Intensive Soil Management in the Humid Tropics

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Cover Photos:
1) One of the treatments in the land clearing experiment.
2) Trafficking the soil when it is too wet.

Intensive Soil Management in the Humid Tropics

The Problem

Slash-and-burn farmers draw on two resources: their own labor and the rain forest. Neither is being used to advantage. Year after year, new cut jungle yields one or two crops; then weeds proliferate, fertility drops, jungle overtakes the land, and the pattern begins anew.

In such a system, human effort generates few long-term rewards. The ladder of progressive accomplishment familiar to the stationary farmer is replaced by a cycle of perpetual poverty. Moreover, as population increases and land becomes limited, the entire system starts to collapse.

Across much of the humid tropics, clear signals foretell just this kind of collapse: fallow periods have shortened, productive lands have been degraded, and farmers have been forced to cultivate fragile, less productive soils. Melillo et al. (1985) estimate that the 1985 clearing rate of tropical rain forest in the Amazon basin and other locations in Latin America was 2.5 to 2.8 million hectares per year. Unless we find ways to reduce these numbers, the human and environmental consequences will be disastrous.

Researchers have long recognized the solution: slash-and-burn agriculture must give ground to permanent systems. By increasing productivity and reducing the need to abandon the best lands, such systems would simultaneously improve the lot of subsistence farmers and ease the strain on marginal, easily degraded lands. The question, of course, has been this: Are permanent, intensively managed systems possible on inherently infertile rain forest soils?

The lack of long-term research on how intensive management affects soil physical properties has been one of the chief obstacles to answering this question. This bulletin seeks to narrow that gap. Results from 12 years of continuous research will clarify the effects of various intensive management practices on soil physical properties, soil chemical properties, and crop performance.

The authors recognize that most farmers in the humid tropics lack the capital, transportation, and marketing infrastructure necessary to implement energy-efficient management options. The scientific evidence and field experience presented in this bulletin suggest, however, that properly managed intensive systems can replace slash-and-burn practices if the above-mentioned socioeconomic constraints are addressed. Economic policies that enable farmers to adopt such technologies could thus yield important human and environmental benefits.

Soil Conditions in the Humid Tropics

Evergreen forests covered 24% of the tropics (Sanchez and Buol 1975), but clearing has continued at a rapid rate for the past two decades. Although soils vary in these forests, rainfall and temperature regimes are favorable for many crops. Soils derived from acidic parent materials are similar to those in the southeastern U.S. and exhibit the same soil properties: low cation exchange capacity (CEC), low pH, and high exchangeable aluminum content.

Under native vegetation, the bulk of the available plant nutrients are bound in the biomass and conserved in an almost closed nutrient cycle. The vegetation density is nearly independent of soil conditions, although vegetation varies with parent material.

Shifting cultivation is common in many of these areas. Farmers use slash-and-burn methods to clear forest biomass and hasten the release of organically bound nutrients accumulated over long periods. These nutrients support cultivated crops for one to three years.

In the humid tropics, soils with low base status are classified mainly as Oxisols, Ultisols, Inceptisols, and Entisols. These soils cover approximately 51% of the tropics, most notably in vast areas of interior South America and Central Africa, along with smaller areas

in the hill country of Southeast Asia (Sanchez and Buol 1975). About half of these soils are under evergreen forests and are most frequently identified in the lower categories of soil taxonomy as Hapludox, Dystropepts, Acrudox, Udults, Aqults, and acid families of Aquents, Orthents, and Fluvents. Such soils are commonly deficient in bases and have toxic levels of exhangeable aluminum.

Phosphorus is often deficient in the more clayey surface soils because it reacts with iron and aluminum oxides and is fixed in nearly insoluble forms. Micronutrient and sulfur deficiencies are common. Correcting these nutritional problems usually involves substantial investments in fertilizer and lime. However, many soils with a low base status, especially the Oxisols, possess excellent physical properties that facilitate tillage and reduce erosion. That no great population centers are found in these areas is related to the soils' chemical infertility (Sanchez 1981). Similar infertile acid soils, mainly Ultisols, support large populations in the southeastern U.S. and southeastern China. These Ultisols are intensively cropped after their acidity is corrected with lime and their nutrient deficiencies are overcome with manure or commerical fertilizer.

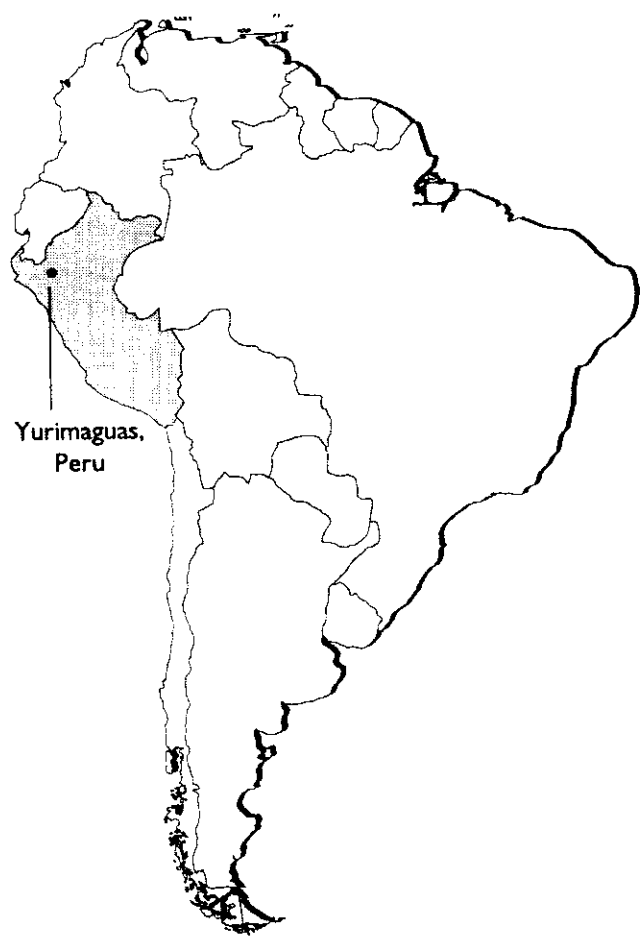

Figure 1. Land-clearing experiments and the initial land-reclamation experiment were conducted at Yurimaguas, Peru.

Research Site and Conditions

The work reported in this bulletin was conducted over a 12-year period at Yurimaguas, Peru (Figure 1). Soils in this region are typical of those found across 171 million hectares in the western Amazon basin, where about 29% of the land is flat and poorly drained and most of the remainder has slopes of up to 30%. Although there are exceptions, soils in the upland landscape positions are generally acid, infertile, and weakly aggregated. In most cases, they are classified as Ultisols.

Table 1 presents physical and chemical properties of a typical profile of Yurimaguas soil series (fine-loamy, siliceous, isohyperthermic, Typic Paledult). Before the land is cleared, pH 4 is typical. The ECEC is relatively uniform with depth, and Al saturation is greater than or equal to 95% at depths below 5 cm. Bulk density tends to be low in the upper 13 cm.

Table 1. Selected properties of the Typic Paleudults (fine-loamy, siliceous, isohyperthermic) at Yurimaguas, Peru.

					Exchangeable							Porosity	
Depth	Clay	Sand	Organic C	pH	Ca	Mg	K	Al	ECEC	Al saturation	Bulk density	Micro	Macro
cm	%				*cmol kg⁻¹*					%	*Mg m⁻³*	*m³ m⁻³*	
0–5	6	80	1.25	3.8	0.84	0.20	0.20	2.05	3.49	59	1.16	0.28	0.19
5–13	10	70	0.84	3.7	0.05	0.04	0.04	2.63	2.76	95	1.16	0.28	0.19
13–43	15	61	0.42	3.9	0.05	0.03	0.03	3.11	3.24	96	1.39	0.14	0.14
43–77	17	57	0.29	4.0	0.03	0.02	0.02	3.12	3.20	98	—	—	—
77–140	25	50	0.18	4.1	0.03	0.01	0.03	4.48	4.58	98	—	—	—
140–200	24	54	0.17	4.4	0.06	0.03	0.04	3.80	3.94	96	—	—	—

Source: Cochrane and Sanchez (1982) and Alegre et al. (1986a).

Post-Clearing Management of Ultisols and Its Effects on Soil Properties

Clearing Methods, Management Practices, and Testing Procedures

Comprehensive research involving various post-clearing tillage and management practices was conducted on a Typic Paleudult near Yurimaguas, Peru, from 1980 to 1992. The experimental design was developed from on-site experiences dating back to 1971 (Seubert et al. 1977). Greater detail on these studies can be found in Alegre and Cassel (1986) and Alegre et al. (1986, 1988, 1990).

Six combinations (i.e., technology packages) of land-clearing, vegetation burning and post-clearing tillage practices were evaluated (Table 2). Treatment 1 was conventional slash and burn: vegetation was cut with chain saws, axes, and machetes; it was then burned. Unburned tree trunks were manually removed, but the stumps remained in place.

For the remaining five treatments, land was cleared with a Caterpillar D-6 bulldozer; all wood was bulldozed from the experimental plots. Treatment 2 was cleared with a straight blade, and the soil was rototilled using a 10-kW tractor prior to seeding the first crop. Treatment 3 was also cleared with a straight blade, but was chisel-plowed to the 25-cm depth and rototilled with a 48-kW tractor prior to seeding the first crop. Treatments 4, 5, and 6 were cleared with a shear blade—so named because it shears off trees near the soil surface. Compared to the straight blade, the shear-blade reduces topsoil disturbance during clearing and topsoil removal when vegetation and logs are pushed off the field (Alegre and Cassel 1994). Treatment 4 was disked to the 30-cm depth using a double disk pulled by the D-6 tractor. Treatments 5 and 6 were rototilled, the latter to the 30-cm depth.

Three post-clearing soil-management practices were superimposed as subplots:

1. Flat-planted; no fertilizer or lime added (F).
2. Flat-planted; fertilizer and lime added at rates based on soil tests (FFL).
3. Bedded at 1.1-meter spacings; fertilizer and lime added at rates based on soil tests (BFL)

Table 2. Six technology packages included various combinations of land-clearing methods, vegetative burning, and soil tillage (from Alegre et al., 1986).

Treatment number	Clearing method	Vegetation burned	Tillage
1	Slash/burn	Yes	None
2	Straight blade	No	Rototill (10 kW tractor)
3	Straight blade	No	Chisel, rototill (48 kW tractor)
4	Shear-blade	Yes	Disk*, rototill (10 kW tractor)
5	Shear-blade	No	Rototill (10 kW tractor)
6	Shear-blade	No	Disk*, rototill (10 kW tractor)

* Disking by bulldozer

Hereafter, subplot treatments 1, 2, and 3 will be denoted by F, FFL, and BFL, respectively.

The cropping sequence was upland rice (*Oriza sativa* L.), soybean (*Glycine max* L.), corn (*Zea mays* L.), rice, and corn. The first crop was seeded November 28, 1980; the last crop was seeded April 6, 1982. Fertilizer applications prior to seeding the first crop were 80 kg N ha^{-1}, 26 kg P ha^{-1}, 100 kg K ha^{-1}, and 30 kg Mg ha^{-1}. Fertilization of the second rice crop was 50, 15, and 50 kg ha^{-1} of N, P, and K, respectively. Fertilizer applied prior to seeding soybean was 20, 26, 66, and 40 kg ha^{-1} of N, P, K, and Mg, respectively. Dolomitic limestone was applied at 2 and 1.5 Mg ha^{-1} prior to seeding the first and second crops, respectively. An additional lime application of 1.0 Mg ha^{-1} preceded the last corn seeding.

Bulk density (BD) was determined on 76-mm high by 76-mm diameter undisturbed soil cores (Blake and Hartge 1986). Cone index (CI)—defined as the force required to push a penetrometer through an increment of soil *divided by* the projected cross-sectional area of the penetrometer tip—was measured with a Soiltest model CN-970 proving-ring cone penetrometer. Cone diameter was 11.8 mm, and the cone angle was 30 degrees. Gravimetric soil water content was measured when CI was measured. The individual CI values were subjected to a $\log_{10}$ transformation prior to statistical analysis. The soil-water characteristic for each undisturbed soil core was determined at soil pressures of 0, –0.3, –5.7, –12.7, –17.8, –22.9, –33.0, and –43.2 kPa. Infiltration rate was measured in the field with a double-ring infiltrometer having inner and outer ring diameters of 30 and 60 cm, respectively. Wilting point was estimated using disturbed soil samples in a pressure chamber at –1,500 kPa pressure (Klute 1986). Aggregate stability was measured by wet-sieving (Yoder 1936), employing the apparatus designed by Van Bavel (1952). Aggregate mean weight diameter (MWD) was calculated according to Van Bavel (1949) and geometric mean diameter (GMD) was calculated according to Mazurak (1950). Organic carbon content of aggregates was determined by the Walkely-Black method (Allison 1965).

Soil physical properties

Bulk density

Bulk density at the 0- to 15-cm depth was not affected by clearing method at 29 weeks after clearing, but at the 15- to 25-cm depth, it was greater for treatments 5 and 6 than for the slash-and-burn treatment (Table 3).

Post-clearing soil management practices had little effect on BD at 29 weeks (data not shown). Bulk density at the 0- to 15-cm depth of subplot BFL was 1.14 Mg m^{-3}, as compared to 1.30 and 1.28 Mg m^{-3} for the F and FFL subplots, respectively. The lower BD for BFL is attributed to less foot traffic by field laborers, who walked in the furrow rather than on the crown of the beds.

Table 3. Bulk density of Yurimaguas soil at two depths at 29 and 98 weeks after clearing as affected by land-clearing method and tillage.

No.	Treatment	29 weeks after clearing		98 weeks after clearing	
		0–15 cm	15–25 cm	0–15 cm	15–25 cm
		Mg m^{-3}			
1	Slash/burn	1.17 a*	1.37 b	1.32 c	1.38 b
2	Straight blade	1.26 a	1.44 ab	1.42 ab	1.56 a
3	Straight blade/chisel	1.25 a	1.49 ab	1.46 a	1.57 a
4	Shear-blade/burn/disk	1.18 a	1.45 ab	1.35 bc	1.52 a
5	Shear-blade	1.28 a	1.52 a	1.32 bc	1.58 a
6	Shear-blade/disk	1.32 a	1.56 a	1.33 bc	1.57 a

* Means with the same letter within a given column are not different at the P=0.05 level by the Waller-Duncan multiple comparison test.

Cone index and soil water content

Mechanical impedance in the 0- to 15-cm depth 29 weeks after clearing was greater for the slash-and-burn treatment than for four of the five other treatments (Table 4). The higher CI values for the slash-and-burn and shear-blade-and-burn treatments are probably due to the loss of organic matter when the cut vegetation was burned. Soil water content, a factor known to affect mechanical impedance, was similar across treatments when CI measurements were taken (Table 4).

Table 4. Cone index and soil water content for the 0- to 15-cm depth of Yurimaguas soil at 29 weeks after clearing.

No.	Treatment	Cone index	Soil water content
		kPa	*g g⁻¹*
1	Slash/burn	557 a*	0.232
2	Straight blade	376 bc	0.215
3	Straight blade/chisel	352 bc	0.207
4	Shear-blade/burn/disk	499 ab	0.217
5	Shear-blade	342 c	0.214
6	Shear-blade/disk	282 c	0.208
			NS

* Means with the same letter are not different at the P=0.05 level by the Waller-Duncan multiple comparison test. NS indicates no significant difference.

Cone index at 29 weeks after clearing was also affected by post-clearing soil management (Table 5). Cone index in the 0- to 15-cm depth was lowest for BFL. As noted, BFL contained furrows that reduced foot traffic during hand-weeding operations, thus minimizing soil aggregate destruction. Traffic by laborers can significantly compact the soil surface and increase mechanical impedance of flat-planted land (Cassel and Lal 1992). The difference in mechanical impedance between BFL and FFL had disappeared by 98 weeks after clearing.

Mechanical impedance in the 15- to 25-cm depth was not affected by bedding or by additions of fertilizer and lime at either depth. The small differences in soil water content (Table 5), although statistically significant, likely have little impact on cone index.

Soil water characteristic and pore size distribution

The soil water characteristic for the 0- to 15-cm depth prior to clearing is shown in Figure 2A (the vertical bar through each point is two standard deviation units long). The water retained between −13 to −1,500 kPa (0.187 m^3 m^{-3}) approximates the plant-available water holding capacity before clearing. Macropores with neck diameters greater than 23 μm were drained at in situ field capacity.

Figure 2B presents the soil water characteristic for the 0- to 15-cm depth for the three soil

Table 5. Cone index and soil water content at two depth intervals 29 weeks after clearing for three post-clearing soil management practices.

Post-clearing soil management practice	Cone index	Soil water content
	kPa	*g g⁻¹*
0- to 15-cm depth		
Flat planted (F)	480 a*	0.211 b
Flat planted, fertilizer, lime (FFL)	432 a	0.226 a
Bedding, fertilizer, lime (BFL)	288 b	0.209 b
15- to 25-cm depth		
Flat planted (F)	579 a	0.216 b
Flat planted, fertilizer, lime (FFL)	577 a	0.226 a
Bedding, fertilizer, lime (BFL)	656 a	0.218 b

* Means with the same letter for each depth are not different at the P=0.05 level by the Waller-Duncan multiple comparison test.

management subplot treatments at 29 weeks after clearing. Subplot BFL had the greatest total porosity and greatest volume of macropores.

Infiltration rate

Cumulative water infiltration during 2-hour periods was used to characterize soil water movement (Figure 3). The mean infiltration rate before clearing was 420 mm h^{-1} (Figure 3A). Continuously cropping the soil for 98 weeks after straight-blade clearing, with no post-clearing tillage or fertilization before flat planting (Treatment 2, F), drastically reduced the infiltration rate to 30 mm h^{-1} (Figure 3B). When soil cleared by the straight blade was chisel plowed prior to flat planting (Treatment 3, F) the infiltration rate exceeded 100 mm h^{-1}, a value similar to that for slash-and-burn (Treatment 1, F). Chisel plowing after clearing was particularly effective in loosening the soil and breaking up small lenses of compacted soil, which may have little overall effect on bulk density, but a great effect on vertical water movement.

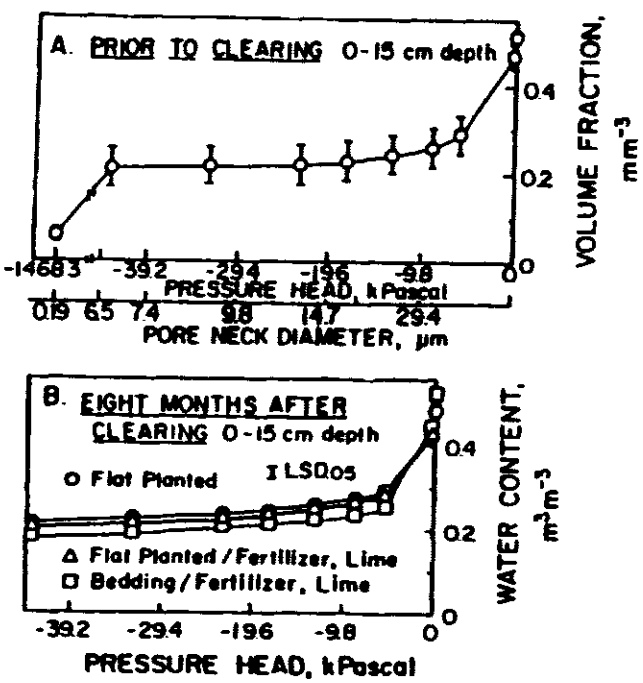

Figure 2. Soil water characteristics of the 0- to 15-cm depth of Yurimaguas soil.

Organic carbon and aggregation

Organic carbon content was higher for subplot treatment BFL than for FFL during the entire 98-week period (Table 6). Higher crop yields and more vegetative material were produced and returned to the soil under BFL (Alegre et al. 1990). Low dry-matter production for subplot F resulted in virtually no return of crop residue to the soil, and its organic carbon content decreased from 1.04% before clearing to 0.80% at 98 weeks after clearing, a 24% reduction. In subplot FFL, organic carbon tended to increase between 29 and 98 weeks after clearing.

The percentages of aggregates in five size classes were similar at 29 and 98 weeks after clearing. Pooled data for these two samplings are shown in Table 7. Small differences among treatments existed for the two smaller classes. Continuous cropping had little effect on soil

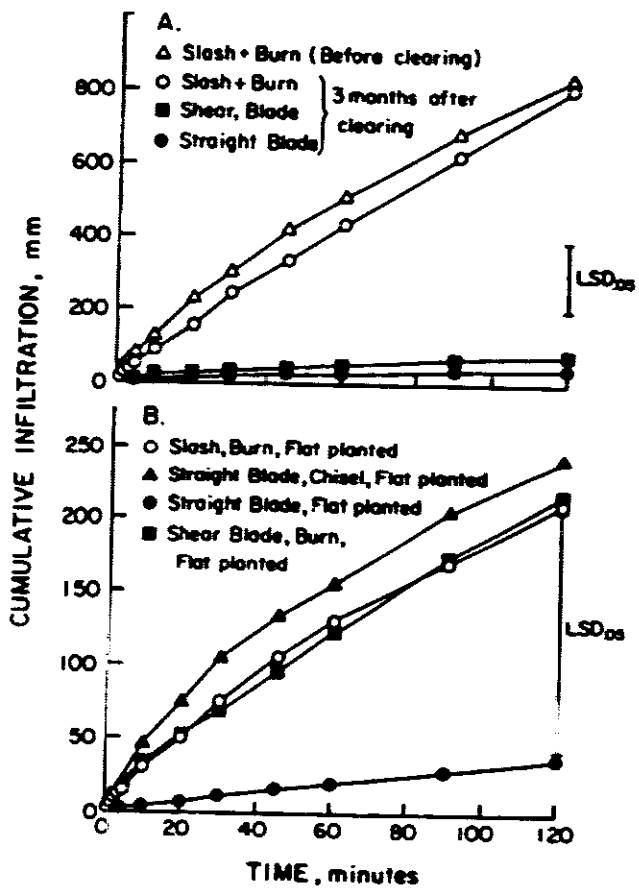

Figure 3. Cumulative infiltration of Yurimaguas soil before clearing (a) and cumulative infiltration for selected land-clearing tillage combinations 98 weeks after clearing.

aggregate distribution over this 98-week period. Table 8 shows the temporal effects on the distribution of water-stable aggregates, averaged across all land-clearing and post-clearing management practices. During the first 29 weeks after clearing, the fraction of aggregates in the 2- to 1-mm class decreased; the fraction in the < 0.1-mm class increased. The percentage of aggregates in the 0.25- to 0.1-mm fraction changed marginally during the following 69-week period of continuous cropping.

Mean weight diameter and geometric mean diameter prior to harvesting rice and corn crops were highly variable (Table 9). These values represent a small decrease in aggregation due to soil tillage from the values measured before clearing. Prior to clearing, the mean weight diameter was 0.484 mm, and the geometric mean diameter was 1.04 mm. Aggregate mean weight and geometric mean weight diameters were correlated with organic carbon at the P=0.05 level.

Soil chemical properties

Whereas tillage affects soil physical properties directly and indirectly, lime and fertilizer additions and tillage incorporation have direct consequences on soil chemical properties.

Table 6. Effect of different post-clearing soil management practices on soil organic carbon content before harvesting rice (29 weeks after clearing) and before harvesting corn (98 weeks after clearing).

Post-clearing soil management practice	Organic carbon content: 29 weeks after clearing		98 weeks after clearing	
	%		%	
Flat planted, no fertilizer or lime (F)	0.88	(0.28) ab*	0.80	(0.19) b
Flat planted, fertilizer, lime (FFL)	0.84	(0.19) b	1.01	(0.26) a
Bedding, fertilizer, lime (BFL)	1.01	(0.32) a	1.03	(0.28) a
Mean	0.91	(0.28)	0.95	(0.26)

* Means in a given column followed by the same letter are not significantly different at the P=0.05 level by the Waller-Duncan multiple comparison test. Standard deviations are shown in parentheses.

Table 7. Water stable aggregate size distribution for the six land-clearing methods averaged across post-clearing management practices at 29 and 98 weeks after clearing.

No.	Treatment	Aggregate size class: 2–1mm	1–0.5mm	0.5–0.25mm	0.25–0.1mm	<0.1 mm
		%				
1	Slash/burn	10.6 (5.6)	15.7 (5.1)	18.5 (4.7)	19.0 (8.4)bc*	35.2 (11.5)ab
2	Straight blade	8.4 (3.9)	14.5 (3.5)	18.4 (3.4)	24.5 (10.0)ab	34.2 (10.1)ab
3	Straight blade/chisel	7.6 (4.6)	13.3 (3.7)	19.6 (4.6)	20.6 (6.4)bc	37.8 (11.4)a
4	Shear-blade/burn/disk	10.6 (2.7)	16.7 (2.8)	18.9 (2.3)	26.9 (5.1)a	27.7 (7.3)b
5	Shear-blade	9.4 (4.5)	15.7 (3.9)	19.6 (4.4)	18.4 (4.9)c	36.9 (9.0)ab
6	Shear-blade/disk	8.3 (3.1)	16.6 (3.8)	18.4 (3.8)	23.6 (7.2)abc	32.9 (10.2)ab
		NS	NS	NS		

* Means with the same letter within a given column are not different at the P=0.05 level by the Waller-Duncan multiple comparison test. Standard deviations are shown in parentheses. NS indicates no significant difference.

Acidity (pH) and percent aluminum saturation
Soil acidity increased in response to additions of lime for all clearing methods (Figure 4). The pH (averaged for FFL and BFL across all land-clearing treatments) increased from its initial value of 4.0 to 5.2 after 98 weeks. No pH change occurred the first 14 weeks after clearing because lime had not yet been added. Changes in percent Al saturation in the topsoil were directly related to changes in soil acidity. For example, percent Al saturation 29 weeks after clearing for the disked shear-blade-and-burn treatment was lower for subplot FL compared to subplot F (Figure 5A). After 29 weeks, percent Al saturation continued to increase for subplot F, but it decreased for subplot FL.

Exchangeable calcium and magnesium
Exchangeable Ca in the topsoil remained low when no lime was applied; it increased with time for the limed subplots (Figure 5B). Transport of Ca into the subsoil occurred in the limed subplots for all land-clearing treatments (Figure 6). Exchangeable Ca concentration in the 15- to 30-cm depth increased seven-fold during the 98 weeks after clearing. Moveover, the Ca concentration of subplot FL increased nearly five-fold at the 30- to 45-cm depth during the same period.

Table 8. Effect of continuous cropping on water-stable aggregate size distribution.

Time	Crop	Aggregate size class				
		2–1mm	1–0.5mm	0.5–0.25mm	0.25–0.1mm	<0.1 mm
		%				
Before clearing	Secondary forest	15.6 (4.0) a*	18.0 (4.7)	17.1 (4.1)	20.3 (6.4) b	29.0 (8.8) b
29 wks. after clearing	Rice	9.5 (4.9) b	15.9 (4.1)	18.8 (4.1)	20.0 (6.8) b	35.2 (11.8) a
98 wks. after clearing	Corn	8.8 (3.9) b	14.9 (3.7)	19.0 (3.8)	24.3 (8.1) a	32.9 (8.6) a
			NS	NS		

* Means with the same letter within a given column are not different at the P=0.05 level by the Waller-Duncan multiple comparison test. Standard deviations are shown in parentheses. NS indicates no significant difference.

Table 9. Mean weight diameter (MWD) and geometric mean weight diameter (GMD) prior to harvesting the first and fifth crops for six land-clearing methods averaged across all post-clearing management practices.

No.	Land-clearing method	First crop (29 weeks after clearing)		Fifth crop (98 weeks after clearing)	
		MWD	GMD	MWD	GMD
		mm			
1.	Slash/burn	0.417 (0.130)*	0.527 (0.088)*	0.378 (0.063)*	0.500 (0.032)*
2.	Straight blade	0.372 (0.090)	0.496 (0.058)	0.359 (0.059)	0.497 (0.031)
3.	Straight blade/chisel	0.336 (0.079)	0.486 (0.067)	0.351 (0.095)	0.489 (0.055)
4.	Shear-blade/burn/disk	0.417 (0.056)	0.519 (0.045)	0.418 (0.050)	0.538 (0.032)
5.	Shear-blade	0.407 (0.114)	0.517 (0.069)	0.362 (0.026)	0.483 (0.020)
6.	Shear-blade/disk	0.373 (0.077)	0.502 (0.059)	0.382 (0.068)	0.513 (0.042)
		NS	NS	NS	NS

* NS indicates no significant difference.

Downward movement of exchangeable Mg also occurred for subplots receiving fertilizers and lime (Figure 7). At 98 weeks, exchangeable Mg in the 15- to 30-cm depth of the limed subplots weeks was three times its initial concentration. Concentrations were always higher in the bedded soil, a result of concentrating Ca and Mg in the beds when they were formed.

Exchangeable potassium

The exchangeable K level (not shown) for all three subplots of the slash-and-burn treatment was above the critical level for plant growth of 0.2 cmol kg^{-1} (Hunter 1974). At 29 weeks after clearing, the K level for the slash-and-burn treatment decreased below the critical level for subplot F. The K level never did increase to the critical level for subplot F of the disked shear-blade-and-burn (Figure 5C). The K levels for all treatments and subplots were below the critical level after 98 weeks. It is possible that levels of K $\geq$ 0.2 cmol kg^{-1} were not found because measurements at 29 and 98 weeks coincided with the end of the growing season when the crop was mature and a significant amount of exchangeable K had been removed from the soil by plant uptake or by leaching.

Effective cation exchange capacity

The ECEC levels were inherently low in this soil because of its kaolinitic clay mineralogy and its acidic pH. The ECEC of the topsoil was unaffected by land-clearing treatment, but it increased by 20% for those subplots receiving lime (Figure 5D).

Phosphorus and nitrogen

Only the slash-and-burn method had a soil-test P

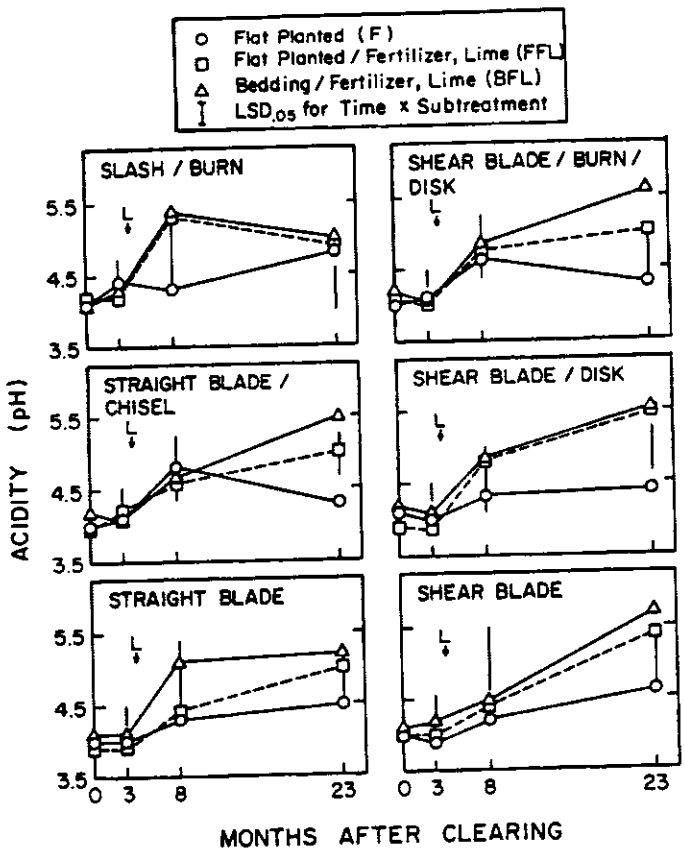

Figure 4. Soil acidity (pH) in the 0- to 15-cm depth vs. time after clearing. Arrows with L shown in the upper-left graph indicate time of fertilizer and lime application. Vertical bars are LSD (0.05) values for subplot effects.

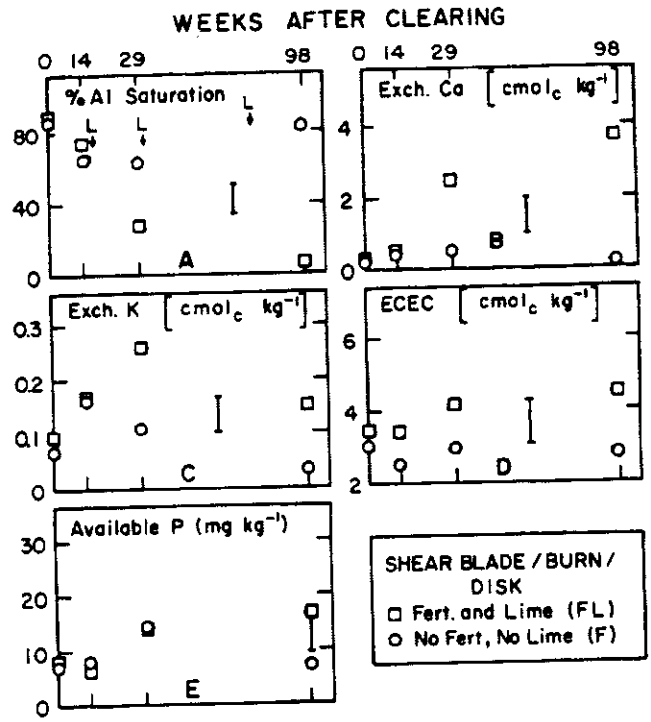

Figure 5. (A) Percent Al saturation; (B) exchangeable calcium; (C) exchangeable potassium; (D) ECEC; and (E) available phosphorus in the 0- to 15-cm depth. vs time after clearing with shear-blade/burn/disk treatment. The arrows in the upper-left graph indicate the times of fertilizer and lime application. Vertical bars are LSD (0.05) values for subplots effects. FL represents the average value for FFL and FBL subplots.

value above the critical level of 15 mg P kg^{-1} (Cano 1973) at 29 weeks. This value declined rapidly in the unfertilized treatments. In general, P fertilization maintained the P level for all treatments just above the critical level. Total nitrogen content was 1.0 g kg^{-1} and was not affected by land-clearing method.

Crop performance

Relative grain yields were calculated for each crop, with the exception of the third crop, which failed due to drought (Table 10). These calculations help to assess how overall patterns in crop yield are affected by specific combinations of experimental variables. Relative grain yield in percent for each grain crop was calculated for each whole plot-subplot combination as follows:

$$\text{Relative grain yield} = (Y_{ts}/Y_m)\times 100 \qquad [1]$$

where Y_{ts} is the yield for a particular whole-plot treatment (t) by subplot treatment (s) combination, and Y_m is the maximum yield for the 18 combinations (Table 10). For each crop, the maximum yield occurred for the slash-and-burn clearing treatments (1-FFL or 1-BFL). Two disked shear-blade-and-burn treatments (4-FFL and 4-BFL)

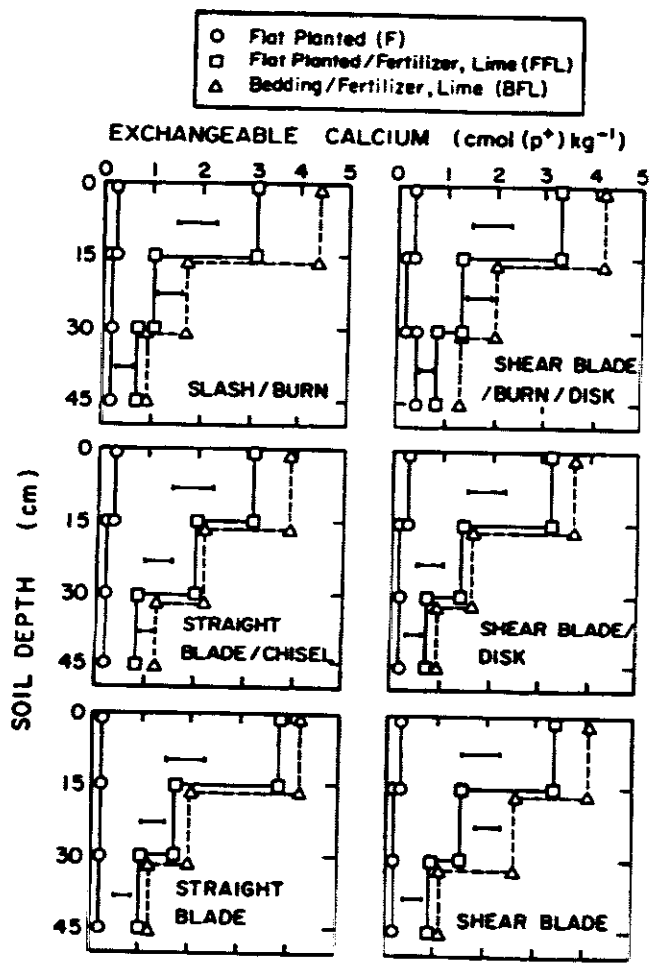

Figure 6. Exchangeable calcium versus soil depth for limed and unlimed subplots for six land-clearing treatments at 98 weeks after clearing. Horizontal bars are LSD (0.05) values for sub-plots.

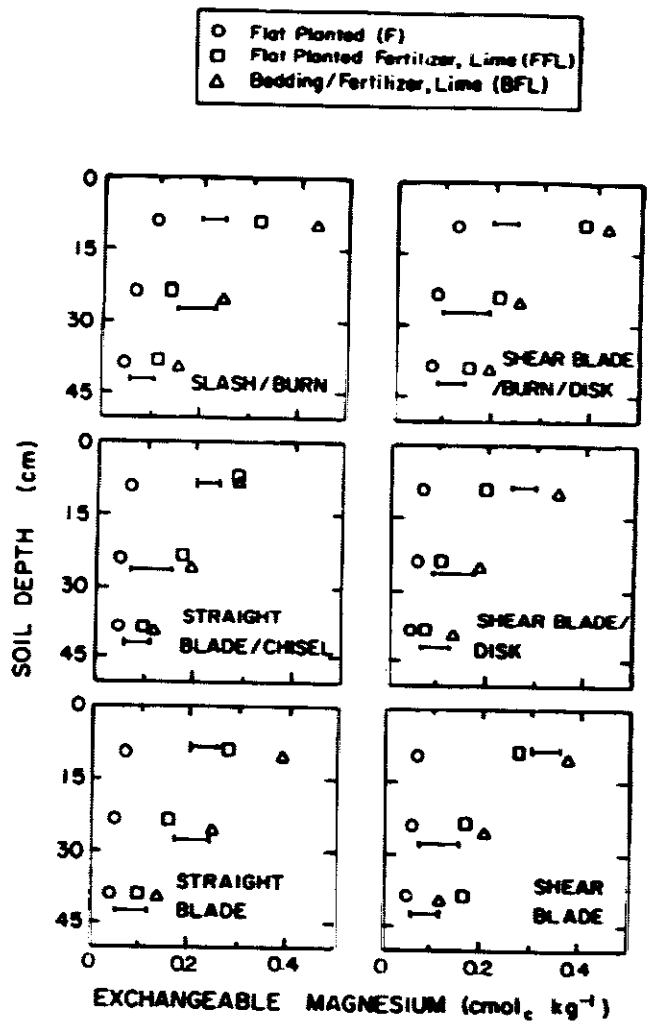

Figure 7. Exchangeable magnesium versus soil depth for limed and unlimed subplots for six land-clearing treatments at 98 weeks after clearing. Horizontal bars are LSD (0.05) values for sub-plots.

and the chiseled straight-blade treatment (3-BFL) also had relative yields exceeding 80%. Chisel plowing the land cleared with the straight blade mitigated the soil compaction that occurred during clearing.

Discussion and Conclusions

This comprehensive land-clearing study intensively evaluated soil physical and chemical properties three times: before clearing, 29 weeks after clearing, and 98 weeks after clearing. Earlier studies found that soil compaction caused by mechanical land-clearing equipment significantly limited yield (Alegre et al. 1986). Compaction-caused differences in mechanical impedance were easier to detect than were compaction-caused differences in bulk density. Shear-blade clearing did not mix the surface and subsurface soil horizons or compact the soil as much as straight-blade clearing. Chisel-plowing and disking alleviated the compaction caused by straight-blade clearing and increased relative yield for four crops from 51 to 83% of the maximum yield.

Few chemical properties were affected by land-clearing method or post-clearing soil management. In general, K, Ca, Mg, K, and P levels increased for the first 29 weeks following traditional and mechanical clearing and burning. Micronutrient levels were unaffected by those clearing methods in the absence of burning. Judicious applications of lime and fertilizers maintained higher nutrient levels in the topsoil. Soil concentrations of Ca, Fe, and Mn were unaffected by clearing method, but the Zn concentration in the topsoil increased with slash-and-burn clearing.

Yields for rice, corn, and soybeans were higher following slash-and-burn clearing than mechanized

Table 10. Relative grain yields for selected land-clearing/post-clearing management practice combinations.

No.	Land-clearing method	Soil management practice	Rice (1st crop)	Soybean (2nd crop)	Rice (4th crop)	Corn (5th crop)	Mean
			Relative yield, %				
1–F	Slash/burn	F	78	18	22	12	33
1–FFL	Slash/burn	FFL	89	100	100	87	94
1–BFL	Slash/burn	BFL	100*	80	81	100	90
2–F	Straight blade	F	23	4	7	0	8
2–FFL	Straight blade	FFL	69	44	45	45	51
2–BFL	Straight blade	BFL	85	65	57	36	61
3–F	Straight blade/chisel	F	29	14	20	0	16
3–FFL	Straight blade/chisel	FFL	72	88	84	87	83
3–BFL	Straight blade/chisel	BFL	71	62	87	56	69
4–F	Shear-blade/burn/disk	F	60	21	45	1	32
4–FFL	Shear-blade/burn/disk	FFL	77	94	99	74	86
4–BFL	Shear-blade/burn/disk	BFL	92	88	85	85	88
5–F	Shear-blade/rototill	F	32	8	28	0	17
5–FFL	Shear-blade/rototill	FFL	76	59	61	41	59
5–BFL	Shear-blade/rototill	BFL	80	81	66	53	70
6–F	Shear-blade/disk/rototill	F	23	5	18	0	12
6–FFL	Shear-blade/disk/rototill	FFL	65	87	53	28	58
6–BFL	Shear-blade/disk/rototill	BLF	69	67	56	59	63

* Maximum grain yields for the 1st, 2nd, 4th, and 5th crops were 3.98, 2.32, 3.48, and 3.30 Mg ha^{-1}, respectively. F is flat-planted, no fertilizer or lime; FFL is flat-planted with fertilizer and lime; and BFL is bedded with fertilizer and lime.

clearing. Nutrients released by burning produced an excellent yield for the first rice crop, but this effect decreased rapidly for successive crops unless lime and fertilizer were applied (Table 10). Fertilizer and lime did not increase first-crop yields for those land-clearing treatments with burning, a result also reported by Seubert et al. (1977). In general, when burning is used after clearing, little or no fertilizer or lime is required for the first crop, although subsequent crops require fertilizer and lime according to soil test recommendations. Applying lime before seeding the first crop may help to increase soil pH for the following crop.

While minor surface-soil compaction occurred under slash-and-burn clearing, severe deterioration of soil physical properties did not occur. Bedding the soil provided good drainage during the wetter periods and, in this study, it generally increased crop yields. However, the yield increases cannot always be attributed specifically to decreased bulk density or mechanical impedance (Alegre et al. 1986).

Of the mechanical land-clearing and post-clearing practices evaluated in this study, the disked shear-blade-and-burn treatment produced the highest rice, soybean, and corn yields. Bedding did not always produce the highest yields for this system (Table 10). For the manual slash-and-burn method, bedding by hoe helped reduce foot-traffic compaction during hand-weeding operations.

Of the systems evaluated, we believe the best mechanized land-clearing system for Yurimaguas and similar soil series is a disked shear-blade-and-burn coupled with (i) applications of fertilizer and lime and (ii) the formation of beds prior to seeding. In addition, we recommend that any mechanical clearing procedure used on Ultisols be followed by some form of secondary tillage, preferably chisel plowing, to alleviate compaction incurred during the clearing operation.

Tillage Experiments

Crop response to any tillage operation is dependent on the geometry of the tillage tool, soil properties, and ambient soil-moisture conditions. The following tillage experiments were conducted to evaluate the effects of wheel compaction, subsoiling, and various conservation-tillage practices on soil physical properties and crop production.

Soil trafficability

The objectives of this field experiment were: (i) to evaluate soil compaction caused by one or more tractor passes on sandy loam and loamy sand Ultisols under a range of soil water contents and (ii) to determine the effect of wheel compaction on corn production.

The experiment was conducted at two sites on the Yurimaguas Experiment Station: Site 1 in 1985 and Site 2 in 1988. The soil at Site 1 had a sandy loam plow layer (60% sand, 20% clay) and had been continuously cropped since 1980. Site 2 had a loamy sand plow layer (80% sand, 10% clay) and had been continuously cropped by mechanical farm machinery since 1987.

Each site was sprayed with paraquat to kill weeds. Lime and P were broadcast on the soil surface according to soil test recommendations and incorporated with a disk harrow.

The experimental design for Site 1 was a split-plot. Soil water contents (0.20, 0.27, and 0.36 $m^3\ m^{-3}$) at the time of wheel compaction were main-plot treatment variables, and the number of repeated compaction events (0, 1, 2, 3) were the subplot treatment variables. The various soil water contents were achieved by allowing the soil to dry naturally for various periods after a rainfall event. At each site, the wettest main-plot treatment was compacted immediately after the rain stopped. All wheel compaction was done using a 48-kW Kubota tractor.

The experimental design for Site 2 was similar to that at Site 1: soil water contents of 0.15, 0.25, and 0.35% $m^3\ m^{-3}$ were main-plot treatment variables, and the number of tractor compaction events (0, 1, 2, 3, 4, 5, and 10) were subplot treatment variables. Bulk density, total porosity, and depth of rut were measured immediately after the tractor passes. At both sites, corn was seeded (with a planting stick) at 20-cm intervals along the wheel track. Rows were 80 cm apart. Corn in the non-compacted plots was planted in non-compacted soil between the wheel tracks. Corn grain yield was measured for all treatment combinations.

Bulk density

At the 0- to 10-cm depth, tractor passes at various soil water contents produced textbook effects on bulk density (Tables 11 and 12). The first pass caused the greatest compaction, regardless of soil

Table 11. Bulk density of the 0- to 10-cm depth of a sandy loam Ultisol (Site 1) as affected by the number of tractor passes and soil water content.

	Number of tractor passes				
Soil water content	0	1	2	3	Mean
$m^3\ m^{-3}$	*Bulk density, Mg m^{-3}*				
0.36	1.33	1.57	1.58	1.59	1.52
0.27	1.35	1.46	1.52	1.56	1.47
0.20	1.36	1.42	1.49	1.50	1.45
Mean	1.35	1.48	1.53	1.55	

$LSD_{.05}$
Soil water content = 0.04
Number of tractor passes = 0.04
Two different water contents for the same number of tractor passes = 0.07
Number of tractor passes at the same soil water content = 0.07

water content. The greatest compaction occurred for the wettest soil at both sites. After the first pass, additional passes increased bulk density on the two drier plots, but not on the wettest plot. The final bulk density from a given level of compactive effort (i.e., the same number of compaction events) decreased as the soil became drier

Total porosity

The maximum compaction at Site 1, obtained for three tractor passes at the soil water content of 0.36 $m^3\ m^{-3}$, reduced total porosity from 0.48 to 0.40 $m^3\ m^{-3}$. The reduction in total porosity at Site 2 (Table 13) was similar to that for Site 1. Total porosity for each bulk density value in Tables 11 and 12 can be calculated using the following equation:

bulk density = particle density x (1 – total porosity) [2]

assuming particle density is 2.65 Mg m^{-3}.

Depth of wheel track

The depth of the rut created by tractor-wheel compaction was more closely related to soil water content than the number of tractor passes (Figure 8). At each soil water content, the first wheel pass created a rut deeper than the combined effect of all additional passes. Statistically, after the first tractor pass, the rut depth did not change with two or three additional tractor passes, although Figure 8 indicates that the rut continues to deepen with each consecutive pass.

Crop response

For the wettest condition of the sandy loam plot (Site 1), one tractor pass reduced corn yield by 50% compared to the non-trafficked yield (Table 14). On the drier plots, compaction from a single tractor pass tended to increase yield. This effect has been observed previously: firming the soil promotes germination by improving seed-soil contact. Although a relationship between decreased corn

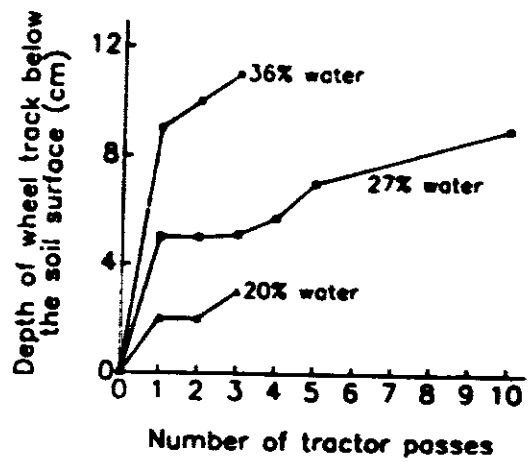

Figure 8. Depth of rut as affected by the number of tractor-wheel compaction events at three soil water contents.

Table 12. Bulk density of the 0- to 10-cm depth of a loamy sand Ultisol (Site 2) as affected by the number of tractor passes and soil water content.

Soil water content	Number of tractor passes							
	0	1	2	3	4	5	10	Mean
$m^3\ m^{-3}$	Bulk density, 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 water content = 0.02
Number of tractor passes = 0.03
Two different water contents for the same number of tractor passes = 0.07
Number of tractor passes at the same soil water content = 0.07

yield and increased number of tractor passes was found at the water content of 0.36 m^3 m^{-3} (Figure 9), this was not observed when soil water content was 0.20 m^3/m^{-3} (Table 14).

For the loamy sand at Site 2, the corn yield decrease due to compaction at the wettest condition (not shown) was only 4%. A positive yield response to one tractor pass was also observed at the two drier water contents.

Implications

In general, the responses to compaction were similar for both soils. Both soils were compacted and total porosity was reduced. Severe reduction in corn yield

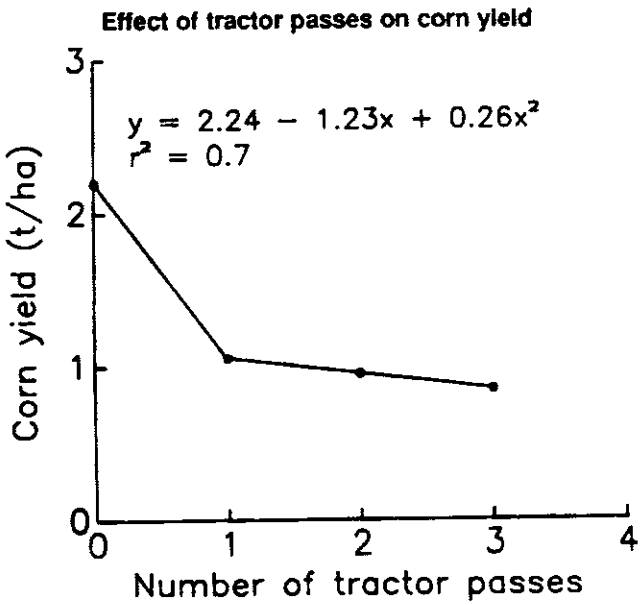

Figure 9. Corn yield as a function of the number of tractor passes at a soil water content of 0.36 m^3 m^{-3}.

Table 14. Corn grain yield as affected by soil water content and number of tractor passes in a sandy loam Ultisol (Site 1).

Soil water content	Number of tractor passes 0	1	2	3	Mean
m^3 m^{-3}	Grain yield, Mg ha^{-1}				
0.36	2.28	1.13	0.93	0.81	1.29
0.27	2.61	2.14	2.33	1.91	2.25
0.20	2.48	2.83	2.12	2.44	2.47
Mean	2.46	2.03	1.79	1.72	

$LSD_{.05}$
Soil water content = 0.64
Number of tractor passes = 0.38
Two different water contents for the same number of tractor passes = 0.66
Number of tractor passes at the same soil water content = 0.85

Table 13. Total porosity of the 0- to 10-cm depth of a loamy sand Ultisol (Site 2) as affected by the number of tractor passes and soil water content.

Soil water content	Number of tractor passes 0	1	2	3	4	5	10	Mean
m^3 m^{-3}	Total Porosity, %							
0.35	45.3	37.7	37.0	36.2	36.6	35.9	35.5	37.7
0.25	45.3	40.4	38.5	38.5	37.0	37.0	36.2	39.0
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 water content = 0.9
Number of tractor passes = 1.0
Two different water contents for the same number of tractor passes = 2.6
Number of tractor passes at the same soil water content = 2.5

always occurred for the highest soil water content of the sandy loam at Site 1. Because a severe yield reduction occurred when the soil was trafficked in its wettest state, an ideal strategy would be to postpone tilling for several days after a heavy rainfall event to allow the soil to dry. But this practice is difficult to implement in a region where rain commonly falls every two or three days during much of the year.

The soil moisture content at time of compaction had a critical effect on corn yield on the loamy sand at Site 2. At lower soil water contents, corn yield increased from "firming" of soil by wheel traffic. The sandy loam at Site 2 can be tilled 1 or 2 days after a rainfall event; 3 or 4 days is preferable on the sandy loam of Site 1.

Subsoiling vs. non-subsoiling

The objectives of this study were to investigate the impacts of six combinations of soil management practices on soil physical properties, root development, and crop yield in continuous cropping systems. The study was conducted on a sandy loam soil from September 1986 to October 1989.

Three of the six treatments included the deep tillage practice called "subsoiling," which loosens the soil with steel shanks below the depth of normal tillage without inverting the soil surface (Table 15). Subsoiling to the 30-cm depth was performed 2 days prior to seeding each crop.

The sequence of seeding and harvesting the six consecutive corn crops is given in Table 16. Each crop in treatment I through IV received 45 kg P ha^{-1}, which was incorporated with a disk harrow prior to imposing the tillage treatments. Treatments V and VI also were disk-harrowed, but P was banded during seeding. All crops received 120 and 83 kg ha^{-1} of N and K, respectively, in split applications. The herbicide Dual was applied after seeding to control weeds.

At tasseling, a 60-cm-deep trench perpendicular to the rows was dug in each plot. One face of the trench was smoothed off and the face marked off in a 10-cm x 10-cm grid. Corn roots were counted in each grid using the trench-profile method (Vepraskas and Hoyt 1988). Rainfall was near normal for the first two crops and drier than normal for the third and sixth crops (Figure 10).

Soil properties

Bulk density at the 0- to 15-cm depth, measured before harvest of the third corn crop, was not affected by management system (Table 17). At the 15- to 30-cm depth, however, bulk density for the three systems with subsoiling was less than those without subsoiling.

Table 15. Description of treatments in the subsoil versus non-subsoil experiment.

Treatment number	Description
1	Bed/subsoil/P broadcast: subsoiled to the 30-cm depth at spacings of 80 cm. A 15-cm high bed was formed over the subsoil slit in a second tractor pass, and corn was planted in the bed using a no-till planter. Herbicide (Dual) weed control was applied after planting. P was subsequently broadcast and incorporated.
2	Bed/P broadcast: decription similar to Treatment 1, but without subsoiling.
3	Flat/subsoil/P broadcast: subsoiled to the 30-cm depth at spacings of 80 cm. Corn was planted in a second tractor pass. Herbicide (Dual) weed control was applied after planting. P was subsequently broadcast and incorporated.
4	Flat/P broadcast: description similar to Treatment 3, but without subsoiling.
5	Bed/subsoil/P banded: description similar to Treatment 1. P banded at planting.
6	Bed/P banded: description similar to Treatment 2. P banded at planting.

Table 16. Dates of planting and harvesting six consecutive corn crops in the conventional-tillage experiment.

Crop number	Date planted	Date harvested
1	17 Sep 1986	23 Jan 1987
2	4 Jun 1987	6 Oct 1987
3	15 Dec 1987	28 Mar 1988
4	11 May 1988	14 Sep 1988
5	18 Nov 1988	17 Mar 1989
6	7 Jun 1989	11 Oct 1989

Mechanical impedance, reported as cone index, was lower in the rows of the subsoiled treatments (Figure 11). The zone of high mechanical impedance present at the 10- to 30-cm depth in the non-subsoiled treatments was eliminated by subsoiling. The bulk density values reported in Table 17 are positively correlated with cone index (i.e., bulk density increases as mechanical impedance increases). Mechanical impedance is also affected by soil water content, but only minor differences in water content existed when cone index measurements were made.

Table 17. Bulk density at two soil depths before harvesting the third corn crop.

Management system	0- to 15-cm	15- to 30-cm
	— *Bulk density, Mg m^{-3}*—	
Bed/subsoil/P broadcast	1.43	1.50
Bed/P broadcast	1.47	1.67
Flat/subsoil/P broadcast	1.45	1.52
Flat/P broadcast	1.51	1.65
Bed/subsoil/P banded	1.42	1.55
Bed/P banded	1.50	1.64
LSD (0.05)	0.09	0.08

Soil tests showed that the chemical constraints of this soil were eliminated by lime and fertilizer applications. Aluminum saturation in the Ap horizon was reduced from 80% to 10%, and the P, Ca, and Mg levels were increased. The split applications of K raised the exchangeable K concentration above the critical level.

Corn root distribution

Root density was greatest in the surface 10 cm of soil for the flat/P broadcast and flat/subsoil/P broadcast systems (Figure 12). Roots extended to a depth of 50 cm under each of the four rows that were subsoiled prior to seeding corn. Rooting depth was shallow in the trafficked and non-trafficked interrows for both treatments. The dense soil layer with high mechanical impedance below the interrows was not ruptured by the subsoiling operation. Subsoiling loosened only soil below and in close proximity to the row. The extra rooting volume created as a result of subsoiling increased the stored volume of plant available water.

Corn response

The extra plant available water made accessible by subsoiling increased yields for all crops except the first one (Table 18). Rainfall distribution during the first crop growing season was excellent and water stress was not a yield-determining factor. The

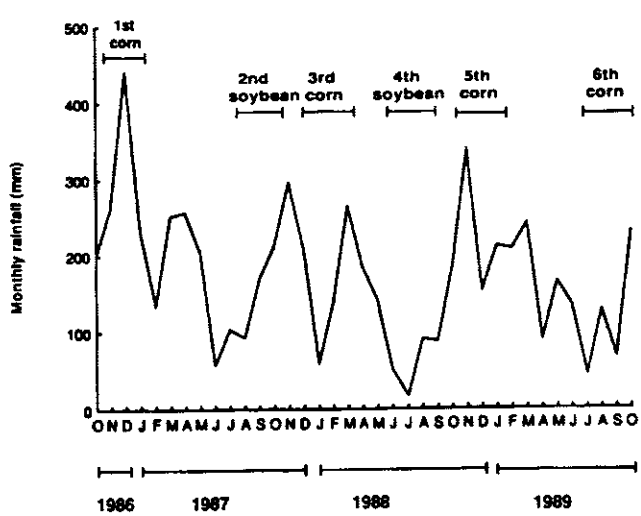

Figure 10. Monthly rainfall from October 1986 through March 1989 at Yurimaguas, Peru.

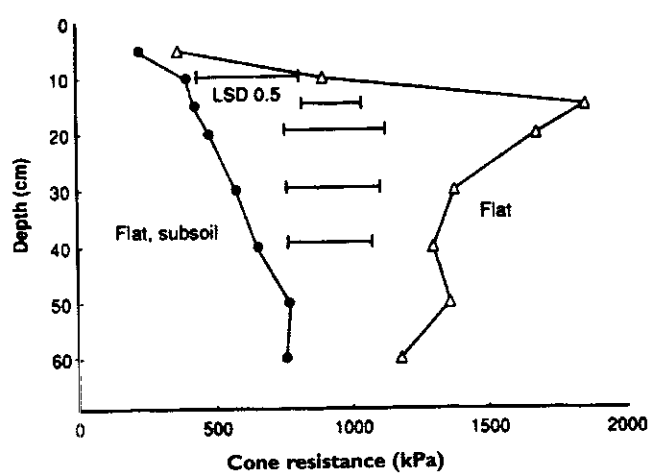

Figure 11. Cone resistance (kPa) at a depth of 0 to 60 cm before harvesting the third corn crop in flat-planted treatments.

response to subsoiling typically decreases as total rainfall increases during the growing season because soil water becomes less limiting to plant growth. The highest yields for four of the six crops were for the bed/subsoil/P-broadcast treatment. Over the three-year period, subsoiling increased corn yield of the bed/P broadcast system by 45% and the flat/P broadcast system by 48%. Responses to subsoiling varied for the bed/P banded system, but average yield increased by 14% during the three-year period.

Conservation tillage

The objectives of this study were: (i) to determine the feasibility of introducing minimum-tillage and no-tillage practices into mechanized, continuous-cropping production systems in the humid tropics and (ii) to determine the effects of each tillage system, with and without in-row-subsoiling, on soil physical properties, soil chemical properties, and crop yields.

The study was conducted from October 1986 to January 1989 on an isohyperthermic Typic Paleudult

Table 18. Corn grain yield for six consecutive crops as affected by soil management.

Management system	1st crop	2nd crop	3rd crop	4th crop	5th crop	6th crop	Mean
	Mg ha⁻¹						
Bed/subsoil/P broadcast	3.54	3.97	3.61	4.23	4.09	4.49	3.99
Bed/P broadcast	3.44	3.15	2.47	2.46	2.32	2.68	2.75
Flat/subsoil/P broadcast	3.43	3.52	3.69	3.88	3.88	3.71	3.69
Flat/P broadcast	3.40	3.25	2.10	1.95	2.21	2.01	2.49
Bed/subsoil/P banded	4.06	3.25	3.41	3.55	2.82	4.33	3.57
Bed/P banded	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	

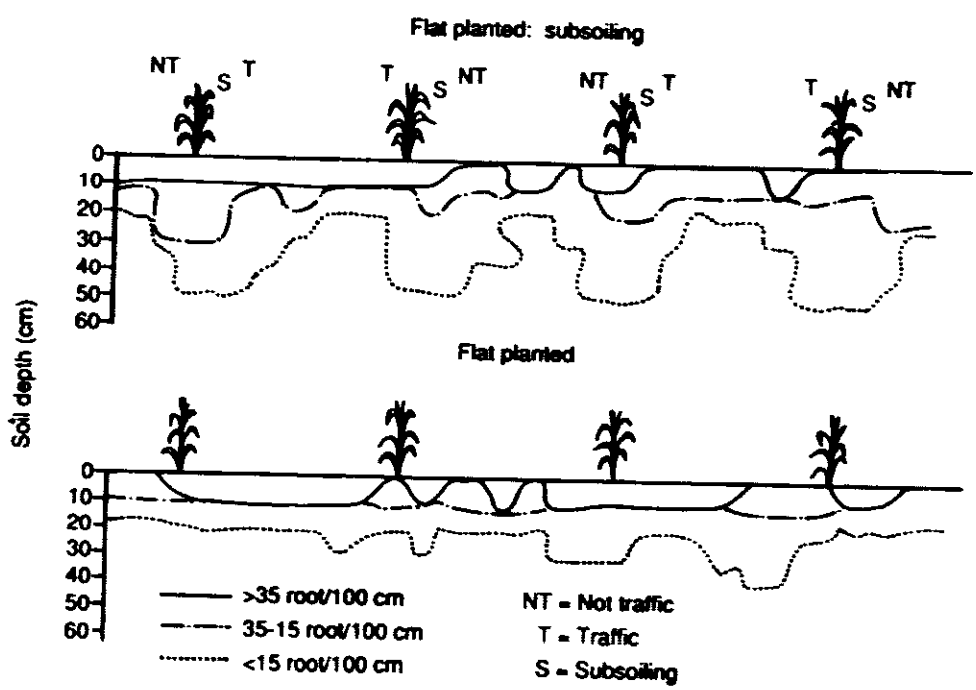

Figure 12. Corn root distribution for the fourth crop.

with slope ranging from 1 to 2%. The site was cleared by traditional slash and burn in 1972 (Seubert et al. 1977) and was continuously cropped until September 1986. During this period, 31 consecutive crops were grown. Lime and fertilizers were applied for these crops at rates determined by soil tests.

Six tillage treatments were imposed in October 1986 (Table 19). The crop rotation for the three-year period was corn-soybean-corn-soybean-corn (Table 20). Nitrogen and K at the rates shown in Table 20 were broadcast on the soil surface and disked before planting the first crop. The first corn crop (cv. Marginal 28) was seeded at 20-cm spacings in rows 80 cm apart. Phosphorus was banded at planting. Dual and paraquat, each at a rate of 2 L ha^{-1}, were applied before planting in the two minimum-tillage (MT, MTS) and the two no-tillage (NT, NTS) treatments.

Lime and P were broadcast before the second crop (soybean, cv. Jupiter) was seeded (Table 20). These materials were incorporated with a disk plow and disk harrow in the CT and CTS treatments, and with a disk harrow in the MT and MTS treatments. The materials were not incorporated into the soil for the NT and NTS treatments. No N or K was applied. Soybean inoculated with the appropriate rhizobium strain was seeded at 5-cm intervals in rows 50 cm apart.

Table 19. Tillage treatments imposed in the conservation tillage study.

Treatment		Cultural operations
Conventional tillage	(CT)	Bush-hog, disk plow, S-tine field cultivator, disk bed, bed shape, and planter. Dual herbicide applied.
Conventional tillage/subsoil	(CTS)	Same as CT, but subsoiled 30 cm deep at the time of disk bedding.
Minimum tillage	(MT)	Bush-hog, Dual and paraquat herbicide applied, no-till planting (coulter opening). Lime and P incorporated every 2 years with disk harrow.
Minimum tillage/subsoil	(MTS)	Same as MT, but subsoiler used ahead of coulters on the planter.
No-tillage	(NT)	Bush-hog, Dual and paraquat herbicide applied; no-till planting (coulter opening).
No-tillage/subsoil	(NTS)	Same as NT, but with subsoiler used ahead of coulter on planter.

Table 20. Seeding and harvest dates and amounts of lime and fertilizer applied before planting each crop.

Crop	Number	Date planted	Date harvested	Chemical applied				
				N	P	K	Mn	Lime
				kg ha^{-1}				
Corn	(1)	17 Oct 1986	1 Feb 1987	100	45	67		
Soybean	(2)	17 Jun 1987	25 Sep 1987		45			3000
Corn	(3)	11 Nov 1987	16 Mar 1988	120				
Soybean	(4)	23 May 1988	1 Sep 1988					
Corn	(5)	13 Sep 1988	5 Jan 1989	120	45	67	10	

The third crop (corn) was managed like the first corn crop, but only N was applied. The fourth crop (soybean) was planted like the second soybean crop, but no lime or fertilizer was applied because soil tests indicated adequate nutrient levels except for Mn. The fifth crop (corn) was fertilized with N, P, K, and Mn (Table 20).

Selected soil chemical and physical properties were measured before seeding and harvesting each crop. The concentration of N, P, K, and Mn were measured in the 0- to 15-cm soil depth. Bulk density was measured on soil cores with a diameter of 7.6 x 7.6 cm (Uhland 1950). Cores were taken in the row at the 0- to 10- and 10- to 20-cm depths. Mechanical impedance was measured in the row using a Soiltest cone penetrometer.

One runoff plot was installed in two replications of the conventional subsoil, minimum tillage/subsoil, and the no-tillage/subsoil treatments. Installation of each 10-m-long by 3.2-m-wide runoff plot was completed in October 1987. The slope was 2%.

Each runoff plot had wooden borders on three sides so that water from the surrounding area would not enter the plot. A collection system of small channels and serially connected containers to catch water and sediment was installed on the downhill side of each runoff plot. Water and suspended soil solids were diverted to a 200-L container. Overflow from this container passed through a multislot divisor with 11 slots. A second container collected one-eleventh of the water and suspended soil solids from the central slot. Daily rainfall was measured with a recording rain gauge. The amount of runoff water from each plot was recorded the day following a rain event. Grain and biomass yield were measured by hand-harvesting a 15-m^2 area in each plot.

Rainfall was above the 35-year average for the first and fifth crops, below average for the third crop, and near average for the second and forth crops (Figure 10).

Soil properties

In general, bulk density increased at both depths for the non-subsoiled treatments (Table 21). Bulk density at the 0- to 10-cm depth after harvest for each tillage treatment with subsoiling was similar to the initial bulk density of 1.40 Mg m^{-3}. Likewise, bulk density at the 10- to 20-cm depth for the subsoiled treatments after harvesting the fifth crop was similar to the initial 1.45 Mg m^{-3} value. For the non-subsoiled treatments, bulk density at the 0- to

Table 21. Bulk density at two soil depths in the crop row before planting the first crop and after harvesting the fifth consecutive row crop for six tillage systems.

Tillage	0- to 10-cm		10- to 20-cm	
	Before	After	Before	After
	Bulk density, Mg m^{-3}			
Conventional	1.40	1.44	1.45	1.55
Conventional/subsoil	1.40	1.41	1.45	1.44
Minimum tillage	1.40	1.51	1.45	1.55
Minimum tillage/subsoil	1.40	1.43	1.45	1.50
No-tillage	1.40	1.55	1.45	1.56
No-tillage/subsoil	1.40	1.45	1.45	1.47
LSD (0.05) (tillage x time)		0.05		0.07

Table 22. Cone index at two soil depths in the crop row before planting the first crop and after harvesting the fifth consecutive row crop for six tillage systems.

Tillage	0- to 10-cm		10- to 20-cm	
	Before	After	Before	After
	Cone index, Mg m^{-3}			
Conventional	0.30	0.50	0.51	1.75
Conventional/subsoil	0.30	0.40	0.51	0.65
Minimum tillage	0.30	1.50	0.51	1.40
Minimum tillage/subsoil	0.30	0.48	0.51	0.83
No-tillage	0.30	1.60	0.51	1.81
No-tillage/subsoil	0.30	0.52	0.51	0.88
LSD (0.05) (tillage x time)		0.30		0.35

10-cm depth was highest for no-tillage. No difference in bulk density among non-subsoiled treatments occurred at the 10- to 20-cm depth.

Cone index followed the same trend as bulk density (Table 22). After five crops, cone index in the 0- to 10-cm depth for the minimum tillage and no-tillage treatments was greater than for the conventional treatment. This was expected because the soil surface of the conventional treatment was mixed by plowing and disking before seeding each crop. At the 10- to 20- cm depth, however, subsoiling reduced cone index for the conventional, minimum tillage, and no-tillage treatments.

Analysis of soil samples collected after harvesting the first and fourth crops indicated that P and Ca accumulated in the surface 5 cm of soil in the no-tillage/subsoil treatment. Magnesium accumulated in the surface of all three treatments (Table 23).

Surface water runoff and soil loss

Surface-water runoff was higher than expected for a soil with a 2% slope. A maximum of 14% of total rainfall was lost to runoff over the 15-month period (Table 24). This occurred for the conventional tillage/subsoil treatment.

An even greater surprise was the 22.4 Mg ha^{-1} soil loss associated with this runoff. Soil loss from all three treatments was unacceptably high for this modestly sloping soil. Both runoff and soil loss were less for the minimum tillage/subsoil and no-tillage/subsoil treatments than for the conventional tillage/subsoil treatment. Although not measured in this study, the amounts of runoff and soil loss were likely even greater for the non-subsoiled tillage practices.

Table 24. Surface water runoff and soil loss for three tillage systems under continuous row crop production from November 1987 through January 1989.

Treatment	Runoff: Total	Runoff: Percent of precipitation*	Soil loss
	mm	%	*Mg/ha*
Conventional/subsoil	249	14.0	22.4
Minimum tillage/subsoil	120	6.8	19.4
No-tillage/subsoil	165	9.4	14.9
LSD (0.05)	43		5.5

*Total precipitation was 1757 mm.

Crop performance

Rainfall in December 1986 was 418 mm (Figure 10); the highest rainfall intensity was 51 mm/h. Subsoiling increased grain yield for the no-tillage/subsoil and minimum-tillage/subsoil treatments for the first crop (Table 25). In general, abnormally high rainfall reduced yields for the first corn crop. The no-tillage treatment became waterlogged during heavy rains, but internal drainage in the no-tillage/subsoil treatment was better and helped mitigate waterlogged conditions.

Both grain and stover yields for the second corn crop (crop 3 in the rotation) were greater for the conventional/subsoil than for the conventional treatment. No yield differences were found for the third crop. In general, corn grain yields tended to be greater for each pair of tillage practices when in-row-subsoiling was performed at or before seeding.

Table 23. Nutrient concentrations in the 0- to 5-cm depth after harvesting the first (corn) and fourth crops (soybean).

Tillage	P 1st	P 4th	K 1st	K 4th	Ca 1st	Ca 4th	Mg 1st	Mg 4th
	ug/L		*cmol/L*					
Conventional/subsoil	26	22	0.29	0.31	1.9	2.0	0.47	1.1
Minimum tillage/subsoil	32	29	0.35	0.27	2.4	1.7	0.46	1.2
No-tillage/subsoil	28	36	0.30	0.31	1.5	2.5	0.41	1.2

Table 25. Corn grain and stover yields as affected by tillage.

Tillage	Crop 1		Crop 3		Crop 5	
	Grain	Stover	Grain	Stover	Grain	Stover
	Mg ha⁻¹					
Conventional	1.90	2.40	2.35	1.94	2.91	3.99
Conventional/subsoil	2.00	2.50	3.39	3.89	2.68	4.53
Minimum tillage	1.44	1.94	2.66	2.32	2.58	4.07
Minimum tillage/subsoil	2.20	2.70	2.41	2.90	3.40	4.36
No-tillage	1.39	1.89	2.58	2.21	2.90	3.53
No-tillage/subsoil	1.90	2.40	2.83	3.27	3.27	3.26
LSD (0.05)	0.63	NS*	0.96	0.39	NS	NS

* NS indicates no significant difference.

Table 26. Soybean grain and stover yields as affected by tillage.

Tillage	Crop 2		Crop 4		Mean	
	Grain	Stover	Grain	Stover	Grain	Stover
	Mg ha⁻¹					
Conventional	1.80	1.32	0.80	1.05	1.30	1.19
Conventional/subsoil	1.99	1.42	1.18	1.50	1.59	1.46
Minimum tillage	1.79	1.27	1.20	1.00	1.50	1.14
Minimum tillage/subsoil	1.63	1.22	1.40	1.10	1.52	1.16
No-tillage	2.18	1.20	0.90	1.15	1.54	1.18
No-tillage/subsoil	2.25	1.37	1.25	1.40	1.75	1.39
LSD (0.05)	0.52	NS*	NS	NS		

* NS indicates no significant difference.

No consistent soybean grain-yield response was observed (Table 26). Although the first soybean crop was seeded later than desirable, the yields were adequate, primarily due to low rainfall (110 mm) during November 1986, which minimized moisture damage for the late-harvested crop. Yields for the second soybean crop were lower and many plants displayed symptoms of Mn deficiency. Soil Mn levels were less than 1 ppm at harvest time.

Conclusions

Conclustions based on this study are as follows:

- In-row subsoiling maintains lower bulk density and mechanical impedance in the crop row compared to non-subsoiled treatments.
- Surface-water runoff and soil loss were greater than expected on nearly level land (2% slope), and losses were greatest for conventional tillage.
- As a general tendency, subsoiling increases slightly grain yields of corn and soybean under no-tillage, minimum tillage, and conventional tillage.
- P, Ca, and Mg accumulated in the topsoil under the no-tillage regime.

Implications

When research on continuous cultivation of Ultisols began in the humid tropics at Yurimaguas, Peru, in the early 1970s, conventional wisdom was that the soils would turn to laterite within a few years after the land was cleared. A series of studies beginning with the land-clearing work of Seubert et al. in 1972 has subsequently refuted the conventional widsom: not only is continuous cropping possible on these soils, but they can be managed in much the same way that soils are managed in the southeastern United States. This finding has profound implications for developing countries; it indicates that a vast knowledge base can be employed to help meet their needs.

If tropical rain forest must be cleared, prudent growers select a clearing method that minimizes damage to the soil. Although slash-and-burn clearing meets this requirement, it is both slow and labor-intensive. Mechanical clearing is faster, but it tends to cause two major problems: topsoil removal and soil compaction.

Our findings indicate (i) that shear-blade clearing removes less topsoil than does straight-blade clearing and (ii) that the resultant compaction can be alleviated through subsoiling or disking.

Although minimum-tillage practices that do not remove crop residues can reduce erosion on rain forest soils, such practices can also reduce soil trafficability (i.e., the soil's ability to support machine and human traffic without undergoing undesirable changes in structure).

Our findings indicate that in-row subsoiling was effective in reducing subsurface compaction and increasing crop yields in areas where moisture conditions and traffic posed a threat to production.

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