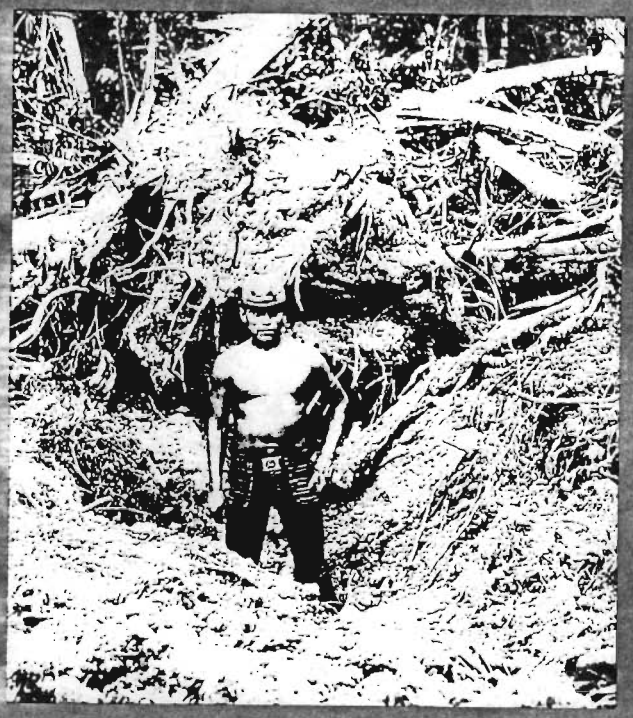
Land Clearing and Reclamation of Ultisols and Oxisols



Soil Management CRSP Bulletin No. 94–01

Land Clearing and Reclamation of Ultisols and Oxisols

Keith Cassel
Department of Soil Science
North Carolina State University
Campus Box 7619
Raleigh, NC 27695-7619
USA

J. C. Alegre
International Center for Research in Agroforestry
Yurimaguas Experiment Station
Yurimaguas, Loretto
Peru

Soil Management CRSP Bulletin Number 94-01. Published in January 1994 by the Soil Management Collaborative Research Support Program, Box 7113, North Carolina State University, Raleigh, NC 27695-7113. Tim McBride, editor. Funded in part by Grant No. DAN-1311-G-00-1049-00 from the U.S. Agency for International Development.

Foreword

Producing adequate food supplies and meeting the other basic needs of growing populations are difficult tasks on the finite soil resources of the humid tropics. All too often, inappropriate land-clearing methods and subsequent management practices degrade these soils, rendering them unproductive. The lands are then abandoned, and more rain forests must be cut. Soil management technologies capable of sustaining production are the key to stopping this environmentally destructive and economically unproductive pattern.

To help develop such technologies, the Soil Management CRSP (TropSoils) program at North Carolina State University—in partnership with the Center for Soil and Agroclimate Research (CSAR) in Indonesia and the Instituto Nacional de Investigacion Agraria y Agroindustrial (INIAA) in Peru—undertook extensive studies on the effects of land-clearing methods on some soils in the humid tropics. The collaborators also evaluated methods for reclaiming degraded soils. This report summarizes the findings of these studies.

The Soil Management CRSP gratefully acknowledges the support and hospitality of its Indonesian collaborators in Bogor, Sukarami, and Sitiung, as well as its Peruvian collaborators in Lima and Yurimaguas. These studies could not have been completed without host-country assistance. The support of USAID missions in Jakarta and Lima has also been invaluable.

This work was supported in part by USAID grant numbers 1311-G-SS-1083 and DAN-G-SS-6018-00, project number 9311311.

Roger G. Hanson, Director
Soil Management CRSP
North Carolina State University
Raleigh, NC 27695-7113
December 14, 1993

Acknowledgments

This research was supported by the U.S. Agency for International Development, North Carolina State University, the Instituto Nacional de Investigacion Agraria y Agroindustrial (INIAA) in Peru, and the Center for Soils and Agroclimatic Research in Indonesia.

Many individuals contributed to this work, but special acknowledgment is directed to Dr. Dale Bandy and Dr. Michael Wade, project managers at the Yurimaguas and Sitiung locations, respectively, when this research was being conducted.

Contents

Land Clearing in the Humid Tropics of Peru and Indonesia 7

Soil Chemical and Physical Properties 9

Land-Clearing Methods and Their Effect on Soil Properties of a Peruvian Ultisol 11

Land-Reclamation Methods in Peru and Their Effects on Soil Properties and Plant Response 21

Land Reclamation of an Oxisol in Indonesia 29

Implications 39

References 41

Land Clearing in the Humid Tropics of Peru and Indonesia

The Problem

In the humid tropics, the question isn't, "*Are* we going to clear more land?" Rather, policy-makers and producers ask, "*How* can we clear it in a way that maximizes long-term productivity and minimizes environmental damage?" The urgency of this request underlies a significant problem: land-clearing practices can be destructive—removing topsoil, compacting subsoil, and encouraging erosion. Because crop yields decline rapidly under these conditions, large tracts of newly cleared land have had to be abandoned.

The purpose of this study is (1) to compare land-clearing methods for their impact on agricultural productivity and (2) to identify land-reclamation strategies for those areas where inappropriate land-clearing methods have degraded the soil.

Soil Conditions

Evergreen forests cover 24% of the tropics (Sanchez and Buol, 1975). Although soils vary in these forests, rainfall and temperature regimes are favorable for many agricultural crops. Depending on the composition of the parent material, soil conditions are somewhat similar to those in the forested areas of the non-glaciated temperate zone. 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. Soils derived from basic materials are less acid and frequently neutral in reaction.

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 exchangeable 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 of 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 temperate regions, such as 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 commercial fertilizer.

Land-Clearing Methods

In the tropics, however, more than fertilizer must be considered if one is to maximize the efficiency of energy-related agricultural inputs. Research on land-clearing methods in the Amazon jungle of Peru, for example, indicates that traditional slash-and-burn methods (which use hand labor) produce higher first-year crop yields and impose lower costs than does mechanized clearing with a bulldozer (Seubert et al., 1977).

When comparing mechanized and traditional land-clearing methods, producers and planners must consider a number of variables, including (1) the high cost of operating and maintaining heavy machinery in a rain forest and (2) the fate of plant nutrients: under the traditional system, nutrients released from the ash of the burned slash can support the first few crops; under mechanized clearing, the plants that supply these nutrients are typically removed.

Clearing several hundred hectares may be attractive to development officials, but it creates havoc for farmers, who must cope with vigorous jungle regrowth, prepare friable seed beds, purchase and apply fertilizers and lime, and solve other severe management problems on a larger scale than that to which they are accustomed. Because farmers are often unprepared to manage areas larger than one or two hectares and unequipped to till compacted surface soil, many large areas are abandoned soon after they are cleared.

Research Sites

To clarify the impact of various land-clearing strategies, researchers conducted two experiments at Yurimaguas, Peru (Figure 1.) Particular attention was devoted to comparing slash-and-burn methods with conventional and improved bulldozing strategies.

To develop methodologies for reclaiming degraded land, researchers again conducted two experiments. The first (at Yurimaguas) focussed on plots that had been bulldozed, cropped, and abandoned. When the study began, the plots had been barren of secondary forest regrowth for six years. The second experiment was conducted at the Sitiung transmigration settlements in Sumatra, Indonesia. Here researchers arrived six years after a government-sponsored land-clearing project had so damaged the land that it was almost entirely devoid of topsoil and vegetation.

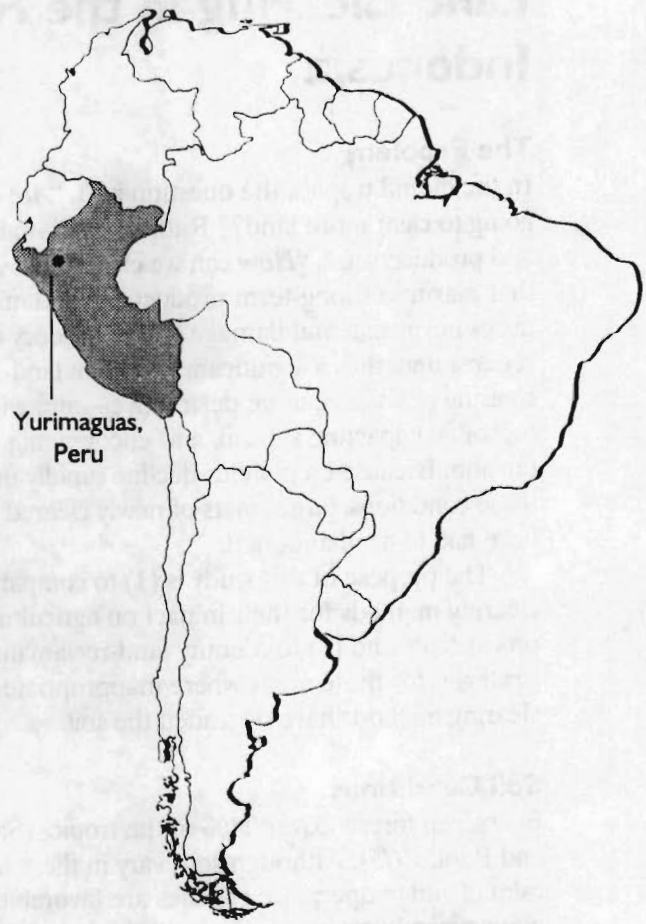


Figure 1. Land-clearing experiments and the initial land-reclamation experiment were conducted at Yurimaguas, Peru.

Soil Chemical and Physical Properties

Ultisol at Yurimaguas, Peru

Table 1 gives soil profile characteristics for a representative pedon at Yurimaguas. Soils in the humid regions of the upper Amazon basin are similar in many ways to soils in the southeastern U.S. They differ only in soil temperature regime. Annual average temperatures are > 22°C in Peru and between 15 and 22°C in the southeastern U.S. (Sanchez and Buol, 1974, 1975).

At the order level, soils are classified as Ultisols because clay content increases ≥ 20% between the A and B horizons. Ultisols are acid, and their percent base saturation decreases with depth. By definition, the base saturation as determined at pH 8.2 is less than 35% at the 1.8-m depth, or at 1.25 m below the top of the argillic horizon, whichever is shallower (Soil Survey staff, 1975).

The soil moisture regime is classified as udic, indicating that the subsoils are not dry more than 90 cumulative days per year in at least six out of ten years. Average rainfall in most of the Amazon basin of Peru is approximately 2000 mm year^{-1}. Poorly drained soils, Aqults, with high water tables occur in parts of Peru; some have a base saturation in the subsoil high enough to be classified as Aqualfs (Tyler et al., 1978).

The argillic horizons of the Udults at Yurimaguas are thick, and the clay content does not decrease by more than 20% of its maximum value within 1.5 m of the soil surface. Soils with these properties are classified as Kandiudults or Paleudults at the great-group level, depending on whether the apparent CEC of the clay is less than or greater than 16 cmol kg^{-1}. The Ultisols at Yurimaguas are Paleudults.

Selected soil physical properties for the Yurimaguas soil (Typic Paledults, fine-loamy, siliceous, isohyperthermic) under forest vegetation are shown in Table 2. These deep, well-drained soils have a sandy loam surface underlain by increasingly finer material. The high percentage of water-stable aggregates in the undisturbed soil surface creates a low bulk density, a low penetrometer resistance, and a high infiltration rate. Retention of plant available water to a rooting depth of 30 cm supports plant

Table 1. Profile characteristics of Yurimaguas series (loamy, siliceous, isohyperthermic, Typic Paleudult).

Horizon	Depth	Color	Sand	Silt	Clay	C	Free Fe	pH	Ca	Mg	K	Exch. acid	KCl ext. Al	Base sat.	Silicate clay minerals
	cm		%			*mg g^{-1}*			*Meq/100 g*						
A1	0–5	7.5YR4/4	80	13	6	30	20	3.8	.84	.37	.20	14.9	1.2	9	K3, Mtr
E	5–13	10YR4/3	70	20	10	80	40	3.7	.05	.03	.04	10.5	2.1	1	K3, Mtr
B1	13–43	10YR4/4	61	24	15	40	60	3.9	.05	.03	.03	9.0	2.8	1	K3, Mtr
B21	43–77	10YR4/4	57	26	17	30	60	4.0	.03	.02	.02	10.8	2.7	1	K3, Mtr
B22	77–140	5YR5/8	51	24	25	20	10	4.1	.03	.01	.03	12.5	4.2	1	K3, Mtr
B3	140–200	5YR5/8	54	22	24	20	80	4.4	.06	.03	—	10.0	3.5	1	K3, Mtr

Source: Tyler, 1975.
K = Kaolinite, M = Montmorillonite, tr = Trace, 3 = More than 50%.

growth for seven days (or fewer), assuming an evapotranspiration rate of 3 mm day^{-1}. The erosion hazard is minimal when the soil is under forest cover. The soil water characteristic indicates rapid release of water at pressures greater than –6 kPa (Figure 2).

Oxisol at Sitiung, Indonesia

Table 3 shows soil-profile data for a representative Oxisol in the transmigration area at Sitiung. Annual rainfall approaches 2600 mm year^{-1} with a weak dry season from June through September (Wade et al., 1988). The large amount of exchangeable aluminum, the low amount of exchangeable calcium, and the low pH in the nearly 2-meter-deep profile constrain rooting in crops that are not acid tolerant. Bulk density is typically about 1.0 g cm^{-3} for these soils and available water capacity ranges from 0.10 to 0.24 cm cm^{-1} soil (Subagio, 1988; Makarim et al., 1988).

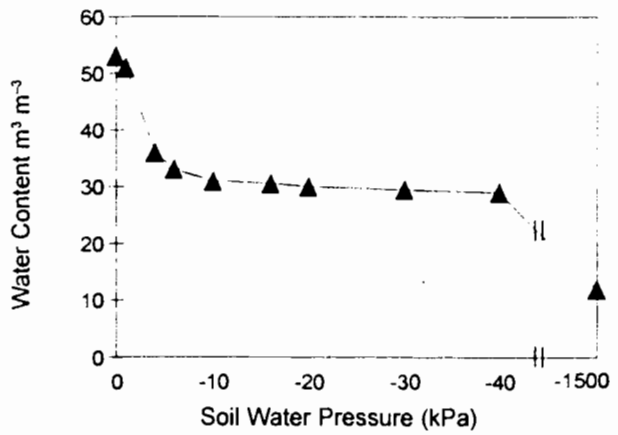


Figure 2. Soil water characteristic of the A horizon of a forested Yurimaguas soil (Typic Paleudult).

Table 2. Selected soil physical properties of a forested Yurimaguas soil (Typic Paleudult).

Depth	Sand	Silt	Clay	Bulk density	Penetration resistance	Infiltration rate	Water stable aggregates	Plant available water
cm	%			*Mg m^{-3}*	*kPa*	*cm h^{-1}*	%	*g g^{-1}*
0–5	60	28	12	1.10	61	117	45	17
5–40	44	36	20	1.35	100			
40–60	48	28	24	1.47	50			
60–90	40	36	24	1.57	115			
90–140	44	26	30	1.58	120			

Table 3. Profile characteristics of Pedon RBIA (clayey, kaolithic, isohyperthermic, Typic Haplorthox).

Horizon	Depth	Color	Sand	Silt	Clay	C	Free Fe	pH	Ca	Mg	K	Exch. acid	KCl ext. Al	Base sat.
	cm		%			mg g^{-1}			Meq/100 g					
A1	0–8	10YR4/3	40	14	46	54	42	3.1	0.4	0.3	0.2	5.0	4.3	1.0
BA	8–22	10YR4/4	36	13	51	14	36	3.5	0.2	0.2	0.2	3.3	3.2	0.8
Bt1	22–47	10YR5/6	28	7	65	8	39	3.8	0.1	0.1	0.1	3.3	3.1	0.8
Bt2	47–73	10YR5/6	25	3	72	5	42	3.8	0.1	0.1	0.1	2.8	2.7	0.4
Bt3	73–108	7.5YR5/6	25	8	67	5	44	3.8	0.2	0.1	0.1	2.8	2.7	0.5
Bt4	108–139	7.5YR4/4	28	2	70	4	63	3.9	0.2	0.1	0.1	2.2	2.1	0.5
Bt5	139–165	5YR5/8	18	9	73	—	45	3.9	0.2	0.1	0.2	2.2	2.1	0.6
Bt6	165–195	5YR5/6	16	9	75	—	48	3.9	0.1	0.1	0.2	1.9	1.8	0.9
BC	195–213	5YR5/6	17	17	66	—	48	4.0	0.2	0.1	0.2	2.3	2.2	0.6

Source: H. Subagjo, 1988, 1975.

Land-Clearing Methods and Their Effect on Soil Properties of a Peruvian Ultisol

Two land-clearing studies were conducted at the experiment station in Yurimaguas, Peru (5° 45' S, 76° 5' W, 184 m above sea level). Soils were fine-loamy, siliceous, isohyperthermic Typic Paleudults. Mean annual air temperature is 26°C, with little monthly or daily variation. Average annual rainfall is 2259 mm. Seasonally, the least rainfall occurs during June, July, and August when the average monthly precipitation is about 100 mm.

Study 1

A two-hectare tract covered by a 17-year-old secondary evergreen forest was cleared in 1972. The split-split-split plot design juxtaposed two clearing systems (slash and burn vs. mechanical) in the main plots, six cropping systems in the subplots, and seven fertility levels in the sub-subplots. Each 280-m^2 subplot was replicated four times.

For the slash-and-burn treatment, trees and underbrush were cut and allowed to dry for three weeks before burning. Tree trunks not burned were manually removed. Mechanical clearing was accomplished with a D-6 Caterpillar tractor with a conventional straight blade. All vegetation was removed, including stumps. Attempts to minimize topsoil removal were not always successful; results depended to a large degree upon the competence of the bulldozer operator.

Cumulative infiltration over 2.5 hours, measured one and eleven months after clearing, was twelve times greater for land cleared by slash and burn than for land cleared mechanically (Figure 3). Bulldozer clearing compacted the soil and increased bulk density (Table 4). Even after the bulldozer-cleared plots were rototilled, soil bulk density was higher at the 0- to 2- and 8- to 10-cm depths.

The plant nutrients in the ash were a valuable input (Table 5). Compared to bulldozed soil, the soil cleared by slash and burn contained more ex-

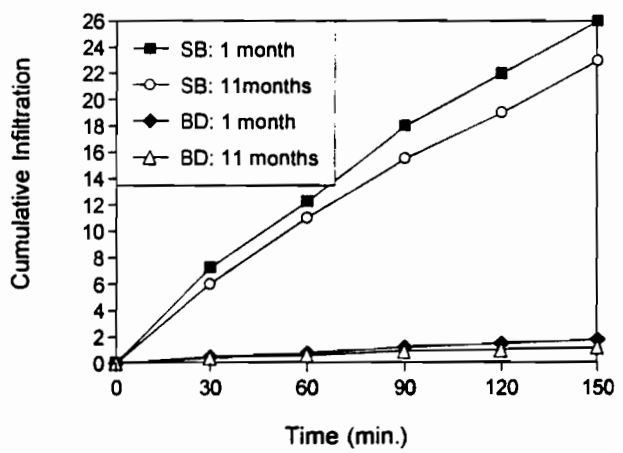


Figure 3. Cumulative infiltration versus time one and eleven months after clearing a Yurimaguas soil by slash and burn (SB) and by straight-blade bulldozer (BD).

Table 4. Soil bulk density of Yurimaguas soil ten months after clearing by two methods.

Tillage treatment	Soil depth	Slash and burn	Bulldozer
	cm	—— *Mg m⁻³* ——	
Untilled	0–2	1.24 a*	1.46 b
	8–10	1.51 b	1.67 c
Rototilled	0–2	1.43 b	1.44 b
	8–10	1.50 b	1.72 c

Source: Seubert et al. (1977).

* Density values in a row followed by the same letter are not different at the 0.05 level.

changeable bases, higher organic carbon and total N contents, and lower exchangeable acidity and percentage aluminum saturation compared to the bulldozed soil.

Table 6 summarizes crop yields during the two-year period following land clearing, when the soil received surface broadcast N, P, K, and lime at rates of 50, 172, and 40 kg ha^{-1} and 4 t ha^{-1}, respectively. All planting was done with a conventional planting stick and no other seedbed preparation. Rice (*Oryza sativa*), corn (*Zea mays*), soybean (*Glycine max*), and guinea grass (*Panicum maximum*) on the bulldozed plots yielded $\leq$ 80 percent of the yields on slash-and-burn land. Cassava (*Manihot esculenta*) yields appear little affected by clearing technique. Crops on the unfertilized, bulldozer-cleared land yielded about one third as much as those on the unfertilized slash-and-burn land. Limited yield responses to adequate fertilizing and liming suggest that this difference was caused by poor soil physical conditions, particularly the compaction that occurs during mechanical land clearing.

During two years of continuous cropping, yields on the bulldozed land progressively declined, and the land was then abandoned. Six years later it was still barren of secondary forest regrowth. Guinea grass continued to grow until 1980, when a land-reclamation study was initiated (Alegre et al., 1986b). The land cleared by slash and burn has supported (to date) 37 consecutive crops in a system of continuous production (Alegre et al., 1991).

Table 5. Nutrient content of the ash from burning the 3969 kg ha^{-1} dry matter (slash) from a 17-year-old secondary forest.

Element	Concentration	Amount
	mg g^{-1}	*kg ha^{-1}*
N	17.2	67
P	1.5	6
K	9.7	38
Ca	19.1	75
Mg	4.1	16
Mn	1.9	7.3
Fe	1.9	7.6
Cu	0.081	0.3
Zn	0.137	0.6

Source: Seubert (1976).

Table 6. Two-year summary of crop yields on land for two land-clearing methods on Yurimaguas soils receiving lime and N, P, and K fertilizers.

	Yield		
Crop	Slash and burn	Bulldozer	Bulldozer as percentage of slash and burn
	t ha^{-1}	*t ha^{-1}*	%
Rice	2.90	2.33	80
Corn	3.11	2.36	76
Soybeans	2.65	1.80	67
Cassava	25.6	24.9	97
Guinea grass	32.2	24.2	75
Mean relative yield			78

Source: Seubert et al. (1977).

Study 2

The second land-clearing study was located on a 2.5-hectare site in a 20-year-old secondary evergreen forest located 0.2 km from Study 1. It was designed to document temporal changes in soil properties due to various land-clearing regimes and post-clearing management systems. Forest mensuration on the nearly level site indicated 232 m^3 wood ha^{-1} for trees with diameter > 3.2 cm. The specific objectives of this study were (1) to determine the rates of change in

Figure 4. Because a conventional straight-blade bulldozer uproots trees, it can remove a great deal of topsoil, leaving huge holes in the cleared land.

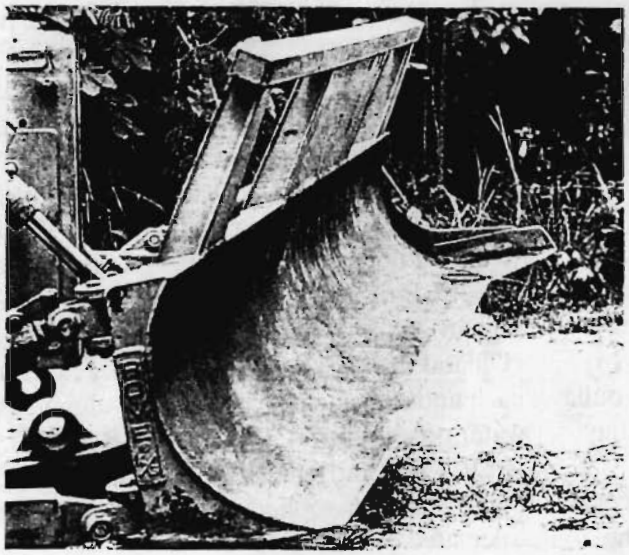


Figure 5. Unlike the conventional blade, the curved shear blade cuts trees off at ground level, thus minimizing disturbance to the soil. Note the stinger at the far end of the blade.

selected soil physical and chemical properties caused by several land-clearing and continuous-cultivation systems and (2) to determine crop performance for the various systems (Alegre et al., 1986a, 1986c, 1988; Alegre and Cassel, 1990).

The experimental design was a split plot replicated three times. Plot size was 6.5 m by 95 m. Two types of bulldozer blades were used for mechanical land clearing. The first was a straight blade, useful for road building, but undesirable for land clearing; due to its ready availability, however, it is often the blade of choice for clearing land in remote tropical regions (Figure 4). The second was a shear blade (Figure 5), so named because it shears off trees near the soil surface, with minimal soil disturbance or mixing. A sharp projection called a *stinger*—located on the lower edge of the curved blade—splinters large trees to facilitate the shearing action.

The six main-plot treatments included various land-clearing and soil-tillage combinations (Table 7). The vegetation in Treatment 1 was slashed by hand using a chain saw for trees and a machete for brush; the vegetation was allowed to dry and then burned. Tree trunks left after the burn were removed by hand, but the stumps remained. In Treatment 2, land was cleared with a Caterpillar D-6 bulldozer with a straight blade; the trees and understory were pushed into windrows. Immediately before planting, the soil

Table 7. Summary of treatments imposed in the 1980 land-clearing study at Yurimaguas.

Treatment number	Clearing method	Vegetation burned	Tillage
1	Slash	Yes	None
2	Straight blade	No	Rototill
3	Straight blade	No	Chisel, rototill[§]
4	Shear blade	Yes	Disk[¶], rototill
5	Shear blade	No	Rototill
6	Shear blade	No	Disk, rototill

[§] 65-hp rototiller, all others used a 14-hp rototiller.
[¶] Disking by bulldozer.

was rototilled to the 10-cm depth using a 10-kW (14-hp) tractor. Treatment 3 was similar to Treatment 2 except that the soil was chisel-plowed to the 25-cm depth and rototilled with a 48-kW (65-hp) tractor before planting. Land for Treatment 4 was cleared with a D-6 bulldozer using a shear blade; the vegetation was then burned, the logs removed by bulldozer, and the soil disked to the 30-cm depth with a bulldozer (Figure 6); before each crop was planted,

Figure 6. Although disking helps to alleviate some surface-soil compaction, it is less effective than chisel plowing in alleviating subsoil compaction.

the soil was rototilled with a 14-hp tractor. For Treatment 5, the soil was cleared by shear blade and rototilled with a 14-hp tractor before planting. Treatment 6 was similar to Treatment 5 except that the soil was also disked to 30 cm.

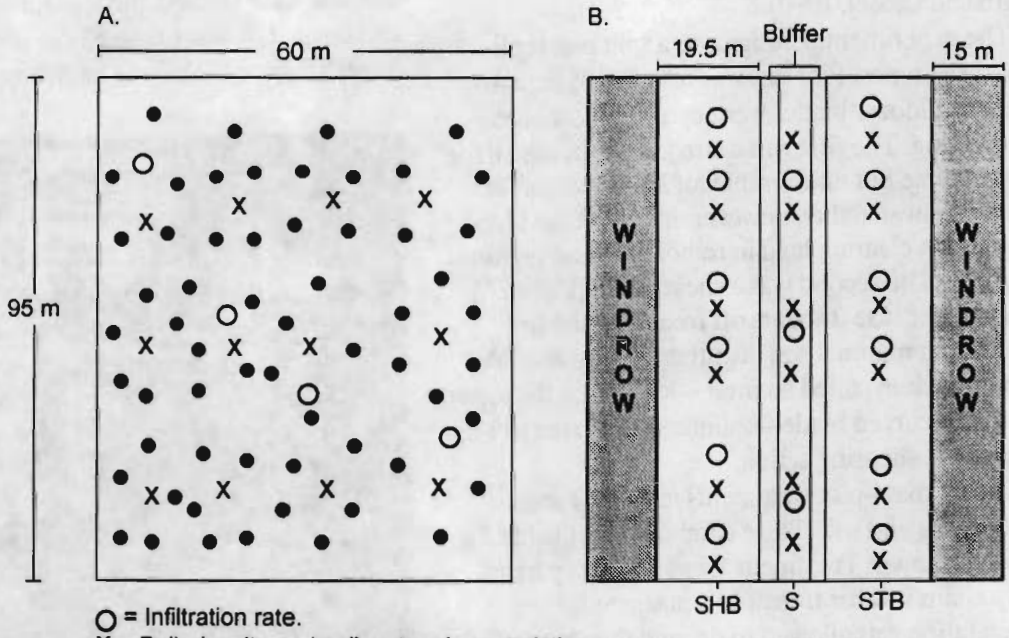
Soil physical and chemical properties were measured four times during this study. Soil physical properties were measured at specific locations in Block 1 before clearing and 14 weeks after clearing (Figure 7). Properties measured before clearing were infiltration rate, soil surface texture (0 to 15 cm), aggregate stability (AS), cone index (CI), bulk density (Db), soil water characteristic, and wilting point in the 0- to 15- (upper) and 15- to 25-cm (lower) soil depths. Measurements taken 14 weeks after clearing, but before rototilling and planting the first crop, included Db, soil water characteristic in the upper and lower depths, infiltration rate, and soil texture.

Soil chemical properties measured before and 14 weeks after clearing were organic carbon (OC), total nitrogen (N), acidity (pH), percent aluminum saturation (Al sat), exchangeable calcium (Ca), exchangeable potassium (K), effective cation exchange capacity (ECEC), and available phosphorus (P).

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 soil-test model CN-970 proving ring cone penetrometer. Cone diameter was 11.8 mm, and the cone angle was 30°. Bulk density was determined on 76-mm high by 76-mm diameter undisturbed soil cores (Uhland, 1950). The soil water characteristic for each undisturbed soil core was developed using soil water pressures of 0, –0.03, –5.7, –8.7, –12.7, –17.8, –22.9, –33.0, and –43.2 kPa. The pore neck diameter (d) at each applied soil water pressure was calculated by

$$d = 400\ S / d_w\ gh$$

where S is the surface tension of the water at 20°C, d_w is the density of the water at 20°C, g is the gravitational acceleration, and h is the soil water pressure head (m). Infiltration rate was measured in the field with a double-ring infiltrometer having inner- and outer-ring diameters of 30 and 60 cm,



○ = Infiltration rate.
X = Bulk density and soil water characteristics.
● = Penetrometer resistance and water content at the 0- to 15- and 15- to 25-cm depth.

Figure 7. Sampling pattern in the 1980 land-clearing study for soil physical properties in Block 1: A, before clearing; B, 14 weeks after clearing (SHB = shear blade, S = slash, STB = straight blade).

respectively. Wilting point was estimated using disturbed soil samples in a pressure chamber at –1500 kPa. Aggregate size distribution (Alegre et al., 1986a) was measured using a modified wet-sieving technique (Yoder, 1936), employing the apparatus designed by van Bavel (1952). Aggregate mean weight diameter (MWD) and geometric mean diameter (GMD) were calculated (Mazurak, 1950).

Ash samples for total nutrient analysis were collected immediately after burning the vegetation. Organic carbon content of the upper soil depth was determined by the Walkley-Black procedure (Hunter, 1974). Total soil N was determined using a modification of the semi-micro Kjeldahl technique described by Bremner (1960). Available P and exchangeable K were extracted from the soil using a modified Olsen extractant with the addition of EDTA according to the International Soil Fertility Evaluation and Improvement Laboratory Procedures (Hunter, 1974). Extracted P was determined calorimetrically by the molybdenum blue method; extracted K was determined by flame photometry. Exchangeable Ca, Mg, Al, and exchangeable acidity were extracted with 1 M KCl (Hunter, 1974). Calcium, Mg, and Al in the extract were determined by atomic absorption. ECEC was calculated as the sum of exchangeable Al, Ca, Mg, and K. Exchangeable acidity was determined by titration with standardized 0.01 M NaOH using a phenolphthalein indicator. Percent aluminum saturation is the amount of exchangeable Al divided by ECEC.

Bulk Density

Mechanical clearing increased Db at both the 0- to 15- and 15- to 25-cm depths (Table 8). Some compaction occurred for slash clearing in the upper depth due to foot traffic during the slashing and trunk-removal processes. The trend was for Db in the 0- to 15-cm depth to be greatest for straight-blade clearing, but it was not statistically different from the shear-blade and slash methods.

Cone Index and Soil Water Content

Cone index data were subjected to a $\log_{10}$ transformation prior to statistical analysis because the CI data were found to fit a log normal distribution. Prior to clearing, CI was slightly, but not significantly, greater for the 0- to 15-cm depth compared to the 15- to 25-cm depth (Table 9). As expected, $\log_{10}$ CI was negatively correlated with water content (individual data not shown); correlation coefficients were –0.5 and –0.7 for the upper and lower depths, respectively, and both correlations were significant at the 5% level.

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 8. The water held between soil water pressures of –13 and –1500 kPa (which is equal to 0.187 $m^3\ m^{-3}$) approximates the plant-available water holding capacity

Table 8. Bulk density and standard deviation (in parentheses) of Yurimaguas soil prior to and 14 weeks after land clearing, but before rototilling and planting the first crop.

Time	Clearing method	Depth (cm) 0 to 15	15 to 25
		Mg m⁻³	
Before clearing		1.16 (0.09) b*	1.39 (0.08) b
Fourteen weeks after clearing	Slash	1.27 (0.07) a	1.37 (0.10) b
	Straight blade	1.42 (0.12) a	1.49 (0.12) a
	Shear blade	1.28 (0.25) a	1.50 (0.15) a

* Means within a given column followed by the same letter are not significantly different at the 5% level by the Waller-Duncan multiple comparison test.

Table 9. Cone index (CI), $\log_{10}$ CI, soil water content and their standard deviations (in parentheses) at two depths for Yurimaguas soil before land clearing.

Depth	CI	Log_{10} CI	Soil water content
cm	*kPa*		*g g⁻¹*
0–15	745 (410)	2.809 (0.239)	0.226 (0.054)
15–25	684 (435)	2.771 (0.227)	0.225 (0.037)

before land clearing. Pores with neck diameters > 23 μm (equation [1]) are drained at *in situ* field capacity.

Figure 8 also shows the soil water characteristic in the 0- to 15-cm depth 14 weeks after clearing for treatments without disking or chisel plowing. Treatments with straight-blade clearing had greater soil water contents at soil water pressures < –2 kPa compared to treatments involving slash-and-burn or shear-blade clearing. These higher water contents are attributed to the destruction of macropores by compaction, which in turn increased the volume of micropores. The same trend was present for the soil water characteristic for the 15- to 25-cm depth 14 weeks after clearing (Figure 8).

Infiltration Rate

Both mechanical-clearing methods reduced the infiltration rate. The mean rate before clearing was 420 mm h^{-1} over a 2-h period (Figure 9). Fourteen weeks after clearing the mean rates during the first two hours of infiltration were 304, 14, and 23 mm h^{-1} for the slash, straight-blade, and shear-blade methods, respectively. A comparison of Figures 9 and 6 shows that infiltration responded similarly for both land-clearing studies.

Aggregate Stability

Figure 10 shows the percentage of water-stable aggregates in each of five aggregate size classes before clearing and for the three land-clearing methods receiving no disking or chisel plowing three months after clearing. Straight-blade clearing damaged soil structure the most, as indicated by the decrease in the percentage of aggregates in the 2- to 1-mm and 1- to 0.5-mm classes, coupled with the large increase in the < 0.10-mm class. Many of the larger aggregates were crushed or removed from the field when the vegetation was pushed into windrows during straight-blade clearing. The percentage of 0.25- to 0.50-mm water-stable aggregates was not altered by any clearing method. The percentage of aggregates in this class tends to be quite stable and is highly correlated with air-filled porosity and water holding capacity (Henin and Gras, 1972).

Mean weight diameter (MWD) and geometric mean diameter (GMD) before and three months after land clearing were not affected by slash-and-burn or shear-blade clearing (Table 10). Straight-

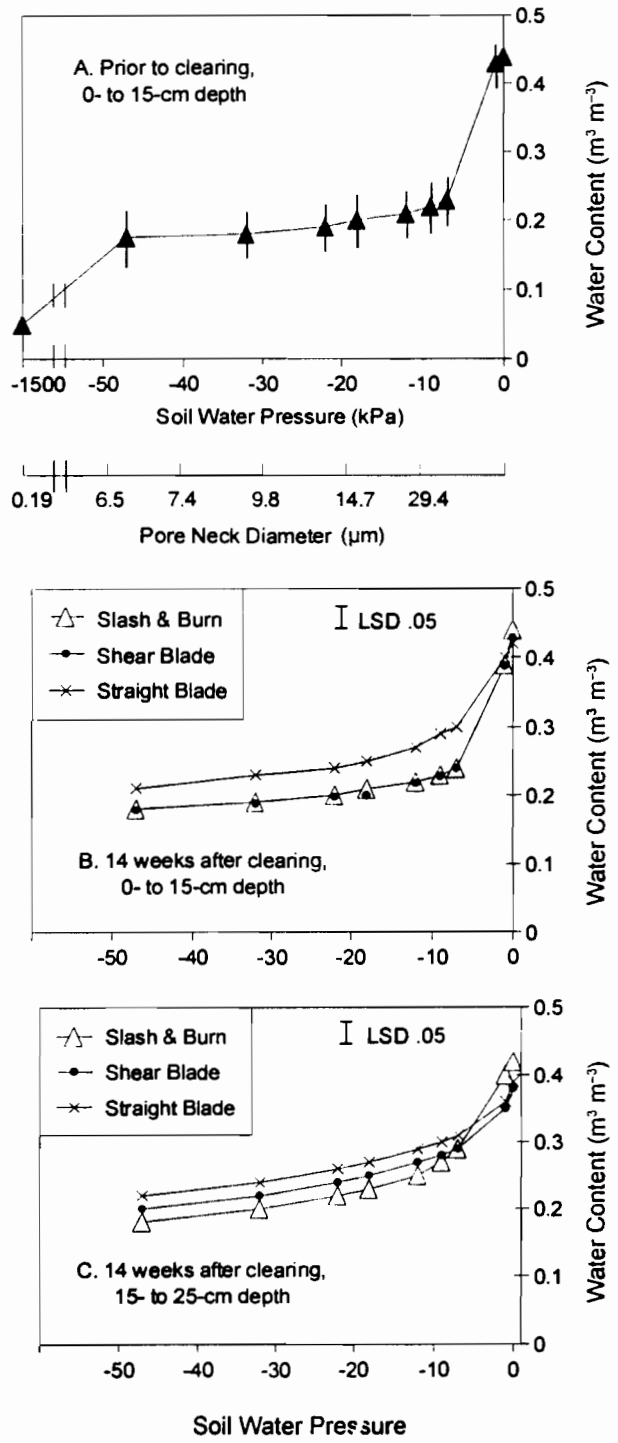


Figure 8. Soil water characteristics and pore neck diameter for the 0- to 15-cm depth and the 15- to 25-cm depth at Yurimaguas. The vertical lines through some of the data are two standard deviations long.

blade clearing reduced MWD and GMD by compaction or by removing some of the well-aggregated material when the larger root debris was removed. Seubert et al. (1977) also reported significant soil disturbance and compaction during mechanical clearing with a straight blade. The bare soil exposed by straight-blade clearing is very susceptible to erosion for two to four weeks, or even longer, until natural vegetation returns or until planted crops provide soil cover.

Additional measurements of soil physical properties were taken about two years after the land was cleared, but the results are similar to those above and are not shown. These data clearly indicate that mechanical land clearing causes undesirable changes in some physical properties of sandy-loam surface-textured soils. Data also indicate that slash-and-burn clearing causes the least amount of deterioration in soil physical properties.

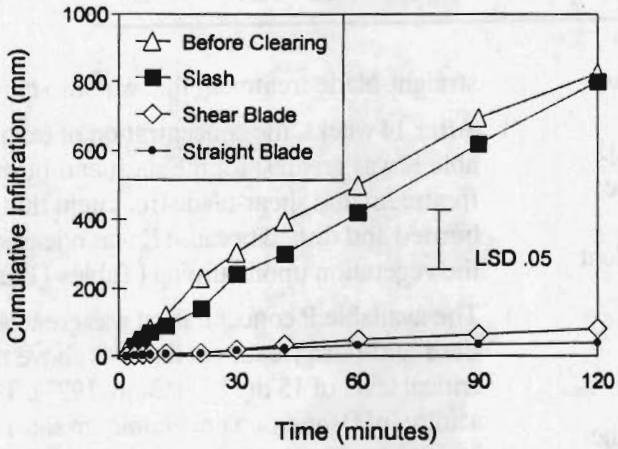


Figure 9. Cumulative infiltration before clearing and 14 weeks after clearing a Yurimaguas soil.

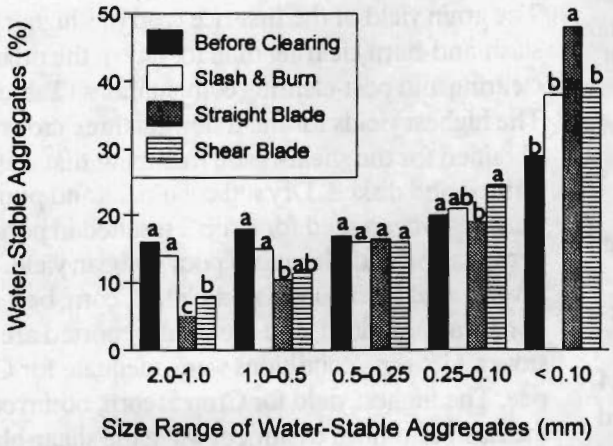


Figure 10. Percentages of water-stable aggregates in five aggregate size classes before clearing and three months after clearing as affected by land-clearing method. For each aggregate size class, columns with the same letter are not significantly different at the 5% level by the Waller-Duncan multiple comparison test.

Nutrient Content of Ash

The concentrations of various chemical species at three soil depths before land clearing were very low, whereas percent Al saturation was > 87% (Table 11). The low pH reflects the high Al saturation and low base status.

Concentrations and amounts of various nutrients derived from burned and partially burned leaf, stem, and litter for the slash-and-burn and shear-blade-and-burn (SBB) treatments are presented in Table 12. The nutrients were released from 7.5 and 6.6 Mg ha^{-1} of ash (not significantly different) for the slash-and-burn and SBB treatments, respectively. Only the amounts of Ca, Mg, Cu, and Zn were significantly greater for the slash-and-burn compared to SBB treatment. The amounts of nutrients were higher than

Table 10. Mean weight diameter (MWD) and geometric mean diameter (GMD) of Yurimaguas soil before and three months after clearing.

Time	Clearing method	MWD Mean	MWD SD	GMD Mean	GMD SD
Before clearing		0.484 a*	0.090	1.04 a	0.20
Three months after clearing	Slash/burn	0.424 a	0.098	1.05 a	0.10
	Straight blade	0.292 b	0.063	0.82 b	0.17
	Shear blade	0.358 ab	0.073	0.87 ab	0.20

* Means within a given column followed by the same letter are not significantly different at the 5% level by the Waller-Duncan multiple comparison test.

Table 11. Selected chemical species and effective cation exchange capacity at three depths in Yurimaguas soil prior to land clearing.

		Total			Exchangeable					
		Available								
Depth	pH	Organic carbon	N	P	Al	Ca	Mg	K	ECEC	Al saturation
cm		*g kg⁻¹*	*— mg kg⁻¹ —*		*——— cmol kg⁻¹ ———*					%
0–15	4.1	11.4	1.06	8	3.02	0.20	0.13	0.08	3.43	87
15–30	4.2			6	3.30	0.20	0.07	0.09	3.66	90
30–45	4.2			5	3.26	0.16	0.07	0.06	3.54	91

those reported by Seubert et al. (1977) for slash-and-burn clearing. The amounts of Ca and Mg derived from the ash of the slash-and-burn method were 131 and 68 kg ha^{-1}, respectively; taken together, they are equivalent to about 600 kg ha^{-1} of dolomitic limestone. Ca plus Mg for the SBB method was equivalent to about 350 kg ha^{-1} of dolomitic limestone.

Organic Carbon and Total N

Organic carbon (OC) content of the topsoil to a depth of 10 cm before clearing was 11.4 g kg^{-1}. Neither slash-and-burn nor shear-blade clearing altered OC content, but straight-blade clearing decreased it to 8.2 g kg^{-1}. This result was anticipated because straight-blade clearing generally removes some of the topsoil and litter, which have the highest OC contents. Shear-blade clearing minimizes the removal of topsoil and litter.

Chemical Content of Cleared Soils

Few chemical properties were affected by land-clearing method. Micronutrient levels did not change except for methods that involved burning (data not shown, see Alegre et al., 1988). The following generalizations can be made:

1) A significant reduction in OC was measured 14 weeks after clearing with the straight-blade and shear-blade treatments due to increased oxidation rates at higher soil temperatures. In addition, some OC on the soil surface was removed during clearing with the straight blade.
2) Due to the additions of ash, exchangeable Ca was greater for slash-and-burn clearing compared to the shear-blade treatment and the straight-blade treatment that was also chiseled.
3) After 14 weeks, the concentration of exchangeable K was greatest for the slash-and-burn treatment and shear-blade treatment that was burned and disked because K was released from the vegetation upon burning (Tables 11 and 12).
4) The available P concentration was greatest for slash-and-burn treatment and was above the critical level of 15 mg kg^{-1} (Cano, 1973). Total N, acidity (pH), and percent aluminum saturation in the 0- to 15-cm depth were not affected by land-clearing treatment.

Crop Response

The grain yield of the first rice crop was higher for slash-and-burn clearing than for any of the other land-clearing and post-clearing combinations (Table 13). The highest yields for the following three crops were obtained for the shear-blade treatment that was burned and disked. Dry soil conditions and poor quality soybean seed for Crop 2 resulted in poor germination and ultimately poor soybean yield. A severe wind storm destroyed Crop 3, corn, before grain was produced, and the yields reported are for stover. Growing conditions were adequate for Crop 4, rice. The highest yield for Crop 5, corn, occurred for the slash-and-burn treatment while the shear-blade treatment that was burned and disked yielded 81.2% of this amount.

A summary of the data in Table 13 shows that the mean relative yields for the five crops are nearly the same for both the slash-and-burn treatment (93.3%) and shear-blade treatment that was burned and

disked (93.4%). Straight-blade clearing without subsequent tillage to break up the soil compaction that occurs during clearing is the least desirable of the evaluated systems. Straight-blade clearing followed by chisel plowing produced higher mean relative yields than the shear-blade and shear-blade-and-disk systems. Clearly, the greatest yields occur for those systems which prevent major compaction (e.g., slash-and-burn) or those which alleviate compaction after it has occurred (e.g., straight-blade-and-chisel).

Table 12. Nutrient content of the ash of a 20-year-old secondary evergreen forest for two land-clearing systems at Yurimaguas, Peru.

Nutrient	Concentration units	Slash and burn		Shear blade and burn	
		Concentration[§]	Amount	Concentration	Amount
			kg ha⁻¹		*kg ha⁻¹*
N	g kg^{-1}	9.5	75	9.5	64
P	mg kg^{-1}	2600	19	2000	14
K	$cmol_c$ kg^{-1}	31.3	89	12.1	31
Ca	$cmol_c$ kg^{-1}	43.5	131	32.5	88
Mg	$cmol_c$ kg^{-1}	38.3	68	20.0	33
Mn	mg kg^{-1}	1400	10.3	800	5.2
Mg	mg kg^{-1}	2600	20	3300	23
Cu	mg kg^{-1}	55.0	0.4	30.0	0.2
Zn	mg kg^{-1}	66.0	0.7	42.0	0.3
Dry matter	—	—	7500	—	6600

[§] Amounts of Ca, Mg, Cu, and Zn were greater for the slash and burn than for the shear blade and burn at the 5% level.

Table 13. Relative crop yield at Yurimaguas as affected by land clearing and post-clearing management.

No.	Whole plot treatment	Rice grain crop 1	Soybean grain crop 2	Corn stover crop 3	Rice grain crop 4	Corn grain crop 5	Mean relative yield
1	Slash/burn	100 a[§]	97.4 ab	80.9 b	88.3 b	100 a	93.3
2	Straight blade	66.2 cd	56.0 d	41.2 c	47.7 d	40.4 c	50.3
3	Straight blade/chisel	64.2 cd	80.2 abc	95.8 a	83.5 b	72.5 b	79.2
4	Shear blade/burn/disk	85.6 b	100 a	100 a	100 a	81.2 ab	93.4
5	Shear blade	70.1 c	74.5 cd	89.0 ab	67.7 c	47.7 c	69.8
6	Shear blade/disk	58.3 d	78.3 bc	86.3 ab	55.3 b	44.0 c	64.4

[§] Means within a given column followed by the same letter are not significantly different at the 5% level. Maximum yields for crops 1–5 are 3.55, 1.57, 3.35, 2.66, and 2.18 t/ha, respectively.

Land-Reclamation Methods in Peru and Their Effects on Soil Properties and Plant Response

The Yurimaguas soil cleared by a straight-blade bulldozer in 1972 (land-clearing Study 1) was abandoned in 1974. Selected physical and chemical properties of this soil (which was covered by guinea grass after being abandoned) were characterized in 1979. A compacted zone between the 15- and 45-cm depth was found (Figure 11). Pertinent soil chemical data are presented in Table 14. Exchangeable acidity and percent aluminum saturation increased with depth (Alegre et al., 1986b).

In February 1980, guinea grass, which covered the entire experimental area, was cut by hand, allowed to dry, and burned. Eight land-reclamation treatments were imposed in a randomized complete block design, with four replications (Table 15). Plot dimensions were 4 m by 10 m. Treatments 1 and 6 required no mechanized tillage, whereas treatments 2, 5, and 8 required small power machinery. A 65-hp tractor was required to pull tillage implements in Treatments 3 and 4. Chisel plow shanks spaced 30 cm apart extended 25 cm below the soil surface and physically disrupted the compacted soil (Figure 12). Because Treatment 7 required a more powerful tractor than was available, subsoiling was simulated manually by loosening the soil to the 30-cm depth with a tile spade at the positions where the rows would later be planted (Gooderham, 1976). The no-till treatment was a facsimile of the traditional slash-and-burn method used in the area; seeds were dropped into small holes made with a sharp-pointed planting stick. Dry plant material for mulch, at the rate of 2 t ha^{-1}, was brought in from outside the plot boundaries for Treatment 8.

The cropping sequence for all eight treatments is shown in Table 16. Tillage was repeated before each successive crop was seeded. Before upland rice (cv. IR 4-2) was planted on 2 February, all plots received lime at the rate of 1.0 t ha^{-1} and were fertilized at rates of 80, 44, 66, and 12 kg ha^{-1} for N, P, K, and Mg,

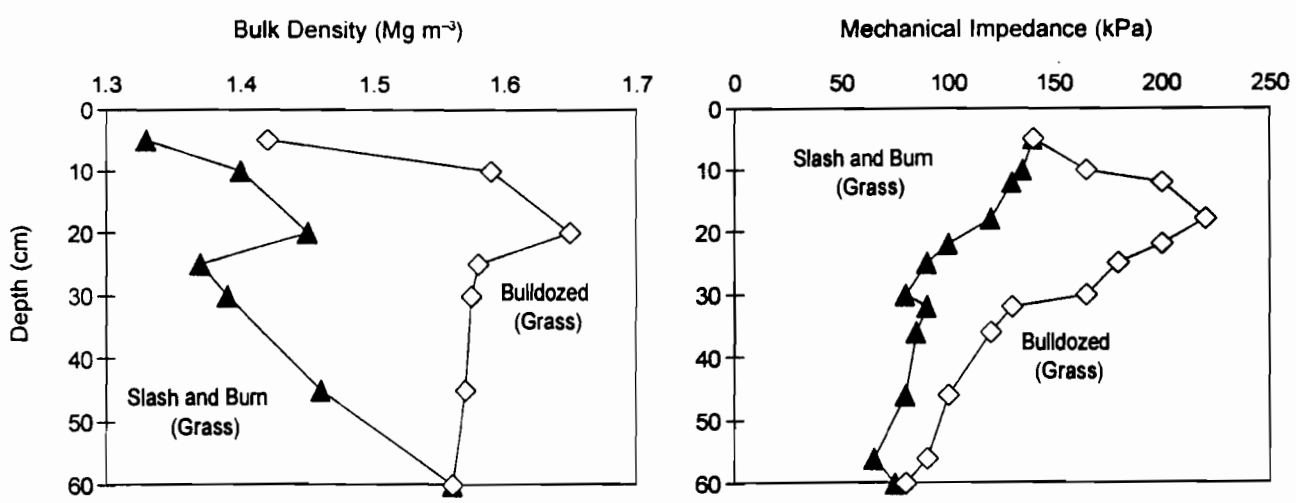


Figure 11. Bulk density and mechanical impedance in the 0- to 60-cm depth before the land-reclamation study began.

Table 14. Soil chemical properties prior to initiating the soil reclamation study in 1979.

Depth	Acidity	Exchangeable acidity	Ca+ Mg	Available P	Aluminum saturation	Organic carbon
cm	*pH*	—— *cmol$_c$ kg^{-1}* ——		*mg kg^{-1}*	%	*g kg^{-1}*
0–15	4.5	1.87	1.10	6.5	62.9	11.4
15–30	4.5	2.82	0.64	2.3	81.5	—
30–45	4.4	3.30	0.35	1.3	90.4	—

respectively. These amendments were tilled into the soil for all except Treatment 1. The sixth crop, rice, received fertilizer at the same rate as the first rice crop. Seed spacing was 20 cm by 20 cm when the planting stick was used; for all other treatments, rice was seeded with a hand planter in continuous rows spaced 20 cm apart. Each rice crop was hand-weeded twice. Rice and grain were harvested from 15 m^2 of area in each plot, and the grain yield was expressed at 13% moisture.

The second and fourth crops in the rotation, soybean (cv. Jupiter), received fertilizer at rates of 20, 44, 66, and 24 kg ha^{-1} for N, P, K, and Mg, respectively. The seed was inoculated with *Rhizobium japonicum* (Nitragin). Seed spacing was 40 cm by 5 cm when stick planted; for the other treatments, soybean was seeded at the identical population using a hand planter in rows spaced 40 cm apart. Each soybean crop was hand-weeded once. Grain was harvested from 15 m^2, and grain yield was expressed at 14% moisture.

The third and fifth crops, corn (cv. Amarillo Planta Baja), received 0.50 t ha^{-1} of lime and 100, 44, 66, 12, and 20 kg ha^{-1} of N, P, K, Mg, and S,

Figure 12. Chisel-plow shanks extend deep into the subsoil and thus help break up compaction.

Table 15. Tillage or seedbed preparation treatments imposed on Yurimaguas soil compacted by mechanical land clearing in 1972.

Treatment Number	Description
1	Control, no-till: cut grass and burn, plant with stick.
2	Rototill (14-hp tractor): cut grass and burn, rototill, and plant with stick.
3	Rototill (65-hp tractor): cut grass and burn, rototill, and plant with hand planter.
4	Chisel plow: cut grass and burn, chisel plow to 35-cm depth, rototill (48-kW tractor), and plant with hand planter.
5	Controlled traffic: cut grass and burn, rototill (14-hp tractor), and plant with hand planter; pathways for foot traffic were assigned.
6	Bedding: cut grass and burn, bed with hoe, and plant with stick.
7	Simulated subsoiling: cut grass and burn, simulate subsoil operation with shovel, rototill, and plant with hand planter.
8	Mulching: cut grass and burn, rototill, plant with hand planter; mulch applied when seedlings were 10- to 30-cm tall.

respectively. Seed spacing for all plots was 80 cm by 20 cm. Corn was harvested from a 14.4-m^2 area, and grain yield was expressed at 15% moisture.

The following soil physical properties were quantified several times during the study: infiltration rate, CI, Db, and the soil water characteristic at the 0- to 15- and 15- to 25-cm depths.

Penetrometer resistance from the 0- to 60-cm depth for several pedons was measured with a Soiltest blunt-tipped pocket penetrometer. Bulk density and water content were determined on 16-cm^3 undisturbed soil cores taken adjacent to the location of the penetration measurements.

Corn root length was determined at tasseling for the third crop. A 170-cm^3 soil sample was collected from the 0- to 20-, 20- to 40-, and 40- to 60-cm depths with a bucket auger. Roots were washed from each sample and root length was determined by the modified line intersect method (Sartain and Kamprath, 1975).

Infiltration

Figure 13 depicts cumulative infiltration over time for four treatments 755 days after the study began (i.e., after growing six consecutive crops). Shallow rototillage did not increase the infiltration rate above that of the no-till control (14 mm h^{-1}) because the tillage operation was not deep enough to loosen the compacted soil below the 10-cm depth. Chisel plowing and simulated subsoiling increased cumulative infiltration because these operations disrupted the compacted soil below the 15-cm depth (Alegre et al., 1986b).

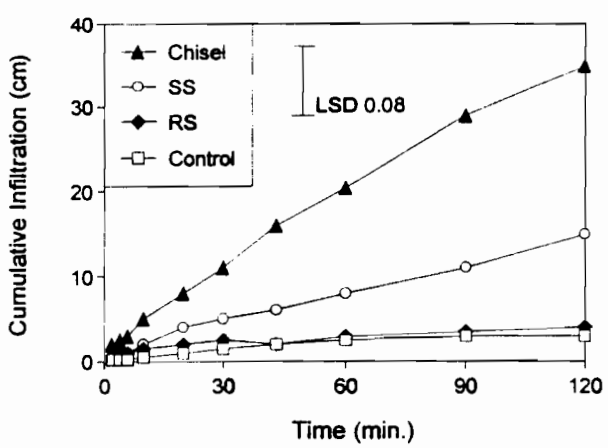


Figure 13. Cumulative infiltration for selected land-reclamation treatments after growing six consecutive crops (SS refers to simulated subsoiling, RS to the rototilling/stick treatment).

Cone Index, Soil-Water Content, and Bulk Density

No differences in $\log_{10}$ CI among treatments were found after 121 and 251 days. However, after 375 days, the no-till control had the greatest $\log_{10}$ CI (Table 17). After 755 days, both the no-till control and the bedded treatments had the greatest $\log_{10}$ CIs. The bedded treatment was hoed by hand to a maximum depth of 10 cm; hoeing did not affect the compacted zone. The chisel-plow and the simulated-subsoil operations consistently had lower $\log_{10}$ CI values because the compacted zone was disrupted. The smaller $\log_{10}$ CI values for the chiseled and subsoiled treatments are consistent with the higher observed infiltration rates for these two treatments. Although soil water content differed among treatments (Table 17), such differences were small and probably had minimal influence on the measured CI values.

In general, no large change in $\log_{10}$ CI occurred in the 0- to 25-cm depth although the values changed with time (Table 18). The small temporal changes are affected by crop, the number of passes of farm machinery, the number and frequency of laborers walking on the soil surface, and the soil-water content when compaction occurred. Soil water content at the time of measurement is also important. The $\log_{10}$ CI values at 375 and 755 days were not different, yet the highest water content occurred at 755 days. Most likely, therefore, the soil

Table 16. Cropping sequence for all treatments in reclaiming Yurimaguas soil damaged by mechanical land clearing.

No.	Crop	Planting date	Harvest date
1	Rice	2 Feb 1980	6 June 1980
2	Soybean	20 June 1980	15 Oct 1980
3	Corn	7 Nov 1980	16 Feb 1981
4	Soybean	20 Mar 1981	7 July 1981
5	Corn	24 July 1981	10 Nov 1981
6	Rice	26 Nov 1981	3 Mar 1982

Table 17. Log_{10} CI and water content and their standard deviations (in parentheses) at the 0- to 25-cm depth before harvesting the third (375 days) and sixth (755 days) crops for eight land-reclamation treatments.

Treatment	Third crop		Sixth crop	
	Log_{10} CI[§]	Water content	Log_{10} CI	Water content
	kPa	*kg kg⁻¹*	*kPa*	*kg kg⁻¹*
Control (no-till)	3.20 ± 0.14 a*	0.174 ± 0.033 b	3.18 ± 0.13 a	0.190 ± 0.017 bc
Rototill (12 kW)	2.99 ± 0.12 c	0.180 ± 0.015 ab	2.96 ± 0.15 bc	0.205 ± 0.016 ab
Rototill (48 kW)	2.97 ± 0.13 c	0.181 ± 0.015 ab	3.01 ± 0.19 b	0.197 ± 0.026 abc
Chisel plow	3.01 ± 0.19 bc	0.172 ± 0.014 b	2.87 ± 0.23 c	0.191 ± 0.019 bc
Controlled traffic	2.99 ± 0.13 c	0.179 ± 0.013 b	3.01 ± 0.17 b	0.196 ± 0.019 abc
Bedding	3.08 ± 0.16 b	0.172 ± 0.016 b	3.15 ± 0.15 a	0.186 ± 0.016 c
Simulated subsoiling	2.99 ± 0.19 c	0.176 ± 0.018 b	2.93 ± 0.16 bc	0.190 ± 0.016 bc
Mulching	2.98 ± 0.18 c	0.190 ± 0.014 a	2.98 ± 0.18 b	0.208 ± 0.016 a

* Means with the same letter in a given column are not significantly different with the Waller-Duncan multiple comparison test.

§ Mean and standard deviation of 80 measurements.

was more compacted at 755 days than at any other time since the reclamation treatments were started. Bulk density data in Table 19 support this viewpoint.

Initially, tillage treatments decreased Db in the 0- to 15-cm depth, but it increased with time during the continuous cropping period (Table 19). Tilling three times a year increased Db due to gradual deterioration of soil structure. Initial bulk density was 1.44 Mg m^{-3}. No significant difference in Db at the 0- to 15-cm depth was observed among treatments at 121 and 251 days. After 375 days, soil in the bedded treatment had the lowest Db because field laborers walked in the furrows rather than on the beds where Db was measured.

Penetrometer resistance (PR) was measured by the blunt-tipped penetrometer. After six crops (755 days), penetrometer resistance decreased at the 0- to 5-, 5- to 10-, and 10- to 12-cm depth for rototilled, chiseled, and simulated subsoil tillage when compared with the no-till control (Figure 14A). A significant difference in PR in the 12- to 21-cm depth occurred only for the chisel treatment.

Bulk density at the 12-cm depth was lower for the rototill, chisel, and simulated subsoil treatments than for the no-till treatment (Figure 14B). At the 18-cm depth, only the chisel and simulated subsoil treatments had a lower Db than the no-till treatment. No Db differences were observed for any other depth. Water content did not vary with treatment at any depth (Figure 14C).

Table 18. Log_{10} CI and water content at the 0- to 25-cm depth at various times after land clearing.

Time	Crop	Log_{10} CI[§]	Water content
Days		*kPa*	*kg kg⁻¹*
121	Rice	3.00 b*	0.175 c
251	Soybean	2.96 c	0.172 d
375	Corn	3.02 a	0.178 b
755	Rice	3.01 ab	0.195 a

* Means with the same letter in a given column are not significantly different at the 5% level by the Waller-Duncan multiple comparison test.

§ Each value is the mean of 320 measurements.

Soil Water Characteristic and Pore Size Distribution

The soil-water characteristic for the 0- to 15-cm depth prior to the study and after 121, 251, 375, and 755 days is shown in Figure 15. The soil water content value for each curve is averaged across treatments. Volumetric water content at all soil water pressures < –2 kPa was lower for all times compared to the initial values.

Each tillage operation temporarily increased the volume of macropores and decreased the volume of micropores. The smallest volume of micropores, arbitrarily defined as those pores that drain at soil water pressures < –4.9 kPa, was measured prior to harvesting the second crop (251 days), after which micropore volume increased. This behavior is probably due to the effect of tillage before seeding each crop, a process that promotes aggregate destruction in soils having a weak to moderate grade of soil structure.

Table 19. Bulk density of undisturbed soil cores from the 0- to 15-cm depth before harvesting crops for eight land-reclamation treatments.

Treatment	121 days	251 days	375 days	755 days	Mean
			$Mg\ m^{-3}$		
Control (no-till)	1.37[§]	1.39	1.51 a[*]	1.55	1.44 a
Rototill (14 hp)	1.34	1.38	1.46 ab	1.45	1.40 ab
Rototill (65 hp)	1.39	1.41	1.49 ab	1.47	1.43 a
Chisel plow	1.34	1.31	1.49 ab	1.47	1.40 ab
Controlled traffic	1.33	1.36	1.47 ab	1.42	1.36 ab
Bedding	1.26	1.32	1.36 c	1.44	1.33 c
Simulated subsoil	1.33	1.42	1.50 ab	1.49	1.43 a
Mulching	1.27	1.32	1.46 b	1.41	1.36 bc
Time means	1.33 C	1.36 B	1.47 A	1.46 A	

[*] Means within a given column with the same lower-case letter, and time means followed by the same upper-case letter, are not significantly different at the 5% level by the Waller-Duncan multiple comparison test.

[§] Means of eight measurements.

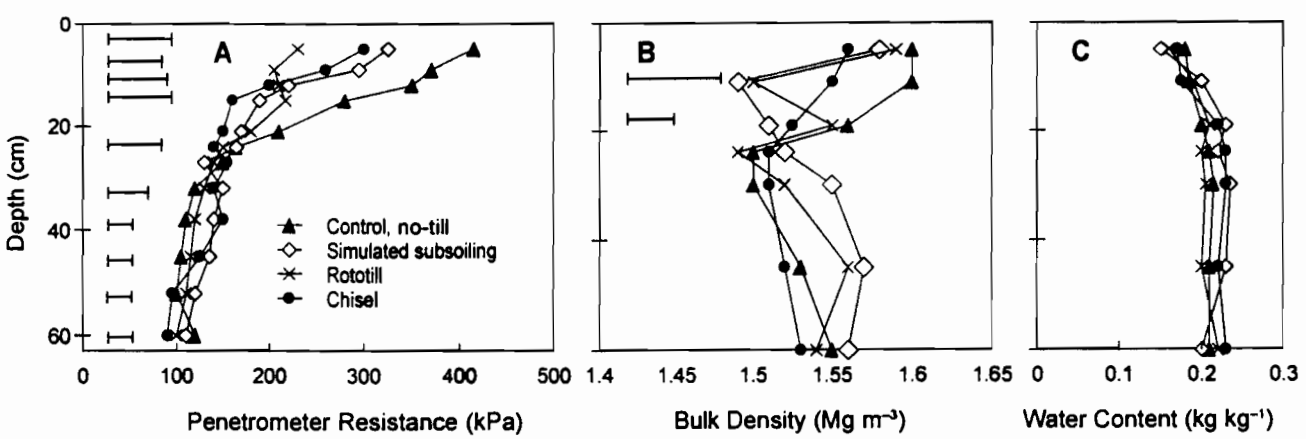


Figure 14. Penetrometer resistance, bulk density, and soil water content profiles for Yurimaguas soil for selected treatments in the reclamation study after 755 days of continuous cropping (six crops). The horizontal bars at each depth are the treatment $LSD_{0.05}$.

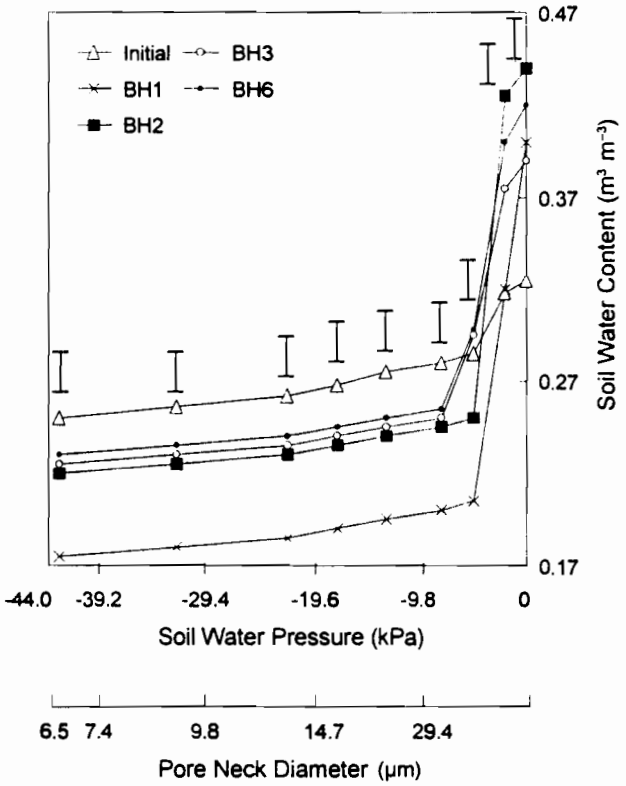


Figure 15. Soil water characteristics of the 0- to 15-cm depth of a Yurimaguas soil. Vertical bars show the $LSD_{0.05}$ for each pressure. BH1 indicates before harvest of the first crop, BH2 indicates before harvest of the second crop, and so on.

Grain Yield and Root Distribution

The first rice crop was the only crop for which yield differences did not occur (Table 20). The low rice yield for the bedded treatment probably resulted from a lower seeding rate compared to all other treatments. Rice plants did not grow well on the edges of the beds because roots were often exposed. The mulch treatment, which also yielded poorly, had competition from grass that germinated from seed carried onto the plots during the mulching process. Rice yields for the sixth crop responded to reclamation treatment. Yield for the no-till treatment was significantly lower than all others. The highest yield was obtained for the chisel-plow treatment.

Soybean yield (second and fourth crops) was lowest for the no-till treatment (Table 20). In general, yields for both crops were poor, but those for the second crop were generally lower than for the fourth crop due to drought and poor germination. Nevertheless, chisel plowing and simulated subsoiling produced some positive response. Mulching produced no yield advantage over the unmulched treatments even though the weather was dry. Lack of response to mulching was probably associated with weed problems stemming from the applied grass mulch.

Corn response was similar to soybean response, with no-till yielding the least and the two deep-tillage methods the most. For the third crop, corn

Table 20. Grain yields for six consecutive crops following initiation of land reclamation at Yurimaguas, Peru.

Treatment	Rice (1st crop)	Soybean (2nd crop)	Corn (3rd crop)	Soybean (4th crop)	Corn (5th crop)	Rice (6th crop)
	$t\ ha^{-1}$					
Control (no-till)	2.08	0.32 c*	0.70 c	0.49 d	0.64 e	1.44 d
Rototill (14 hp)	2.24	1.16 ab	2.66 ab	1.23 bc	2.41 cd	2.51 bc
Rototill (65 hp)	2.15	0.98 ab	2.51 ab	1.04 c	2.38 cd	2.29 bc
Chisel plow	1.99	1.40 a	3.22 a	2.05 a	3.45 a	3.12 a
Controlled traffic	2.19	0.79 b	2.16 b	1.09 c	2.12 d	2.16 c
Bedding	1.56	1.01 ab	1.16 c	1.43 bc	2.10 d	2.51 bc
Simulated subsoiling	2.15	1.27 a	3.25 a	1.61 ab	3.06 ab	2.57 bc
Mulching	1.63	1.16 ab	3.13 a	1.47 bc	2.74 bc	2.67 b

* Means within a given column with the same letter are not significantly different at the 5% level by the Waller-Duncan multiple comparison test.

root length was greatest in the 0- to 20-cm depth (Table 21). Deep tillage increased root length in the lower depths. Few roots penetrated below 40 cm for any treatment except chisel plowing and simulated subsoiling. Clearly these deep-tillage operations improve physical conditions in compacted subsoil and allow deeper and denser rooting.

Table 22 summarizes relative yields for rice, soybean, and corn for each reclamation treatment. The greater relative yields were obtained for the deep-tillage practices and mulching, probably due to greater water use and possibly due to increased uptake of nutrients below 20 cm. Chisel plowing consistently produced the greatest yield. No-till produced the lowest.

Table 21. Corn root length for the third crop vs. soil depth as affected by land-reclamation treatment.

Treatment	Depth 0 to 20 cm	20 to 40 cm	40 to 60 cm	Mean
	$km\ m^{-3}$			
Control (no-till)	20.7[§]	3.1	0	8.0[§§]
Rototill (14 hp)	42.7	7.1	1.6	17.1
Rototill (65 hp)	34.6	3.8	2.1	13.5
Chisel plow	45.8	22.2	11.3	26.4
Controlled traffic	44.2	5.5	2.7	17.5
Bedding	31.5	4.0	1.8	12.4
Simulated subsoiling	38.5	18.3	8.3	21.7
Mulching	35.9	9.8	2.0	15.9
$LSD_{0.05}$				
Treatment =	5.0			
Treatment x depth =	8.6			

[§] Each value is the mean of 12 measurements.
[§§] Mean of 36 measurements.

Table 22. Effect of land-reclamation treatment on relative grain yield for each crop.

Treatment	Rice	Soybean	Corn	Mean
	%			
Control (no-till)	69[§]	23	20	37
Rototill (14 hp)	93	69	76	79
Rototill (65 hp)	87	59	73	73
Chisel plow	100	100	100	100
Controlled traffic	85	54	64	68
Bedding	80	71	49	67
Simulated subsoiling	92	83	94	90
Mulching	84	76	88	83

[§] Each value is the mean of the relative yield for two crops.

Land Reclamation of an Oxisol in Indonesia

The island of Sumatra is sparsely populated and is largely covered by tropical rain forests on Andisols, Oxisols, and Ultisols (Figure 16). In an attempt to relieve the high population pressure on Java, the Indonesian government initiated large transmigration projects to settle people in rural areas with low populations. Some of the land assigned to transmigration farmers is on Oxisols and Ultisols and exhibits severe constraints for crop production. Much of the land has been mechanically cleared. In the early 1980s, a research program sought to identify existing technologies that could increase crop production on this mechanically cleared land. The land-reclamation study presented here is a part of that research effort.

The study was conducted from September 1983 to May 1985 at Sitiung, West Sumatra, Indonesia (2° S 102' E, 60 m above sea level). Daily air temperature ranges from 20 to 33°C. The wet season (precipitation > 200 mm month^{-1}) lasts six months, the dry season (precipitation < 100 mm month^{-1}) three to four months.

A 0.23-ha field was selected in an area cleared by a straight-blade bulldozer in 1977. The soil is a very-fine, kaolinitic, isohyperthermic Typic Hapluox. Located in an area of undulating topography, the field had a 10% slope, and most of its topsoil had been removed when wood was placed in windrows during clearing. Soil erosion had removed some additional soil material. Local farmers had little success growing crops on this field.

Soil physical and chemical properties were measured prior to formulating an array of reclamation alternatives. Textural class of the 0- to 15-cm depth was clay (74% clay, 12% silt, 14% sand) and Db was 1.09 g cm^{-3}. The infiltration rate of 20 cm h^{-1} was considered adequate to allow infiltration of most rainfall events. Mechanical impedance, measured with an impact penetrometer at *in situ* field capacity, was highly variable. The penetrometer had a 10-mm diameter cone and a 30-degree included angle. Each blow or drop of the 2.0 kg weight from the height of 0.178 m delivered 0.356 kgf m^{-1}.

Initial soil chemical properties in the 0- to 15-cm depth and their method of measurement were as follows:

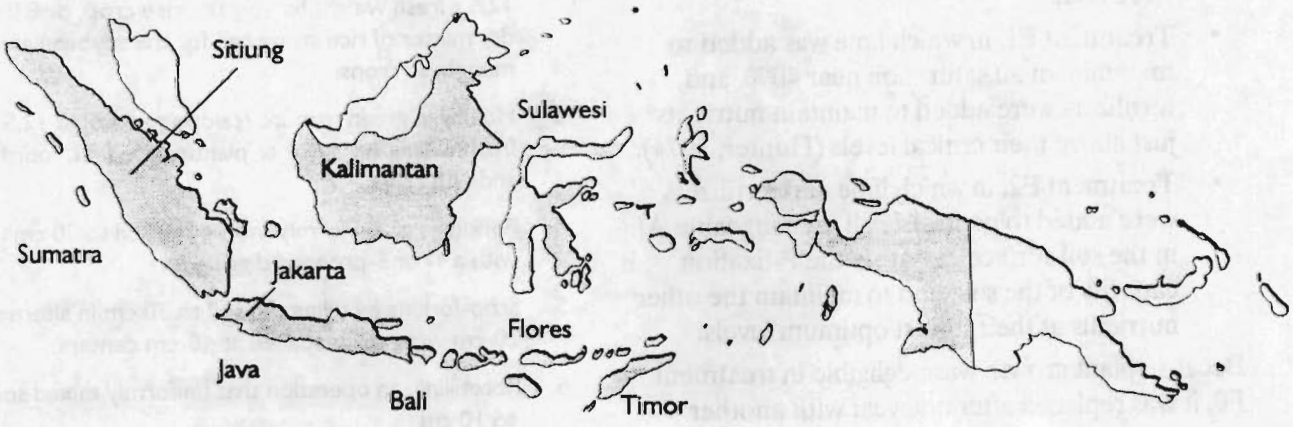


Figure 16. The Sitiung region of Sumatra, Indonesia.

- 12 mg organic C g^{-1} (Walkley and Black, 1934)
- 1.0 mg total N g^{-1}, determined by Kjeldahl (Bremmer, 1960)
- 0.4 mg extractable P L^{-1}, Modified Olsen (Hunter, 1974)
- 0.12 $cmol_c$ extractable K L^{-1}, Modified Olsen (Hunter, 1974)
- 0.73 $cmol_c$ exchangeable Ca + Mg L^{-1}, 1 N KCl extraction (Thomas, 1982)
- 2.22, 7.7, 4.2, and 69 mg extractable Mn, Zn, Cu, and Fe L^{-1} respectively, Modified Olsen (Hunter, 1974)
- 3.7 pH, as determined on a 1:2.5 (g g^{-1}) soil to water suspension
- 4.61 $cmol_c$ L^{-1} ECEC, as determined by summing K, Ca, Mg, Al, and H.

These initial measurements indicated that the unfavorable soil physical properties which had constrained crop production on the Yurimaguas Ultisol were not the major constraint on this Oxisol. Instead, soil acidity and insufficient extractable P levels were the chief constraints. Although the chemical properties in general were somewhat similar to those at the Ultisol in Yurimaguas (Tables 1 and 3), specific constraints for the Ultisol were high bulk density and mechanical impedance caused by compaction (Alegre et al., 1986b).

Data on soil chemical and physical properties led to the formulation of three main-plot fertility treatments:

- Treatment F0, in which no lime or fertilizers were added.
- Treatment F1, in which lime was added to maintain an Al saturation near 40%, and fertilizers were added to maintain nutrients just above their critical levels (Hunter, 1974).
- Treatment F2, in which lime and fertilizers were added to neutralize all exchangeable Al in the soil surface, to satisfy the P-fixation capacity of the soil, and to maintain the other nutrients at their lowest optimum levels.

Because plant growth was negligible in treatment F0, it was replaced after one year with another treatment:

- Treatment F1-2, in which lime was applied in amounts to maintain Al saturation near 20%, while other nutrients were kept just above their critical levels.

Six tillage treatments were formulated. One was rototilled to 10 cm, three were hoed to 15 cm, and two were forked to 30 cm (Table 23). The forked and strip-forked treatments were deep tilled once per year, before planting rice. In the strip-forked treatment, crops were planted in the tilled soil. All six tillage treatments were hand hoed before planting the second, third, and fifth crops.

Fertilizers and lime were broadcast one to seven days before planting, except for Cu, Zn, and Mn—all of which were foliar applied (Table 24). Rates of lime and P were doubled for the forking treatment prior to planting each rice crop; these chemicals were incorporated into a volume of soil two times greater than for the other five tillage treatments. Lime and fertilizers were applied to the strip-forked treatments on a whole-plot basis, but concentrated in the forked strips. N was also applied 30 and 60 days after planting.

Table 23. Tillage treatments investigated to reclaim a degraded Oxisol in West Sumatra, Indonesia.

Treatment	Description
1	Hand hoeing to 15 cm (the accepted tillage practice in the area).
2	Hoeing to 15 cm followed by mulching with calopogonium (*Calopogonium mucunoides*) at 12.5 t fresh weight ha^{-1} for the rice crop, or 8.0 t dry matter of rice straw ha^{-1} for the soybean and mungbean crops.
3	Hoeing in green manure (calopogonium) at 12.5 t fresh weight ha^{-1} prior to planting the first, fourth, and fifth crops.
4	Forking, i.e., uniformly mixing the soil to 30 cm with a 4- or 5-pronged digging fork.
5	Strip-forking by tilling the soil to 30 cm in alternate 20-cm wide strips spaced at 40-cm centers.
6	Rototilling, an operation that uniformly mixed soil to 10 cm.

Table 24. Rates of lime and fertilizers applied, based on nutrient units for each level of lime/fertilizer input for each consecutive crop.

Lime/ Fertilizer	Nutrient unit	Rice (1)[§]			Soybean (2)			Mungbean (3)		
		F0	F1	F2	F0	F1	F2	F0	F1	F2
Lime[¶]	$CaCO_3$	0	1500	6840	0	0	0	0	313	0
Urea	N	0	120	150	0	0	0	0	0	0
TSP[§§]	P	0	39	567	0	0	0	0	39	0
KCl	K	0	73	146	0	58	149	0	0	0
$MgSO_4 \cdot H_2O$	Mg	0	70	140	0	0	0	0	0	0
$MgSO_4 \cdot H_2O$	S	0	93	187	0	0	0	0	0	0
$CuSO_4 \cdot 5H_2O$	Cu	0	1	2	0	0	0	0	0	0
$ZnSO_4 \cdot H_2O$	Zn	0	4.5	9	0	0	0	0	0	0
$MnSO_4 \cdot 3H_2O$	Mn	0	0	0	0	1	2	0	0	2

Lime/ Fertilizer	Nutrient unit	Rice (4)			Soybean (5)			Total			
		F1	F1–2	F2	F1	F1–2	F2	F0	F1	F1–2	F2
Lime[¶]	$CaCO_3$	100	2200	0	0	0	0	0	1913	2200	6840
Urea	N	120	135	150	0	0	0	0	240	135	300
TSP[§§]	P	22	150	0	0	0	0	0	100	150	567
KCl	K	46	152	140	46	93	140	0	224	245	576
$MgSO_4 \cdot H_2O$	Mg	0	105	0	0	0	0	0	70	105	140
$MgSO_4 \cdot H_2O$	S	0	140	187	0	0	0	0	93	140	187
$CuSO_4 \cdot 5H_2O$	Cu	0	1	0	0	0	0	0	1	1	2
$ZnSO_4 \cdot H_2O$	Zn	1.7	1.7	1.7	0	0	0	0	6.2	1.7	10.7
$MnSO_4 \cdot 3H_2O$	Mn	0.8	0.8	0.8	0	1	2	0	1.8	0.8	4.8

[§] Crop number.

[¶] All fertilizers and lime were broadcast and incorporated by tillage, except Cu, Zn, and Mn, which were foliar applied. Broadcast applications were made one day before planting except for lime and P, which were applied seven days before planting. Two N applications were made 30 and 60 days after planting; foliar application was made 30 days after planting.

[§§] Triplesuperphosphate.

Treatments were arranged in a split plot with fertility as the whole plot and tillage as the subplots. The experimental design was a randomized complete block with four replications. Subplot size was 4 m by 8 m.

The test crops were those commonly grown by farmers (Table 25). Rice (cv. 'Sentani') was planted with a dibble stick at 25-cm by 25-cm spacings (160,000 hills ha^{-1}) except for the strip-fork subplot, which required a 40-cm by 15-cm spacing (166,000 hills ha^{-1}) to accommodate the tillage strips. Five seeds were planted per hole. Seed was treated with

Table 25. Cropping sequence used in the land-reclamation experiment in West Sumatra, Indonesia.

No.	Crop	Planting date	Harvest date
1	Rice	22 Oct 1983	14 Feb 1984
2	Soybean	8 Mar 1984	4 June 1984
3	Mungbean	10 June 1984	18 Aug 1984
4	Rice	14 Oct 1984	5 Feb 1985
5	Soybean	12 Feb 1985	12 May 1985

granular insecticide carbifuran (2, 2-dihydro-s, 2-dimethyl-7-benzofuranylmethylcarbamate (3 G)) at the rate of 30 g carbonfuran kg^{-1} seed. Soybean (cv. *Orba*) was planted at spacings of 40 cm by 20 cm (125,000 seeds ha^{-1}).

The effects of the imposed reclamation treatments on soil bulk density, mechanical impedance, and infiltration rate were measured periodically. Bulk density in the 0- to 15-cm depth was determined on all 72 subplots within one week after harvest of all crops, except for the second and third crops, for which measurements were taken on the 24 subplots of the F0 fertility treatment. In all cases, one 76-mm-long by 76-mm-diameter undisturbed soil core was taken from each subplot with a Uhland sampler (Blake and Hartge, 1986). The sample was located at the center of a square formed by four hills of rice spaced 25 cm apart, or in the soybean or mungbean row.

Soil mechanical impedance was determined with an impact penetrometer one day after a rainfall event, approximately one week before crop harvest. Seven measurements were taken in each subplot. Data are reported as soil penetrometer depth per five blows of the impact hammer: hence, the lower the mechanical impedance, the larger the value reported.

Cumulative water infiltration was measured for the first four crops on 40 subplots (24 subplots of F0 or F1-2 plus the hoeing and forking subplots in each main plot). Measurements were made one day following a rainfall event that occurred one to two weeks before harvest. The measurement was taken near the center of each subplot using a ring infiltrometer (Makarim et al., 1988).

The soil water characteristic for selected treatments was measured on undisturbed soil cores 2.6 cm in length and 7.6 cm in diameter; the measurement was taken after the fourth crop was harvested. The soil water content at soil water pressures of 0, –10, –20, –30, and –40 kPa were determined in the laboratory using pressure outflow cells (Cassel, 1974).

The following soil chemical properties were measured before each crop harvest using the procedures referenced above: pH; exchangeable Al; Al saturation percentage; extractable P; exchangeable K, Ca, and Mg; ECEC; and extractable Mn. Soil samples for the strip-forked treatment were taken from the soil strips where lime and fertilizers had been incorporated.

Exchangeable Al, Al Saturation, and pH

All three acidity-related variables were affected by lime and fertilizer input level (Table 26). The pH increased, and exchangeable Al and Al saturation decreased with increasing lime and fertilizer inputs.

Before the fourth crop (rice) was planted, treatment F1-2 (Table 25) was created by applying lime and fertilizers to treatment F0. When rice was harvested 17 weeks later, soil pH for treatment F1-2 had increased from 3.9 to 4.9. Treatment F1, which received only 100 kg lime ha^{-1} before planting the fourth crop, maintained its pH at 4.6. For treatment F2, although no lime was added for the fourth crop, the soil pH after rice harvest remained high (5.9).

Tillage effects on these three variables were less pronounced than those for chemical inputs, so only the data for Al saturation are presented. Only mulch and fork tillage consistently lowered Al saturation below levels produced by hoeing. Where mulches or green manures were applied, temporary complexing of Al by organic acids may have occurred.

Exchangeable Cations

The levels of exchangeable Ca + Mg increased (Table 27) as the level of exchangeable Al decreased for each fertility level. The addition of lime and fertilizers to treatment F2 increased ECEC (individual data not shown) at the harvest of the first crop to 7.8 $cmol_c$ L^{-1} as compared with the 4.7 $cmol_c$ L^{-1} for treatment F0. At the harvest of the third crop, the ECEC of treatment F2 was still 2.2 $cmol_c$ L^{-1} greater than the 4.7 $cmol_c$ L^{-1} value for treatment F0.

Exchangeable K levels in the check-plot treatment F0 (Table 27) were far below the critical level of 0.2 $cmol_c$ L^{-1} (Hunter, 1974). Increasing the initial K level and maintaining it near the critical level for treatment F1, and at the high level of 0.2 to 0.3 $cmol_c$ L^{-1} for treatment F2, required a total of 224 and 576 kg ha^{-1}, respectively, for the duration of the study. Although the target soil K level for treatment F2 was only two times greater than for treatment F1, 2.6 times more K fertilizer was required to maintain that level in the field. Soil K was maintained near 0.3 $cmol_c$ L^{-1} for treatment F1-2.

Table 26. Soil acidity (pH), exchangeable Al, and Al saturation as affected by lime and fertilizers and Al saturation as affected by tillage for five successive crops on an Hapludox soil.

Treatment	Rice (1)[§]	Soybean (2)	Mungbean (3)	Rice (4)	Soybean (5)
			pH		
F0	4.2[¶]	4.1	3.9	—	—
F1	4.8	4.6	4.6	4.6	4.4
F1–2	—	—	—	4.9	4.8
F2	6.6	6.3	6.1	5.9	6.1
$LSD_{0.05}$	0.2	0.3	0.2	0.3	0.2
			Exchangeable Al (cmol$_c$ L^{-1})		
F0	4.3	3.6	3.7	—	—
F1	1.8	1.8	1.6	1.7	2.0
F1–2	—	—	—	0.5	1.0
F2	0.4	0.1	0.2	0.2	0.2
$LSD_{0.05}$	0.4	0.6	0.3	0.2	0.3
			Al saturation (%)		
F0	90	80	79	—	—
F1	39	46	38	38	55
F1–2	—	—	—	10	27
F2	5	2	2	3	4
$LSD_{0.05}$	8	8	7	6	6
Hoe	47	47	44	25	30
Mulch	41	41	36	18	32
Green manure	45	43	39	19	31
Fork	40	36	35	7	15
Strip-fork	51	47	43	20	28
Rototill	44	43	40	15	28
$LSD_{0.05}$	5	5	6	6	6

[§] Crop number.
[¶] Initial pH was 3.7

Tillage had little influence on soil exchangeable K level (not shown) although some K was released from the applied mulch. No interaction between fertility level and tillage was found.

Extractable P

Table 28 shows the effect of chemical inputs and tillage on soil extractable P after the harvest of each crop. The extractable soil P level for the check plot, treatment F0, was initially below and remained below the critical level of 12 mg L^{-1} (Hunter, 1974). Treatment F1, designed to maintain P near the critical level, received P fertilizer three times (Table 24). The P level for F1 decreased below the critical level for each of the five crops at harvest. Phosphorus fertilizer was added to treatment F1 after harvesting the second crop, in an attempt to increase extractable levels. After the third crop was harvested, residual soil P increased to 8 mg L^{-1}, which was still below the critical level. Further applications of P to treatment F1 maintained the P level slightly below the critical level.

The P fertilizer regime for treatment F1-2 successfully maintained P above the critical level. For treatment F2, P underwent an abrupt initial

decrease and then a slower rate of decrease but remained in the high range of availability. For this treatment, we anticipate that maintenance applications of P fertilizer will be required three to five years after the initial P application.

With regard to tillage effects on soil P, the largest extractable P values were found for the forking treatments and are attributed to the higher P rates applied in conjunction with incomplete mixing throughout the 30-cm depth. No significant interaction between chemical input level and tillage was observed.

Bulk Density

Deep tillage by forking loosened the soil to a depth of 30 cm while the remaining tillage treatments loosened soil only to a depth of 10 to 15 cm. For the first rice crop, the forking and strip-forking deep-tillage treatments decreased Db in the 0- to 15-cm depth by 0.18 and 0.15 g cm^{-3}, respectively, as compared to

Table 27. Exchangeable Ca + Mg and exchangeable K levels as affected by lime and fertilizers for five successive crops on an Hapludox soil.

Treatment	Rice (1)	Soybean (2)	Mungbean (3)	Rice (4)	Soybean (5)
			Ca + Mg (cmol$_c$ L^{-1})		
F0	0.4	0.9	1.0	—	—
F1	2.7	1.9	2.5	2.6	1.4
F1–2	–	–	–	4.0	2.3
F2	7.2	5.6	6.5	5.3	5.1
$LSD_{0.05}$	0.5	0.3	0.2	1.3	0.4
			Exchangeable K *(cmol$_c$ L^{-1})*		
F0	0.05	0.05	0.04	—	—
F1	0.10	0.18	0.15	0.12	0.20
F1–2	—	—	—	0.25	0.29
F2	0.23	0.30	0.21	0.25	0.38
$LSD_{0.05}$	0.13	0.04	0.02	0.07	0.12

Table 28. Extractable P as affected by chemical inputs and tillage for five successive crops on an Hapludox soil.

Treatment	Rice (1)	Soybean (2)	Mungbean (3)	Rice (4)	Soybean (5)
			cmol$_c$ L^{-1}		
F0	2	1	1	—	—
F1	10	4	8	8	6
F1–2	—	—	—	15	17
F2	118	57	47	38	35
$LSD_{0.05}$	13	18	8	6	11
Hoe	38	18	15	16	17
Mulch	48	17	17	19	18
Green manure	35	14	13	14	13
Fork	56	37	33	36	38
Strip-fork	30	12	12	16	18
Rototill	55	24	22	22	18
$LSD_{0.05}$	14	13	13	8	9

Table 29. Bulk density in the 0- to 15-cm depth at harvest as affected by tillage.

Treatment	Rice (1)	Soybean (2)	Mungbean (3)	Rice (4)	Soybean (5)
			$Mg\ m^{-3}$		
Hoe	1.21 c[§]	1.05 a	1.07 a	1.15 b	1.01 a
Mulch	1.12 abc	1.00 a	1.05 a	1.09 ab	1.04 a
Green manure	1.13 bc	1.02 a	1.08 a	1.09 ab	1.03 a
Fork	1.03 a	0.95 a	1.05 a	1.04 a	1.05 a
Strip-fork	1.06 ab	0.95 a	1.05 a	1.04 a	1.03 a
Rototill	1.18 c	1.05 a	1.07 a	1.08 ab	1.05 a
Mean	1.12	1.00	1.06	1.08	1.04

[§] Each value is the mean of four observations except for the first and second crops which have 12 observations. Means in a given column with the same letter are not significantly different at the 5% level by LSD test.

conventional hoeing (Table 29). Although the effect was not as great, deep tillage also decreased Db for the second rice crop. The effect of the initial deep-tillage operations on surface-soil Db was short-lived, disappearing by the harvest of the second crop. The hand-hoeing operation, which all six treatments received prior to planting the second and third crops, removed any carryover effect of deep tillage on surface-layer Db. The soil was deep-tilled again prior to planting the fourth crop, and the effects on Db of these tillage operations were still present at harvest. Once again, hoeing the deep-tilled treatments prior to planting the last soybean crop erased these differences.

The mulch treatment, even though it protected the soil surface, did not maintain a lower Db compared to hoeing. Soil fertility level had no effect on Db.

Mechanical Impedance

Reductions in mechanical impedance from deep tillage were transient, disappearing in six to eight months (Table 30). Mechanical impedance, as measured by penetration depth of the penetrometer, was significantly less (although higher values of cm (5 blows)$^{-1}$ are depicted in Table 30) for the deep-tillage treatments compared to hoeing. The decrease in mechanical impedance persisted until the harvest of the second crop after forking, except for strip-forking. The effect disappeared completely in the forking treatment at mungbean harvest. Because the deep-tillage operations were reimposed prior to planting the fourth crop, their effects on mechanical impedance were again significantly different from hoeing. The effect started to dissipate following the fifth crop.

Soil Water Characteristic

The soil water characteristic for the 0- to 15-cm depth is noticeably different for the green-manure and forking treatments compared to hoeing (Figure 17). Deep forking and green-manure incorporation increased total porosity as indicated by the higher soil water content measured on the undisturbed soil cores at saturation (0 kPa), an observation in agreement

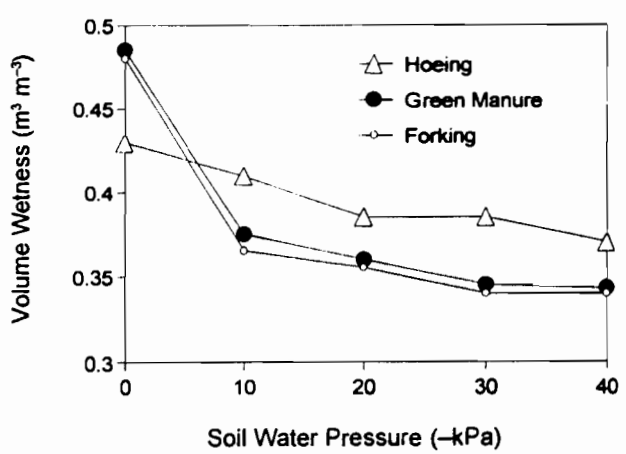


Figure 17. Soil water characteristic for the 0- to 15-cm depth of an Oxisol for three treatments.

with the Db data presented in Table 29. The abrupt decrease in water content between 0 to –10 kPa indicates that the fork and green-manure treatments had large amounts of easily drainable macropores. Total porosity was 0.48 m^3 m^{-3} for both treatments, and 22% of this quantity consisted of macropores with neck diameter > 0.03 mm. In contrast, the hoe treatment had a total porosity of 0.42 m^3 m^{-3}, of which only 5% was macropores with neck diameters > 0.03 mm.

Water Infiltration

Cumulative infiltration after 15 minutes was greatest for the two deep-tilled treatments, but the effect was significantly greater than hoeing for the first crop only (Table 31). The large variation among replicate infiltration observations may have masked actual differences. The combined effects of lower Db and lower mechanical impedance for forking and strip forking compared to hoeing indicate greater total porosity for the deep-tilled treatments, which in turn would increase cumulative infiltration. The rototilled treatment for the first crop was the only other treatment that exhibited greater cumulative infiltration than hoeing.

The effect of the primary tillage operation on infiltration dissipated with time, but fertility had a marked effect on infiltration after one year (Table

Table 30. Penetrometer resistance one day after a rainfall event as affected by tillage.

Treatment	Rice (1)	Soybean (2)	Mungbean (3)	Rice (4)	Soybean (5)
	cm (5 blows) $^{-1}$				
Hoe	9.4 a[§]	11.6 a	9.3 abc	12.3 b	10.6 a
Mulch	10.1 a	11.1 a	8.9 ab	11.8 b	10.9 ab
Green manure	10.6 a	11.1 a	9.8 bc	12.7 b	10.5 a
Fork	12.0 b	14.8 b	10.0 c	15.5 d	10.8 ab
Strip-fork	12.2 b	12.9 a	9.2 abc	14.2 c	11.7 b
Rototill	9.8 a	10.9 a	8.8 a	10.6 a	10.1 a
Mean	10.7	12.1	9.3	12.9	10.8

[§] Each value is the mean of 12 observations except for the second crop, which has three observations. Means in a given column with the same letter are not significantly different at the 5% level by LSD test.

Table 31. Mean and standard deviation of cumulative water infiltration in a 15-minute period as affected by tillage and crop.

Treatment	Rice (1)	Soybean (2)	Mungbean (3)	Soybean (5)
	cm			
Hoe	9.3±4.2 a[§]	13.6±5.1 abc	7.3±3.6 a	16.7±7.3 ab
Mulch	18.1±8.8 ab	13.2±5.1 ab	9.4±3.4 a	16.3±3.4 ab
Green manure	10.7±3.4 a	8.6±3.0 a	8.3±2.4 a	17.7±4.7 ab
Fork	24.6±11.5 b	18.0±4.3 bc	13.1±7.1 a	21.2±9.0 b
Strip-fork	26.5±11.0 b	19.2±3.9 c	12.9±1.7 a	18.1±4.8 ab
Rototill	22.4±3.4 b	14.7±5.4 b	10.4±3.8 a	11.1±1.1 a
Mean	18.6	14.6	10.3	16.9

[§] Each value is the mean of four observations. Means in a given column with the same letter are not significantly different at the 5% level by LSD test.

32). The higher fertility levels resulted in more extensive plant root systems, which promoted more rapid infiltration. Treatment F2, the highest fertility level, had the highest cumulative infiltration value throughout the entire 90-minute infiltration period.

Crop Response

The effects of lime and fertility, averaged across all tillage treatments, are presented for four crops in Table 33 (Cassel et al., 1990). The mungbean crop experienced severe drought, and no grain was harvested. Grain and straw yields were very low for treatment F0, the check plot, because most plants died before producing grain. Poor growth of rice in the check plot is attributed to the Al saturation > 80% and to the low levels of soil P, K, and Ca, all of which were below their respective assumed critical levels. Lack of N may also have limited yield.

Modest additions of lime and fertilizers produced significant yield increases of grain and stover. Grain and straw yields of F1 were about 15 times greater than F0. Grain and straw yields for F2 were greater than those for both F0 and F1. Yields for treatments F1 and F2 were not statistically different. The F2 plants grew faster early in the season and maintained this advantage until harvest.

The effects of tillage on yield, averaged across all lime and fertilizer treatments, are also shown in Table 33. The higher yield for the green-manure treatment is attributed to higher fertility levels caused by the addition of the green manure. When all crop yields are considered together, yields increased as lime and fertilizer levels increased. For tillage, the highest yields were obtained in the mulch and green-manure treatments. This response is more likely related to the addition of plant nutrients than to the modification of soil physical properties.

Table 32. Cumulative water infiltrated after 15, 60, and 90 minutes as affected by fertility level after one year of continuous cropping.

Fertility level	Time (min) 15		60		90	
	cm					
F0	10.35	a[§]	25.6	a	32.3	a
F1	13.2	ab	29.0	ab	35.4	a
F2	19.0	b	47.0	b	57.4	b

[§] Each value is the mean of eight observations. Means in a given column with the same letter are not significantly different at the 5% level.

Table 33. Rice and soybean yields as affected by chemical inputs and tillage.

Main effect	Rice (1) Grain	Rice (1) Straw	Soybean (2) Grain	Rice (3) Grain	Rice (3) Straw	Soybean (4) Grain
	Fertility and lime (Mg ha⁻¹)					
F0	0.13	0.35	0.02	—	—	—
F1	1.87	5.76	0.77	2.23	3.38	0.24
F1–2	—	—	—	1.83	3.38	0.42
F2	2.20	8.71	2.32	2.23	4.47	0.73
$LSD_{0.05}$	0.21	1.69	0.25	0.24	0.52	0.18
	Tillage (Mg ha⁻¹)					
Hoe	1.24	4.21	0.94	1.76	3.32	0.32
Mulch	1.39	5.36	1.08	2.66	4.32	0.45
Green manure	2.10	6.71	1.05	2.77	4.43	0.76
Fork	1.33	5.05	1.16	1.74	3.08	0.48
Strip-fork	0.86	2.81	0.96	1.71	3.34	0.35
Rototill	1.38	5.00	1.02	2.16	3.97	0.42
$LSD_{0.05}$	0.30	1.08	0.16	0.35	0.65	0.12

Implications

Reclaiming land degraded by inappropriate mechanical land-clearing practices begins with an assessment of the soil properties. A thorough analysis of soil properties at the Yurimaguas and Sitiung sites led to different reclamation strategies.

Initial soil characterization at Yurimaguas revealed a compacted layer at the 20- to 30-cm depth. This compact layer reduced crop rooting depth. Confining the root system to the shallow zone near the soil surface prevented ready uptake of soil water stored in and below the compacted layer. This reduction in water uptake, along with a concomitant reduction in the ability of the crop to take up any nutrients leached below the compacted zone, caused poor plant growth and poor yields.

Detailed soil characterization of the acid, clay upland soil at Sitiung led to a different conclusion with regard to the soil factors limiting crop growth. Unless crops were acid-tolerant, root growth was very poor at this site, even in the topsoil. The detailed soil-characterization data revealed that soil acidity and low extractable P levels were probably the primary causes of restricted plant growth at Sitiung.

The reclamation strategy for the Yurimaguas soil with the high mechanical impedance called for physical disruption of the compacted layer. Subsoiling and chisel plowing to a depth of 25 cm or deeper proved sufficient. At Sitiung, the application and incorporation of lime and phosphorus were employed to overcome the main constraints to crop growth.

The successful reclamation of a compacted soil at Yurimaguas led to a study for developing a combination of land-clearing and post-clearing tillage practices that minimize such problems. That study indicates (1) that soil compaction must be minimized during land clearing or (2) that if compaction occurs due to heavy land-clearing machinery, it must be alleviated using deep-tillage prior to planting the first crop.

References

Alegre, J. C., and D. K. Cassel. 1986a. Effect of land-clearing methods and post clearing management on aggregate stability and organic carbon content of a soil in the humid tropics. Soil Sci. 142:289–295.

Alegre, J. C., D. K. Cassel, and D. E. Bandy. 1986b. Reclamation of an Ultisol damaged by mechanical land clearing. Soil Sci. Soc. Am. J. 50:1026–1031.

Alegre, J. C., D. K. Cassel, and D. E. Bandy. 1986c. Effects of land clearing and subsequent management on soil physical properties. Soil Sci. Soc. Am. J. 50:1379–1383.

Alegre, J. C., D. K. Cassel, and D. E. Bandy. 1988. Effect of land clearing method on chemical properties of an Ultisol in the Amazon. Soil Sci. Soc. Am. J. 52:1283–1288.

Alegre, J. C., and D. K. Cassel. 1990. Effect of land clearing method and soil management on crop production in the Amazon. Field Crops Res. 24:131–141.

Alegre, J. C., P. A. Sanchez, and T. J. Smyth. 1991. Manejo de Suelos con cultivos continuos en los tropicos humedos del Peru. *In* Smyth, T.J., W.R. Raun, and F. Bertsch (eds.) Manejo de suelos tropicales en Latinoamerica. North Carolina State Univ., Raleigh, NC.

Blake, G. R., and K. H. Hartge. 1986. Bulk density. *In* Klute, A. (ed.). Methods of soil analysis. Part 1. Physical and mineralogical methods. Second ed. American Soc. Agron. Madison, WI.

Bremmer, J. M. 1960. Determination of nitrogen in soil by the Kjeldahl method. J. Agric. Sci. 55:1–23.

Buol, S. W., and P. A. Sanchez. 1986. Red soil in the Americas: Morphology, classification and management. *In* Proceedings of the International Symposium on Red Soil. Institute of Soil Science (Ed.). Academic Sinica. Science Press, Beijing, China. Elsevier, Amsterdam, 14–43.

Cano, M. 1973. Evaluación de la fetilidad de suelos en el Perú. Dirección de Investigación Agraria Bol. Tec. 78. Ministerio de Agricultura, La Molina, Perú.

Cassel, D. K. In situ unsaturated soil hydraulic conductivity for selected North Dakota soils. Bulletin 494. North Dakota Agricultural Experiment Station, Fargo, North Dakota.

Cassel, D. K., M. K. Wade, and A. K. Makarim. 1990. Crop responses to management of a degraded Oxisol site in West Sumatra. Soil Technology 3:99–112.

Gooderham, P. T. 1976. The effect on soil conditions of mechanized cultivation at high moisture content and of loosening by hand digging. J. Agric. Sci. 86:567–571.

Henin, S., and R. Gras. 1972. El Perfil Cultural. Ed. Mundi. Prensa, Madrid, 341 pp.

Hunter, A. H. 1974. International soil fertility evaluation and improvement laboratory procedures. Mimeograph. Dept. of Soil Science, North Carolina State University, Raleigh.

Makarim, A. K., D. K. Cassel, and M. K. Wade. 1988. Effects of land reclamation practices on physical properties of an acid, infertile Oxisol. Soil Technology 1:195–207.

Makarim, A. K., D. K. Cassel, and M. K. Wade. 1989. Effects of land reclamation practices on chemical properties of an acid, infertile Oxisol in West Sumatra. Soil Technology 2:27–39.

References

Mazurak, A. P. 1950. Effect of gaseous phase on water-stable synthetic aggregates. Soil Sci. 69:135–148.

Sanchez, P. A., and S. W. Buol .1974. Properties of some soils of the Upper Amazon Basin of Peru. Soil Sci. Soc. Am. J. 38:117–121.

Sanchez, P. A., and S. W. Buol. 1975. Soils of the tropics and the world food crisis. Science 188:598-603.

Sanchez, P. A. 1981. Soils of the humid tropics. *In* Blowing in the wind: Deforestization and long-range implications. Ed. Studies in Third World Societies. Publication 14.

Sartain, J. B., and E. J. Kamprath. 1975. Effect of liming a highly Al-saturated soil in the top and root growth and soybean nodulation. Agron. J. 67:507–510.

Seubert, C. E., P. A. Sanchez, and C. Valverde. 1977. Effects of land clearing methods on soil properties of an Ultisol and crop performance in the Amazon jungle of Peru. Trop. Agric. (Trinidad) 54:307–321.

Soil Survey Staff. 1975. Soil taxonomy. Agr. Handbook 436. U.S. Govt. Printing Office. Washington, DC. p. 754.

Soil Survey Staff. 1992. Key to Soil Taxonomy. Soil Moisture Support System Technical Monograph No. 19. 5th ed. Pocahontas Press. Blacksburg, VA.

Subagjo, H. 1988. Vocanic ash influence and characterization of soils on the Eastern Plain of the Barisan Range between Sitiung-Kotabaru and Bangko, Sumartra. Ph.D. Dissertation. North Carolina State University. 296 pp.

Thomas, G. W. 1982. Cation exchange capacity. *In* Page, A.L., R.H. Miller, and D.R. Keeney (eds.). Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd ed.

Tyler, E. J., S. W. Buol, and P. A. Sanchez. 1978. Genetic association of soil properties encountered in a detailed soil survey in the upper Amazon Basin. Soil Sci. Soc. Am. J. 42:771–776.

Uhland, R. E. 1950. Physical properties of soils modified by crops and management. Soil Sci. Soc. Am. Proc. 14:361–366.

Van Bavel, C. H. M. 1952. Compacted wet-sieving apparatus for soil aggregate analysis. Agron. J. 44:97–87.

Wade, M. K., D. W. Gill, H. Subagjo, M. Sudjadi, and P. A. Sanchez. 1988. Overcoming soil fertility constraints in a transmigration area of Indonesia. Tropsoils Bull 88-01. North Carolina State Univ., Raleigh, NC.

Walkey, A., and I. A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37:29–38.

Yoder, R. E. 1936. A direct method of aggregate analysis and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28:337–351.