2
Outreach Plot
Farmer and Location: Pak Sampan, Sitiung I Blok C
Extension Worker: Yunida
Rural Extension Center: Sitiung
Planting Date: September 9, 1989
Harvest Date: December 8, 1989
Collaborators: Farmer/Extension/SARIF/TropSoils



Land preparation: Farmer initially prepared land. On September 5, work crew added lime and hoed entire field to about 7 to 10 cm.

Other fertilizer added: Farmer provided approximately 2.8 t/ha cow manure for all treatments; manure was incorporated at time of final land preparation (September 5). NPK was not added to any treatments.

Total area of this field: 704 m2, about 1/14 ha.

Planting distance: All planted in rows at 40 x 15 cm, 2 seeds per hole.

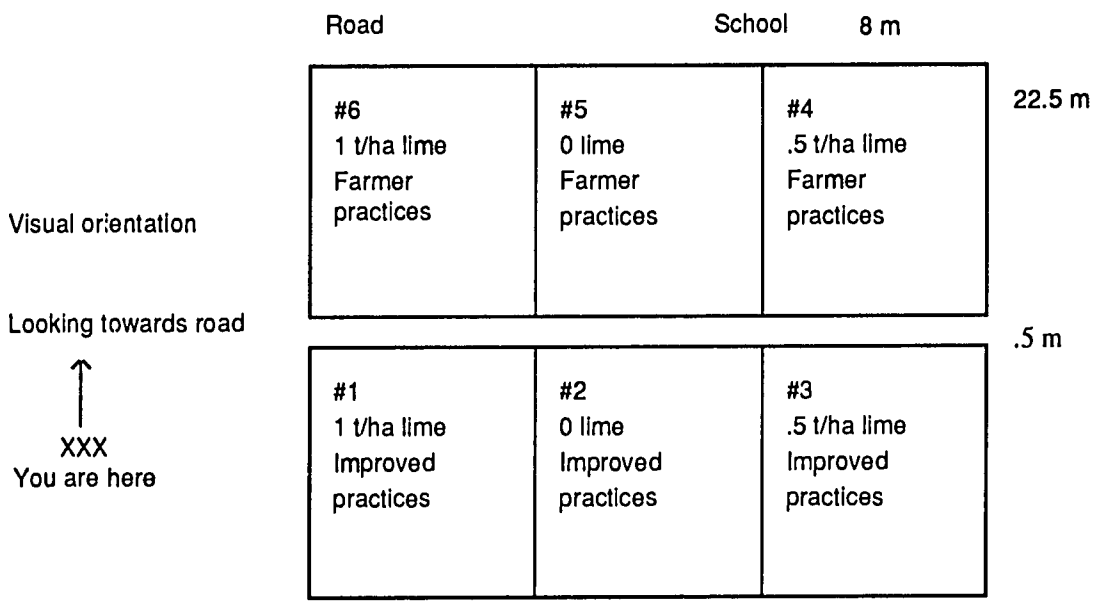
Method of application of lime: For plots (3, 4, 5, 6) where 1.25 t/ha or 2.5 t/ha lime added, broadcasted by hand and hoed-in. For plots (1, 8) where 200 kg/ha lime added, banded lime by hand about 15cm (width of band) on top of soil, hoed in to about 10 cm.

• Dibble-sticks were used for planting. Field all planted in rows. Curator was applied at planting with seed.

Yield Data Field Design #2
Yield data should be interpreted with caution. Estimating production per hectare from harvest data taken from small plots results in per-hectare production figures that are imprecise.

Plot #	*Tons/ha*
1	0.355
2	0.295
3	0.909
4	1.281
5	0.994
6	0.653
7	0.127
8	0.295

Field Design #3
Outreach Plot
Farmer: Pak Semin
Location: Sitiung V, Blok C
Extension Worker: Pak Amdi
Rural Extension Center: Sitiung
Planting Date: October 5, 1989
Collaborators: Farmer/Extension/SARIF/TropSoils



Crop: Soybeans.
Plot size: Each 22.5m x 8m; area of Petak Pengalaman = 1092m^2; approximately 1/10 ha.
Liming: Farmer advised this field had not been previously limed. Lime recommendation was computed, based on results of soil sample analysis from three sections of the field, using Acid 4. Sample results showed high variability; thus, the average lime recommendation (1 t/ha) was selected as the recommended rate.
Improved practices: Recommended doses from extension of NPK: Urea = 25 kg/ha; TSP = 100 kg/ha; KCL = 50kg/ha. Recommended doses from SARIF of cow manure: 2 t/

ha. Recommended seed from SARIF: Orba; planted in rows 40 x 10cm, 2 seeds per hole, with dibble-stick, applied Curator at planting in seed holes. Recommended spraying schedule and dosage from SARIF.

Farmer practices: Seed: locally-purchased mixed-seed (Galunggung, Wilis, Orba); planted according to farmer method with dibble-sticks using farmer spacing of about 25 cm x 17.5cm, 2 to 3 seeds per hole, and adding Curator mixed with cow manure to each seed hole at planting. Farmer added about 1 1/3 t/ha cow manure to farmer practice treatments. All other inputs and practices determined and provided by farmer.

Field measurement and layout: Completed September 26.

On all treatments, broadcasted lime and incorporated to about 10 cm; additionally, on improved practice treatments, broadcasted cow manure and incorporated along with lime; hoed control plots. Completed September 28.

On improved practice treatments, broadcasted NPK and incorporated to about 7 to 10 cm: Completed October 3.

Planting: Completed October 5.

Yield Data Field Design #3

Yield data should be interpreted with caution. Estimating production per hectare from harvest data taken from small plots results in per hectare production figures that are imprecise.

Plot #	*Tons/ha*
1 + 2 + 3	0.491
4 + 5 + 6	0.217

Note: A very preliminary economic analysis, excluding labor costs, was conducted on the profitability of the three Outreach Plots. Further study is required but the imprecise data available suggest that it was not always profitable for farmers to purchase the inputs required to increase their yields.

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Technical Support for Research Networks in the Humid Tropics: NC-8

Technical Support To Research Networks: Y-700

Thomas Jot Smyth

Approach

Many key components of soil-management options can now be transferred to national institutions for validation and extrapolation across the humid tropics. National institution involvement is important for several reasons: 1) available resources limit the extent to which TropSoils alone can systematically validate developed technology; 2) if developed technology is to be used, information must be disseminated, and local soil-management expertise must be acquired; and 3) feedback to TropSoils from its eventual users will enhance TropSoils' ability to develop agronomically and economically sound soil-management practices through refinements or modifications of ongoing research.

Attempts to perform such technology transfer require a minimum level of on-site expertise in participating national institutions and an organizational framework conducive to and supportive of systematic evaluations of their results. Research networks are an effective means for both tapping personnel resources and providing useful training to scientists in collaborating countries.

Throughout the humid tropics, several soil-management networks at various stages of development are fostering technology transferral, validation, and extrapolation with emphasis on specific research areas. A Latin American tropical soil-management research network (named RISTROP for *Red de Investigación en Suelos Tropicales*) was developed by participants of a training workshop conducted by North Carolina State University at Yurimaguas during 1986. RISTROP now operates in eight Latin American countries with network experiments in low-input systems, mechanized continuous cropping, agroforestry, legume-based pastures, and paddy rice. Network coordination and technical backstopping support are provided by NCSU/TropSoils.

The Tropical Soil Biology and Fertility (TSBF) network initiated the research phase after its third workshop, held in Yurimaguas during 1986. The TSBF network focuses on the role of soil biological processes in tropical soil fertility. The research program is based on four major themes: 1) synchrony of decomposition processes with plant growth demands, 2) soil organic-matter management, 3) soil-water relations in natural and managed systems, and 4) socioeconomic characteristics of traditional and improved management systems. Research was initiated in late 1986 at program centers selected on the basis of their commitment to perform a set of measurements by standardized procedures on natural and managed ecosystems. Current centers are in Australia, Cote d'Ivoire, Peru (Yurimaguas), Puerto Rico, Sri Lanka, Venezuela, Zimbabwe, Zambia, Malawi, Uganda, Rwanda, Tanzania, and Kenya.

Since its creation in 1983, the International Board for Soil Research and Management, Inc. (IBSRAM) has sought to promote the development and utilization of sustainable soil-management technologies in developing countries as a means of removing constraints to food production. IBSRAM's emphasis on acid tropical soils is a result of their large geographical concentration in the humid tropics and savannas of the least-developed countries. After several workshops and regional meetings on acid soils in Latin America, Africa, and Asia, regional research networks were developed among countries in Africa and Asia. Two types of network studies have been developed: core experiments, designed to compare alternative management options for acid tropical soils; and component research projects, focusing on liming, germplasm screening for soil constraints, residual fertilizer-P effects, quality of organic inputs, and fertility capability classification. National cooperators in Africa have expressed concern for improving the tropical soil-management expertise of scientists who would conduct such investigations. Consequently, IBSRAM was encouraged to develop training courses which would expose front-line scientists in participating African countries to recent research advances in the management of acid tropical soils.

The goal of this project is to help transfer TropSoils' knowledge of acid soil management to national research institutions already participating in research networks in humid tropical regions. In so doing, the project makes the result of CRSP-sponsored research available to national research institutions. The specific objectives are as follows: 1) to help personnel at network-collaborating national research institutions conduct, interpret, and report user-oriented soil-management research; and 2) to systematically validate and extrapolate available soil-management technologies to regions beyond TropSoils' primary research sites.

This project involves major institutional and financial collaboration. Supplementing TropSoils' CRSP input, the RISTROP network is directly supported by national institutions and their donor agencies in 11 Latin American countries, plus a grant for small activities from AID/S&T. TSBF activities were supported by various donors. The Yurimaguas African workshop, a joint effort of TropSoils, TSBF, and IBSRAM, was supported primarily by a grant from the Rockefeller Foundation to North Carolina State University.

This report describes the activities in which NCSU personnel played a lead role. Additional information is available in the TSBF and IBSRAM reports.

Summary of Results

After four years of operation, the RISTROP network is producing positive results and has expanded to 15 countries in Latin America. Site-specific adaptations in each country ensure the realistic transfer of technologies.

The link between soil-management research in Africa and South America has effectively been established by the Yurimaguas African workshop and follow-up activities. TSBF and IBSRAM have been established (with African scientists trained in Yurimaguas) in Zimbabwe, Zambia, Madagascary, Uganda, Rwanda, Kenya, Côte d'Ivoire, and Guinée. Continued participation of TropSoils personnel in the TSBF African network provides follow-up advice and, in the case of Zimbabwe and Zambia, direct collaborative research.

RISTROP Network Follow-up: Y-770

Thomas Jot Smyth, N.C. State University

RISTROP *(Red de Investigación de Suelos Tropicales)* was created in 1986 by the 31 scientists from 15 national institutions in ten Latin American countries attending the soil-management workshop in Yurimaguas, Peru. The network's primary objective is to help transfer and validate improved soil-management technologies throughout tropical Latin America. Network collaborators obtain local support for their research, and NCSU provides the central coordination and technical backstopping.

The locations of ongoing field experiments and the national institutions collaborating with RISTROP are shown in Figure 1. The research topics and collaborators for each experiment are enumerated in Table 1. Ongoing network activities are based on the direct collaboration of 27 scientists distributed among eight Latin American countries. Investigations include local evaluations of the Soil Fertility Capability Classification (FCC) system or validation of technologies in five different soil-management options: low-input cropping with acid-tolerant species, mechanized continuous cropping, agroforestry, improved pastures, and paddy rice.

Chemical surface-soil properties for the network sites are shown in Table 2. Annual rainfall varies from 1000 mm in Danli to 5000 mm in Bolivia. Research sites include Entisols, Inceptisols, Ultisols, and Oxisols. Soil-

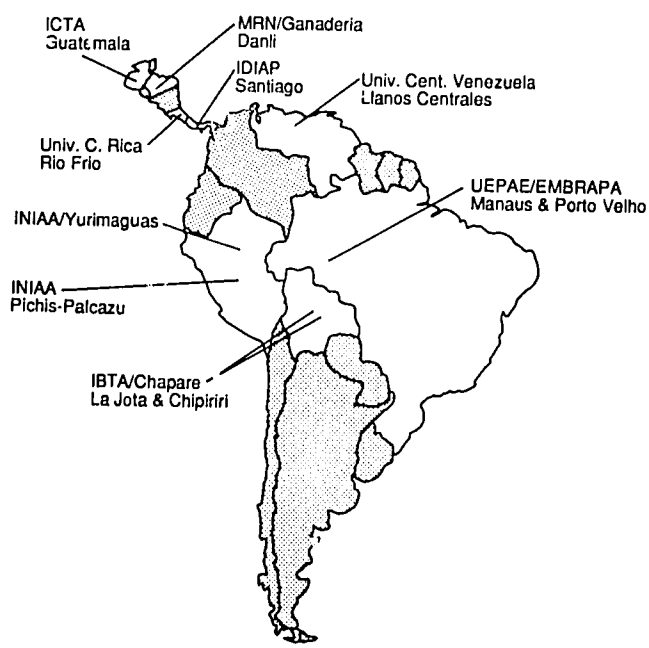

Figure 1. Distribution of national institutes and locations actively collaborating in the RISTROP network in Latin America.

management options are being evaluated across a range of soil and climatic regimes. Evaluations of low-input cropping, for example, include ranges from 2 to 88% Al saturation, 4 to 21 mg/L Modified Olsen P, and 175 to 450 mg/kg sorbed P at solution P levels of 0.1 M $CaCl_2$. Comparisons of results for the rice-cowpea crop rotation among these sites should provide a good indication of the minimum fertilizer inputs required across a range of soil acidity and P conditions.

Once TropSoils' results clearly indicated that alley-cropping systems in nutrient-poor Oxisols and Ultisols would not succeed without the selection of acid-tolerant species, interested national institute scientists were invited to participate in a meeting to discuss future research plans. The Workshop for Alley-Cropping in Acid Soils was held in December 1987 at Yurimaguas with support from IDRC (Canada). Sixteen scientists conducting agroforestry research in eight different locations in Latin America attended the seven-day workshop. Priorities were grouped into basic, intermediate, and advanced research modules corresponding to the different levels of knowledge at each research site. Field experiments were designed to allow a systematic progression in research: selecting of adapted tree species, managing pruning frequency, monitoring tree-crop interactions, and monitoring soil-tree-crop nutrient interactions. As a result of this meeting, agroforestry trials compared biomass production, pruning frequency, and the ability of locally selected and introduced legume tree species to survive. Network results will help validate existing technology and refine methodologies for evaluating alley-cropping practices.

Strong working linkages were established with CIMMYT's Central American network of Strategic Agronomic Trials, coordinated by Dr. William Raun (CIMMYT-Guatemala). Scientists from national institutes throughout the region collaborate with CIMMYT in corn trials, which include investigations seeking 1) to overcome P and S constraints in soils derived from volcanic ash and 2) to

Table 1. Distribution by country, institution, and research topic of scientists collaborating in the RIS-TROP network.

Country	Institution	Research topic	Collaborator
Bolivia	IBTA/Chapare	Low input & Agroforesty	Ing. Jorge Aldunate Ing. Raul Mejia Ing. Roberto Delgadillo
		Improve Pastures	Ing. Franklin Lastra Ing. Armando Ferrufino
		FCC System	Dr. Alfredo Alvarado
Brazil	EMBRAPA/Manaus	Paddy Rice	Ing. Manoel Cravo
	EMBRAPA/Porto Velho	Low input	Dr. Nelson Sampaio Ing. Haroldo Duarte
		Agroforestry	Ing. Marilia Locatelli
Costa Rica	Univ. Costa Rica	Low input	Ing. Floria Bertsch
Guatemala	ICTA & CIMMYT	Continuous Cropping	Ing. Rosa M. Mayorga Ing. Francisco Olivet Dr. William Raun
Honduras	Ministerio de Recursos Naturales	Improved Pastures	Ing. Jorge Rivera Ing. Conrado Burgos Dr. Linus Wege
		FCC System	Dr. Manuel Zantua Ing. Roque Morris
Panama	IDIAP & CIMMYT	Continuous Cropping	Ing. Benjamin Name Dr. William Raun
		FCC System	Ing. Santander Jaramillo
Peru	INIAA	Low input	Ing. Luis zúñiga Ing. Rafael Chumbimune Dr. Julio Alegre
Venezuela	Univ. Central de Venezuela/Maracay	Paddy Rice Continuous Cropping	Dr. Melinton Adams Dr. Eduardo Cassanova Ing. Pedro Solorzano

develop management practices for rotating legume cover crops with corn. NCSU has collaborated in planning the studies and analyzing the soil. Coordination of activities among the networks in Central America has increased the accessibility of both RISTROP and CIMMYT expertise to national institute collaborators in Central America.

Table 2. Selected surface soil properties for RISTROP sites.

Country	Location	Network trial§	pH	Exchangeable Ca	Exchangeable Mg	Exchangeable K	Exchangeable Al	Eff. CEC	Al sat.	Extractable P Melich	Extractable P Olsen	Sorbed P	Org. C
				cmol/L					%	mg/L		mg/kg	%
Bolivia	Chipiriri	3	4.5	1.52	0.23	0.19	2.7	4.64	58	9	10	150	1.00
	La Jota	1 & 2	4.5	1.51	0.50	0.22	3.3	5.53	60	14	21	450	2.00
Brazil	Manaus	5	5.8	11.40	2.30	0.27	0.2	14.17	1	118	—	—	1.00
	P. Velho	1	3.8	0.13	0.11	0.08	2.4	2.72	88	6	10	375	2.09
		2	4.5	0.38	0.12	0.11	1.7	2.31	74	3	—	—	—
Costa Rica	Rio Frio	1	5.9	7.66	1.52	0.29	0.2	9.67	2	2	4	—	4.61
Guatemala	Cristina	1	5.2	1.33	0.43	0.28	0.8	2.84	28	9	6	175	1.37
Honduras	Danli	3	5.5	6.03	1.83	0.32	0.2	8.38	2	—	4	—	2.85
Panama	Calabacito	4	4.5	1.90	0.32	0.10	5.1	7.42	69	2	3	350	1.10
Peru	Pichis	1	4.3	0.29	0.23	0.12	9.9	10.54	94	—	5	—	1.78
	Yurimaguas	1	4.4	0.56	0.23	0.08	0.8	1.67	48	6	7	175	1.08

§ 1 = Low input, 2 = Agroforestry, 3 = Improved pastures, 4 = Continuous cropping, 5 = Paddy rice.

Yurimaguas African Workshop: Y-771

Thomas Jot Smyth, N.C. State University

The commonality in soil resources and soil constraints between the humid and subhumid tropics of Africa and South America is evident from glancing at maps of both continents. Key questions on how to provide alternatives to slash-and-burn agriculture and how to develop sustainable low-input systems on soils low in native fertility are common to both continents. Many African visitors to research sites in Latin America consider the work highly relevant to African conditions.

From August 28 to September 11, 1988, 24 scientists from 16 African countries participated in the Workshop on Acid Tropical Soils Management and Land Development Practices in Yurimaguas, Peru. Countries and institutions represented at the workshop are shown in Figure 1. Workshop participants are listed in Table 1. The workshop was organized and conducted by INIAA, IBSRAM, and NCSU. Support came from the Rockefeller Foundation, IRDC (Canada), the German Ministry for Economic Cooperation, U.S. AID, TropSoils, and TSBF. The workshop's objectives were 1) to acquaint African scientists with the most recent techniques in acid tropical soils management, 2) to foster the exchange of soil-management technologies between South America and Africa, and 3) to help IBSRAM-network participants implement experiments to be conducted by their national institutions.

The workshop staff of 25 scientists combined a broad range of theoretical and practical experience. They included 10 professors from NCSU, Cornell, Texas A&M, and the University of Hawaii; two IBSRAM coordinators; 10 INIAA scientists; and four NCSU graduate students conducting their thesis research in Yurimaguas.

The workshop program, patterned after the 1986 Latin American workshop that launched the RISTROP network, consisted of a mixture of lectures, field and laboratory exercises, computer work, and group discussions. Participants were updated on the basic concepts of, and provided hands-on training in, field and laboratory techniques for soil classification, physics, chemistry, fertility, biology, and experimental design. Extensive coverage was also given to sustainable soil-management options for the humid tropics, including low-input cropping, paddy rice, continuous mechanized cultivation, legume-based pastures, and agroforestry.

Workshop evaluations by participants emphasized 1) the value of being exposed to simple, but scientifically

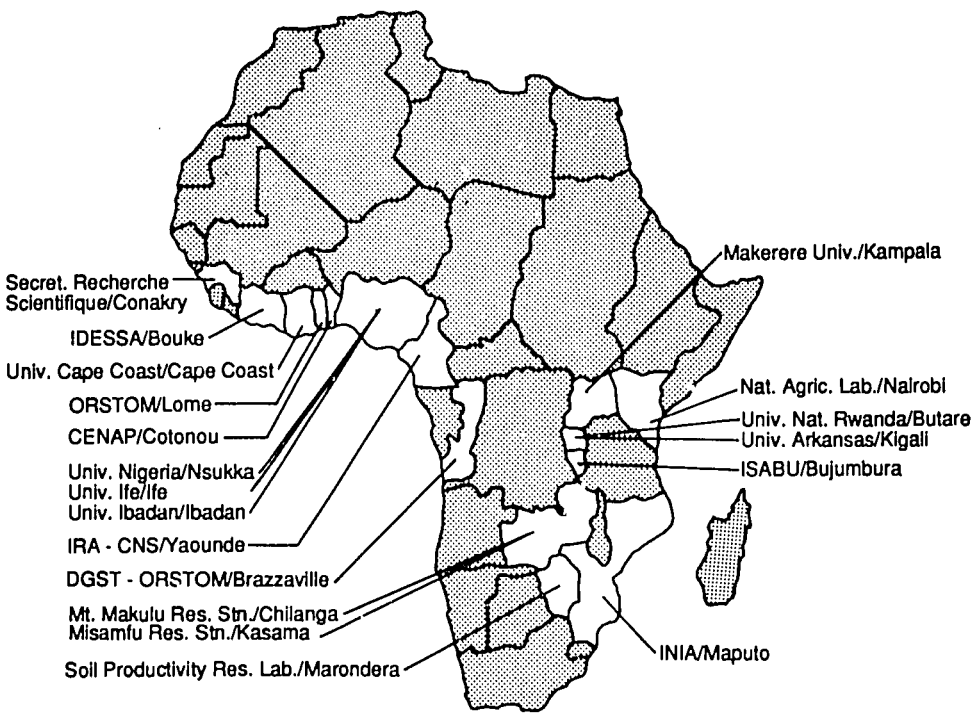

Figure 1. Distribution of primary research locations and national research institutions in Africa represented at the Yurimaguas workshop in Septmeber 1988.

ound, field and laboratory methods; 2) the need for long-erm research plots to evaluate sustainability; and 3) the nportance of an integrated multidisciplinary approach to olving the soil-management problems of relatively isolated locations with limited budgets. Exposing African scientists to long-term research on tropical soils in South America was perceived by all as an effective way to transfer technology.

Table 1. Participants in the Yurimaguas African Workshop.

Country	Participants	Institution
Benin	Attanda M. Igue	Centre National d'Agro-Pedologie
Burundi	Christine Kibiriti Yves B. Goblet	Institut des Sciences Agronomiques Université de Burundi
Cameroon	Onguene Mala	Centre National de Sols, Yaounde
Central African Republic	Damegaza, Edouard David	Bureau National de la Pedologie
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Publications

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Ayarza, M. A. 1988. Potassium dynamics in a humid tropical pasture in the Peruvian Amazon. Ph.D. dissertation, North Carolina State University, Raleigh, N.C.

Buttler, Imo. 1989. Predicting water constraints to productivity of corn using plant-environmental simulation models. Ph.D. dissertation, Cornell University, Ithaca, N.Y.

Carsky, Robert James. 1989. Estimating availability of nitrogen from green manure to subsequent maize crops using a buried bag technique. Ph.D. dissertation, Cornell University, Ithaca, N.Y.

Costa, F. J. 1988. Evaluation of the nitrogen supplying potential of legumes placed on the surface or incorporated in a Brazilian Oxisol. M.S. thesis, Cornell University, Ithaca, N.Y.

Davis-Carter, Jessica Gwyn. 1989. Influence of spatial variability of soil physical and chemical properties on the rooting patterns of pearl millet and sorghum. Ph.D. dissertation, Texas A&M University, College Station, Texas.

Elsenbeer, Helmut. 1989. Hillslope hydrological processes and their controls in a tropical rainforest environment. Ph.D. dissertation, North Carolina State University, Raleigh, N.C.

Evenson, Carl I. 1989. Alley cropping and green manuring for upland crop production in West Sumatra. Ph.D. dissertation, University of Hawaii, Honolulu, Hawaii.

Fontes, Mauricio Paulo Ferreira. 1988. Iron oxide mineralogy of some Brazilian Oxisols. Ph.D. dissertation, North Carolina State University, Raleigh, N.C.

Gandah, Mamadou. 1988. Response of pearl millet [*Pennisetum americanum* L. (K. Schum)] to soil moisture in one agroclimatological zone of Niger West Africa. M.S. thesis, Texas A&M University, College Station, Texas.

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