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Soil Structure Effects on Hydrologic Processes and Crop Water Availability in Ultisols and Oxisols of Sitiung, Indonesia

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Foreword

The University of Hawaii, a member of Soil Management Collaborative Research Support Program (CRSP), has worked with Indonesian scientists and the Center for Soil and Agroclimate Research since 1983. The challenge was to bring sustainable production to the transmigration farmers on newly cleared land near Sitiung, Sumatra. From the start, the aim of that research has been to develop land-clearing methods that conserve soil and prevent erosion; to develop strategies for reclaiming degraded and infertile lands; to develop cropping systems suited to the soils, climate, and economy of the region; and to ensure that these systems respond to farmers' needs and aspirations.

Acidity, aluminum toxicity, and low fertility are the major soil-related agronomic constraints in this region of Sumatra, Indonesia. This report provides useful knowledge on how soil structure and soil hydrologic processes can be used to manage these soil and water resources. The report also identifies management strategies that can lead to soil resource enhancement of these and similar soils in the humid tropics. Such strategies are prerequisites to sustainable production.

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Roger G. Hanson, Director
Soil Management CRSP
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Contents

Summary 7

The Sitiung Region: Physical Environment 9

Soil Mechanical Characteristics 11
- Soil Texture 11
- Tilth and Structural Stability 11
- Bulk and Particle Density 14
- Mechanical Impedance 14

Soil Hydrologic Characteristics 17
- Water Retention and Water-holding Capacity 17
- Field Estimates of Water-holding Capacity 17
- Water Flow Rates 17
- Internal Pore Structure 20
- Hydraulic Conductivity 22

Field Water Regime 25

Limitations to Crop Water Use 29
- Acidity and Aluminum Saturation 29
- Effect of Al Toxicity on Root Growth and Plant Production 29
- Root Growth, Plant Production, and Water-depletion Patterns 31
  - *Liming Depth and Soil Water-pressure Patterns* 32
  - *Liming Depth and Crop Use of Soil Water* 34
  - *Rooting Depth and the Effect of Drought* 36
  - *Local Forages vs. Food Crops* 37

Field Water Balance 39
- Annual Water Balance for Sitiung 39
- Seasonal Water Balance 39

Contents

Estimation of Drainage and Runoff 40
Water Balance 41

Implications of Rapid Drainage for Soil Fertility and the Environment **43**

Conclusions and Implications for Research **47**

References **49**

Summary

Rainfall and soil structure play a major role in determining soil hydrologic processes. These processes, in turn, greatly influence the soil's chemical environment. Soil fertility and crop water availability are closely related to the chemical environment in Sitiung's highly weathered soils. This technical bulletin attempts to characterize soil structural properties and hydrologic processes, as well as to analyze the problems of soil fertility and crop water availability.

The major findings discussed in this report are summarized below:

1. Sitiung's climate is humid tropical. It rains frequently, and 20- to 50-mm rainstorms are common. Annual rainfall averages around 3000 mm, and the evaporative demand is low, generally between 3.5 to 4.0 mm/day.

2. Highly weathered Ultisols and Oxisols are the most common soils in Sitiung and many other regions in Indonesia. Acidity, aluminum toxicity, and low fertility are the chief agronomic constraints associated with these soils. Soil pH typically ranges from 4 to 5. Aluminum saturation ranges from around 50% in the surface soil to over 80% in the subsoil.

3. Sitiung Ultisols and Oxisols are clayey, with clay contents ranging from around 50 to over 70%. These soils have low bulk density (around 1.0 to 1.2 g/cm^3) and low mechanical impedance (3 to 6 kg/cm^2). In general, soil tilth is excellent.

4. The physical structure of the soil is characterized by large and highly stable aggregates with a wide range of pore sizes in the surface, a predominantly microporous subsoil, and a network of macropores that extend from the surface through the subsoil. The fraction of macropores generally decreases with depth, from around 30 to 40% of the total pore space in the surface to about 5 to 8% in the subsoil. However, the decrease in the macropore volume with depth is accompanied by an increase in macropore size. Subsoil macropores are preserved only if they are overlain by stable-structured topsoil.

5. These soils retain large volumes of water, but they also transmit water rapidly. Water-retention at field capacity indicates pore saturation values of 80 to over 90%. Field-measured field capacity values far exceed those estimated by water retention in the laboratory samples at –330 cm pressure. Field capacity in the field generally occurs at soil water pressures of –30 to –50 cm in the surface and –10 to –20 cm into the subsoil.

6. Water intake rates of 60 to 100 mm/hr are common in these soils, which do not flood and remain tillable even soon after heavy rainfalls. Most of the rainfall is absorbed in the soil. Runoff is very low relative to the amount of rainfall.

7. Saturated hydraulic conductivities range from 30 to 40 mm/hr in the surface to 90 to 100 mm/hr in the subsoil; however, they drop abruptly by several orders of magnitude as soon as water flow in the macropores ceases. The steep drop in hydraulic conductivity indicates that the nonmacroporous portion of the soil matrix consists of very fine pores.

8. Aluminum toxicity affects food crops such as corn, soybean, peanut, mungbean, and rice to varying degrees, inhibiting root growth and rooting depth. Root systems of aluminum-sensitive plants generally do not extend below 20 to 30 cm. Locally adapted species, on the other hand, root deeply.

9. Restricted root growth limits the extraction of soil water by aluminum-sensitive plants. These plants exhibit symptoms of water stress if rainless periods exceed three or four days. Locally adapted species do not suffer from water stress.

10. Food crops generally affect soil water content only in the surface soil, where most of the

roots are concentrated. This effect decreases sharply with depth and rarely extends below 30 cm. Soil moisture beneath this level is virtually unaffected and thus remains high. Locally adapted species, on the other hand, extract soil water from considerably greater depths.

11. The water-extraction capacity of food crops can be increased by incorporating lime deep into the subsoil. The beneficial effects result from an increase in rooting density and depth. A liming depth of 25 to 30 cm appears quite adequate.

12. Evapotranspiration and drainage are the main components of water balance in the Sitiung region. On average, deep drainage accounts for about 40 to 50% of the total rainfall. Runoff may account for 10 to 15%, depending on the slope and surface characteristics of the landscape. The remaining rainfall is disposed of primarily by evapotranspiration. Changes in the soil water storage are generally insignificant on both seasonal and annual bases.

13. The large capacity for internal drainage seems necessary for the rapid and safe disposal of the region's torrential and voluminous rainfall. Disposal by surface runoff can destroy the landscape. The nature of internal water movement, however, has important consequences for the chemical environment in the soil profile. Because of a wide range in the pore sizes, rainwater interacts longer with the surface soil than it does with the subsoil, which consists of a few macropores and a predominance of micropores. Readily movable fertilizer nutrients and other chemicals dissolved in the water move downward. After leaving the surface soil, drainage water moves primarily in the macropores. Because the subsoil generally remains quite wet, the nutrient-carrying drainage water may not adequately exchange with the resident water in the subsoil. As a result, nutrients leached from the surface probably do not accumulate in the subsoil. Thus, treating the surface soil with fertilizers may be an ineffective way to build and maintain fertility.

Our findings have several important implications for soil fertility. These include the following:

a. The leaching of soluble fertilizer nutrients and other agricultural chemicals may lead to groundwater contamination.

b. Because water moves slowly in the microporous matrix of the subsoil, nutrients may be better protected against leaching if they could be placed in this matrix. The difficulty, however, is that preferential flow and the almost continuously moist subsoil may not allow the nutrients to move into the finer soil matrix. The very slow movement of water under unsaturated conditions may not be an effective means of transporting nutrients to the more protective microporous regions in the subsoil.

c. Amelioration of the subsoil is necessary to enable plant roots to explore a large volume of soil for water and, possibly, nutrients.

d. The mechanism by which nutrients are transported to the subsoil micropores is not clear. Nutrients probably reach these micropores via the root systems of deep-rooted vegetation. If that is the case, the inclusion of such vegetation in the cropping system along with deep liming and fertilization may bring about a lasting improvement in soil productivity in Sitiung and other acid soils in Indonesia. Local vegetation adaptable to the food cropping system may include deep-rooting grasses, forage legumes, and some trees.

The Sitiung Region: Physical Environment

Most soils in the Sitiung region (Figure 1) are either Ultisols or Oxisols (e.g., Soil Research Institute, 1979; Subagjo, 1988). Soil acidity, aluminum toxicity, and low fertility are considered the chief agronomic constraints to food crop production (e.g., Wade et al., 1988; Adiningsih et al., 1988).

Rainfall and pan-evaporation data for the Sitiung area are reported in Table 1. The average rainfall varies from 2500 to 3500 mm per year. Most of the heavier rainfall occurs from September to May. June to August is considered relatively dry even though rainfall averages 130 to 180 mm per month. It rains frequently, and 20- to 50-mm rainstorms are common (Dierolf, 1992). The relative humidity typically ranges from 60 to 80%, and potential evaporative demand averages less than 4 mm per day.

Nonetheless, crop moisture stress is common in Sitiung and similar regions in Indonesia. Generally, this problem has been explained as the result of the low water-holding capacity of Ultisols and Oxisols (Rusman, 1990; Kasli, 1991; Adiningsih et al., 1988). But recent investigations in Sitiung by the Soil Management CRSP (Arya, 1990; Dierolf et al., 1991) have produced results that do not support this explanation. Water-holding capacities in Sitiung soils appear to be among the highest observed in mineral soils.

Hydrologic properties and processes in the Sitiung area have not received much attention. What happens to the 3000 mm of rainfall? How much of it is retained in the soil and how much is lost through surface runoff and deep drainage? What is the prevailing field moisture regime? How much of the water retained in the soil is actually used by crops? What effects do the hydrologic processes have on soil acidity and fertility? Given the high rainfall and low evaporative demand, why is crop water availability a problem?

This report presents quantitative information on how soil structure influences soil hydrologic properties and processes. We attempt to evaluate crop water availability in terms of potential water supply and extraction by crops. Implications of hydrologic processes for the overall problems of soil acidity and fertility are discussed. Finally, potential management strategies are identified.

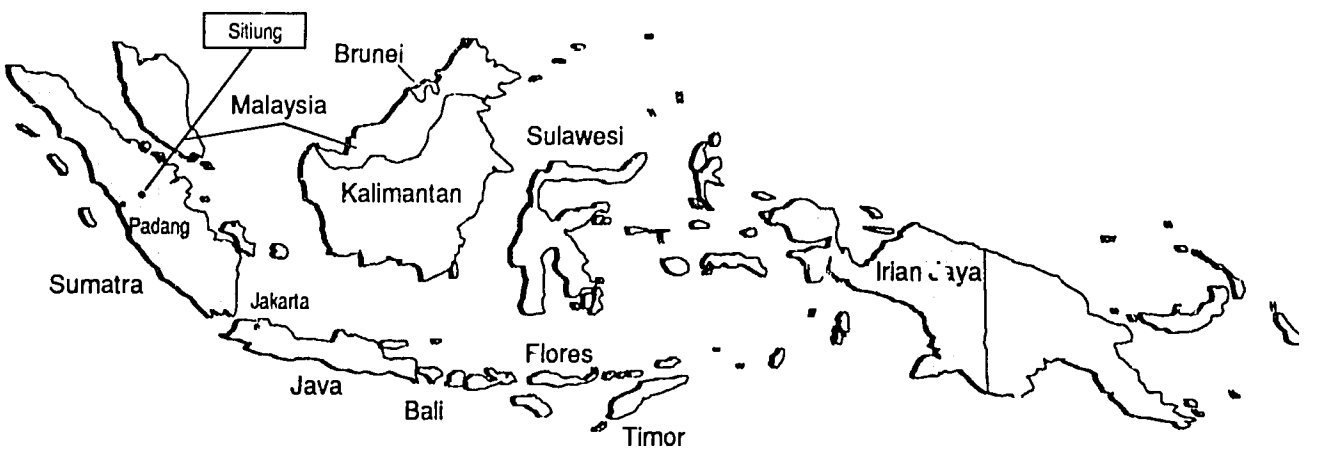


Figure 1. Map of Indonesia showing Sitiung region.

Table 1. Rainfall and pan evaporation data near the Soil Management CRSP Project, Sitiung, Indonesia.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Balittan, Gunung Medan													
1981													
R[§]	73	336	123	404	352	41	167	8	356	299	204	160	2523
N[¶]	11	12	14	20	14	7	10	4	15	19	12	18	156
1982													
R	118	212	386	542	708	161	79	103	101	109	322	585	3426
N	15	14	23	20	18	8	11	6	8	17	17	23	180
1983													
R	328	180	165	475	292	89	257	259	239	310	386	313	3293
N	28	19	8	14	13	10	15	9	12	14	19	20	181
1984													
R	387	267	523	436	na	127	186	111	231	129	201	177	2775
N	22	18	25	19	na	11	14	8	17	13	17	14	178
1985													
R	239	141	335	135	180	16	104	382	199	340	255	635	2961
N	18	11	18	14	11	4	11	10	18	14	18	25	172
1986													
R	477	162	367	503	155	101	249	32	286	416	448	402	3598
N	22	18	22	22	13	7	10	5	17	18	18	22	194
1987													
R	252	149	337	298	279	136	164	6	160	240	260	171	2452
N	17	9	17	17	16	9	11	2	10	10	19	17	154
1988													
R	545	194	341	254	370	220	217	456	176	199	174	230	3376
N	26	17	23	19	15	9	12	16	16	10	20	20	203
1989													
R	459	233	182	117	198	207	78	189	209	294	531	331	3027
N	20	14	15	13	9	7	7	11	12	15	22	20	165
Soil Management CRSP Project, Gunung Medan													
1987													
R	225	159	377	297	312	196	114	9	165	264	236	176	2530
N	na[¶¶]	na	na	na	na	11	12	3	12	12	18	17	85
E[§§]	na	na	na	na	na	106	110	106	110	107	119	115	773
1988													
R	679	197	344	243	366	227	384	414	177	149	209	229	3618
N	28	18	22	16	13	10	10	14	14	9	17	20	191
E	97	111	124	122	120	107	111	111	104	130	102	98	1337
1989													
R	414	234	195	113	187	215	61	213	442	264	515	294	3147
N	18	16	15	10	10	7	7	10	9	13	21	17	153
E	100	96	125	128	129	117	127	99	128	121	112	102	1384
1990													
R	102	495	514	296	191	77	176	90	179	401	440	425	3386
N	15	16	20	17	13	9	16	5	12	18	15	20	176
E	118	108	129	117	138	115	103	118	104	120	120	114	1404

[§] R = Rainfall (mm); [¶] N = Number of rainy days; [§§] E = Pan evaporation (mm); [¶¶] na = Not available.

Soil Mechanical Properties

Soil Texture

Table 2 presents textural data for a number of pedons in the Sitiung area. These data show that Ultisols and Oxisols in Sitiung are generally clayey, with clay contents mostly in the range of 50 to 70%. Soils with somewhat lower clay contents (30 to 50%) have also been reported. In most soils, the clay content increases with depth. High clay contents indicate high water retentivity.

Tilth and Structural Stability

Despite their clayey texture, Sitiung soils are not very sticky because the minerals in the clay fraction are chiefly kaolinitic (Soil Research Institute, 1979; Suharta and Kimble, 1988; Subagjo, 1988; unpublished data, R. C. Jones, University of Hawaii). In addition, the soil material in the surface 10 to 20 cm is highly aggregated. The chief cementing agents seem to be iron and aluminum oxides and hydroxides. These substances create a highly stable bond between the particles As a result, Sitiung Ultisols and Oxisols exhibit a high degree of aggregate stability and remain friable and tillable even soon after a heavy rainfall.

Data on aggregate size distribution are unavailable. Visual observations, however, suggest an abundance of aggregates in the range of 1 to 5 mm. Some data on aggregate stability and plastic properties of the soils are presented in Table 3. Because these data are influenced by the measurement method, they probably do not represent the soil physical condition in the field. Nevertheless, the data suggest a high degree of stability in the surface. High structural stability results in a soil with friable tilth, high infiltrability, and low erodibility.

The structural stability of the subsoil, on the other hand, appears to be conditional. Arya et al. (1992) conducted water-flow tests in a delineated

Researchers evaluating soil properties in Sitiung.

Soil Mechanical Properties

Table 2. Textural composition of Ultisols and Oxisols in Sitiung.

Location	Source	Depth	Sand	Silt	Clay
		cm	%	%	%
Kerinci transect	Subagjo (1988)	0–10	10	14	76
Pedon K 2A		10–29	9	8	83
		29–54	9	9	82
		54–76	8	12	80
		76–112	8	8	84
		112–141	10	8	82
		141–161	10	11	79
		161–202	11	14	75
Kuamang, Sitiung II	Soil Research	0–12	1	69	30
Pedon AE-Jd-51	Institute (1979)	12–33	2	67	31
		33–77	1	64	36
		77–100	2	61	37
Sitiung II, Block E	Soil Research	0–11	4	33	63
	Institute (1979)	11–39	4	35	61
		39–64	6	33	61
		64–108	3	32	65
		108–140	3	34	63
Sitiung I	Suharta and	0–13	7	22	71
Pedon 86P124	Kimble (1986)	13–37	6	19	75
		37–68	6	21	73
		68–100	6	26	68
		100–127	8	33	59
		127–170	9	38	53
Gunung Medan	Fakultas Pertanian,	0–19	16	53	31
Pedon P4	Universitas Andalas (1982)	19–37	16	33	51
		37–58	13	32	55
		58–96	15	32	53
		96–125	17	57	26
		125–150	49	39	12
Ragusa, Sitiung V	Suharta and	0–17	41	11	48
Pedon 86P128	Kimble (1986)	17–46	38	10	52
		46–86	36	10	54
		86–125	31	9	60
		125–168	31	11	58
		168–200	29	13	58
Rimbobujang	Subagjo (1988)	0–8	40	14	46
Pedon RBI		8–22	36	13	51
		22–47	28	7	65
		47–73	25	3	72
		73–108	25	8	68
		108–139	28	2	70
		139–165	18	9	73
		165–195	16	9	75
		195–213	17	17	66
Gunung Medan	Fakultas Pertanian,	0–19	38	5	57
Pedon P12	Universitas Andalas (1982)	19–44	39	6	55
		44–91	28	9	63
		91–150	19	8	73

field monolith and in soil cores obtained from various depths in the soil profile. They observed rapid downward flow in the field monolith. However, when subsoil cores were brought to the laboratory and placed under a head of water, they showed extremely low rates of flow, suggesting a clogging of the pores. There was no reduction in flow rates for the cores taken from the aggregated surface soil.

A comparison of the field- and laboratory-measured flow rates is presented in Table 4. These observations suggest that pore structure in the subsoil is capable of conducting water rapidly. However, stability of the water-conducting pores in the subsoil is preserved only as long as the subsoil is overlain and protected by the stable-structured

Table 4. Steady-state saturated flow of water in a field monolith and laboratory cores from various depths in an Ultisol.

	Soil core depth (cm)			
	Field monolith	Laboratory cores		
Core number	0–120	10–20	20–30	40–50
	Flow rate (cm/hr)			
1	6.8	7.36	0.54	0.89
2	—	49.51	0.36	0.89
3	—	3.79	0.46	0.89
4	—	17.72	3.07	3.82
5	—	3.16	1.04	0.16
6	—	16.91	—	0.13
Mean	6.8	16.41	1.09	1.13

Cross-sectional field and lab. core areas = 28,130 and 88 cm^2, respectively.

Table 3. Aggregate stability and Atterberg values for some soils in the Sitiung/South Jujuhan area. Data taken from Soil Research Institute (1979).

Soil series	Depth	Aggregate stability	Stability index	Atterberg values: Liquid limit	Plastic limit	Plasticity index
	cm	%				
AU-Bd-51	0–5	75.49	117.65	65.75	46.23	19.52
	25–30	85.26	64.94	75.40	55.63	19.77
AU-Bd-21	0–5	81.74	81.31	79.80	49.57	30.23
	20–25	75.30	70.42	79.80	48.27	31.53
AU-Gd-71	0–5	81.82	263.16	85.50	60.63	24.87
	15–20	81.26	133.33	69.15	41.43	27.72
AC-Bd-31	0–5	84.25	216.76	64.85	46.30	18.55
	20–25	57.28	344.83	71.85	49.13	22.72
AC-Bd-51	5–10	76.46	88.50	67.45	46.23	21.22
	25–30	82.05	49.50	89.70	59.87	29.83
AC-Bd-31	13–15	74.76	68.97	67.90	44.76	23.16
	30–35	68.13	71.94	70.40	44.70	25.70
AC-Bd-51	26–31	83.36	54.64	82.80	52.07	30.73
	46–51	73.01	53.76	87.30	52.63	34.67
AC-Bd-51	8–13	83.39	78.13	84.30	49.93	34.37
	37–42	73.12	66.67	93.80	50.53	43.27
AU-Bd-21	0–5	75.03	46.30	110.30	51.27	59.03
	33–38	82.82	100.00	97.60	45.40	52.20
AU-Bd-51	0–5	73.12	106.38	75.40	45.07	30.33
	20–25	73.97	81.30	79.50	45.67	33.83
AU-Bd-31	0–5	76.30	62.89	80.65	45.77	34.88
	30–35	79.76	54.35	82.10	44.83	37.27
VU-Lo-31	0–5	77.97	84.75	76.20	44.33	31.87
	8–13	80.94	78.74	78.50	44.34	34.07
TU-Pc-31	0–5	75.15	188.68	70.55	46.37	24.18
	10–15	77.16	106.38	77.30	46.57	30.73
AU-Bd-21	0–5	75.35	133.33	68.85	44.83	24.02
	10–15	71.04	45.45	76.85	49.87	26.98

Table 5. Examples of bulk and particle density values in Sitiung soils.

A. Bulk Density

I		II		III		IV		V	
Depth	B.D.	Depth	B.D.	Depth	B.D.	Depth	B.D.	Depth	B. D.
cm	*g/cm³*	*cm*	*g/cm³*	*cm*	*g/cm³*	*cm*	*g/cm³*	*cm*	*g/cm³*
0–10	1.10	0–11	0.93	0–4	—	0-10	0.97	3.75	0.91
12–22	1.14	11–40	1.00	4–34	1.28	10-20	1.10	15	0.93
24–34	1.11	40–73	1.00	34–62	1.28	20-30	1.27	30	1.09
36–46	1.08	73–102	0.95	62–106	1.27	30-40	1.31	45	1.05
48–58	1.08	102–154	0.96	106–142	1.26	40-50	1.33	60	1.03
60–70	1.10	154–200	0.99	142–180	1.24	50-60	1.37	75	1.00
72–82	1.12					60-70	1.38	90	1.01
84–94	1.12					70-80	1.35	105	1.00
96–106	1.12								

B. Particle Density

VI		VII	
Depth	P.D.	Depth	P.D.
cm	*g/cm³*	*cm*	*g/cm³*
3.75	2.61	0–5	2.60
15	2.61	5–10	2.60
30	2.73	10–15	2.62
45	2.73	15–20	2.64
60	2.73	20–25	2.68
75	2.73	25–30	2.73
90	2.73	30–35	2.73
105	2.73	35–40	2.73
		40–45	2.69
		45–50	2.73
		50–55	2.72
		55–60	2.75
		60–65	2.73
		65–70	2.73
		70–75	2.76
		75–80	2.74

I. Sitiung IA, data from Arya et al. (1987).
II. Sitiung II, data from Suharta and Kimble (1986).
III. Sitiung V, data from Suharta and Kimble (1986).
IV. Gunung Medan, data from Arya et al. (1988 I).
V. Sitiung IA', data from Dierolf et al. (1991).
VI. Sitiung IA', data from Dierolf et al. (1991).
VII. Gunung Medan, unpublished data, S. M. CRSP Project.

topsoil. Subsoil pores tend to seal up when they are exposed and in contact with free water. On the other hand, the behavior of the subsoil material changes when it is removed from the soil profile, pulverized, and allowed to dry. The resulting aggregates show a very high degree of stability (undocumented field observation by Arya et al.).

Bulk and Particle Density

Table 5 presents examples of data on bulk and particle density. Bulk densities generally range from less than 1.0 to 1.2 g/cm³ and rarely exceed 1.3 g/cm³. Low bulk density appears to be characteristic of all soil horizons regardless of depth. Particle densities range from 2.60 to 2.64 g/cm³ in the surface horizons and 2.68 to 2.76 g/cm³ in the subsurface horizons. High total porosity is thus a common characteristic of these soils.

Mechanical Impedance

Data on mechanical impedance (Table 6) confirm what would be expected from low bulk-density values. Data from the Soil Research Institute (1979) indicate mechanical impedance values that are generally less than 1 kg/cm². Arya et al. (1987) and Winardi (1988) report mechanical impedances ranging from 3 to 7 kg/cm². Similar data have been obtained in an alley-cropping trial in Sitiung V

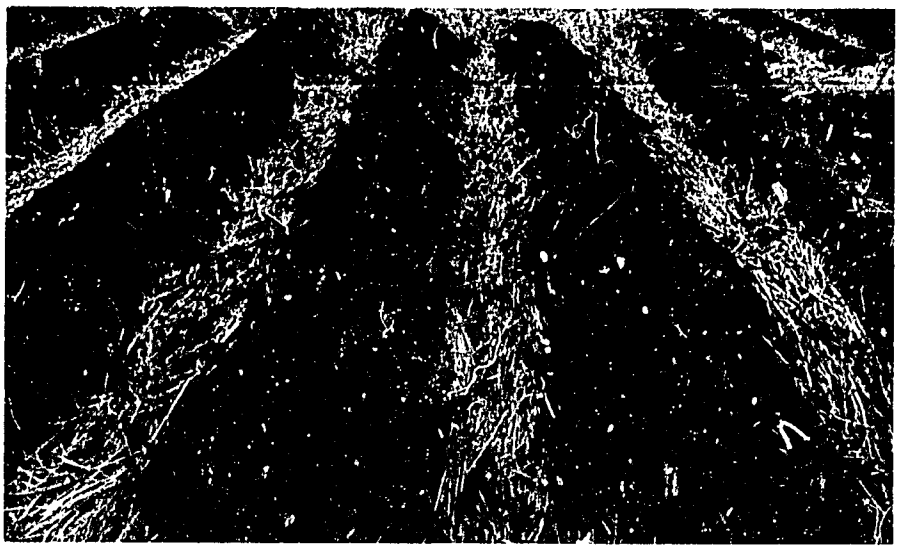
Table 6. Examples of mechanical impedance (MI) in Oxisols and Ultisols in Sitiung.

I		II		III			IV			
Depth	MI	Depth	MI	Depth	MI		Depth		MI	
cm	*kg/cm²*	*cm*	*kg/cm²*	*cm*	*kg/cm²*		*cm*		*kg/cm²*	
					(a)	(b)			Rice	Corn
0–10	4.0	0–15	4.4	0–10	0.96	0.73	0–10	a	8.0	3.7
12–22	6.3	15–30	6.6	10–20	0.89	0.73	10–20		6.9	5.7
24–34	5.9	30–45	6.4	20–30	0.71	0.77	0–10	b	6.9	2.9
36–46	5.6	45–60	5.8	30–40	0.69	0.69	10–20		6.0	4.4
48–58	5.6	60–75	5.4	40–50	0.68	0.66	0–10	c	7.2	2.0
60–70	5.5	75–90	5.9	50–60	0.64	0.64	10–20		6.6	4.4
72–82	5.6	90–105	6.1	60–70	—	0.60	0–10	d	7.8	3.0
84–94	4.9	105–120	6.1				10–20		7.0	5.2
96–106	5.1	120–135	6.1				0–10	e	7.4	3.0
		135–150	5.9				10–20		6.8	5.0
							0–10	f	7.3	1.8
							10–20		5.6	4.5
							0–10	g	7.6	3.5
							10–20		6.8	5.5
							0–10	h	7.7	2.9
							10–20		6.0	5.0
							0–10	i	7.4	1.7
							10–20		6.0	3.8

I. Sitiung 1A, data from Arya et al. (1987).
II. Sitiung V (alley-cropping trial), unpublished data from T. S Dierolf.
III. Data from Soil Research Institute (1979); (a): Soil series AU-Bd-21; (b): Soil series AU-Bd-51.
IV. Data from Winardi (1988) for a soil in Central Kalimantan; a, b, c etc. are various combinations of nitrogen and green-manure treatments.

Researchers gathering soil cores for root-growth measurements.

(unpublished data, Dierolf, Soil Management CRSP). Despite some variation between sources, all data show low to very low impedance in Sitiung soils. The obvious conclusion is that there are no soil physical barriers. Mechanical impedances have to be in the range of 12 to 18 kg/cm² to limit seedling emergence and root growth (Taylor and Klepper, 1978).



The ridge-furrow system of cultivation facilitates deep placement of lime. It is also an effective way to control erosion.

Soil Hydrologic Characteristics

Water Retention and Water-holding Capacity

Table 7 presents examples of laboratory-measured data on soil water retention for several pedons in the Sitiung area. Data show water contents retained at –0.01, –0.1, –0.33, and –15 bar pressures. Water contents at –0.1 or –0.33 bar pressures are accepted by many soil scientists and agronomists as estimates of field capacity. Field-capacity values are often used to indicate whether the water-holding capacity of a soil is high or low. Data presented in Table 7 indicate a generally high water-holding capacity. Based on the bulk and particle density data (Table 5), total porosity in Sitiung Ultisols and Oxisols averages around 63% for the surface soil and around 58% for the subsoil. Water contents at –0.1 and –0.33 bar pressures average around 52 and 47%, respectively, for the surface 5 to 10 cm of the soil, and 54 and 50%, respectively, for the subsoil. These water contents represent saturation values ranging from 75 to 93% of the total pore space. Saturation percentages of this magnitude are considered high. They are consistent with the high clay contents (Table 2) and low bulk-density values (Table 5).

Field Estimate of Water-holding Capacity

Laboratory measurements on small unconfined samples often grossly misrepresent field water retention, especially in the high pressure range. Field capacity is a *field* phenomenon and is better measured by a *field* procedure (Cassel and Nielsen, 1986). Such a procedure involves delineating a field plot to the desired depth, saturating it, and then letting it drain naturally while preventing evaporative water loss or additions of water through rain or irrigation. Soil water content and soil water pressure are monitored as a function of depth and time. Field capacity is reached when the downward drainage of water has *materially* decreased, a point that separates the initial rapid drainage from the subsequent slow drainage. Ritchie (1981) suggests that the phrase *upper drained limit* replace *field capacity*, and he also recommends that it be measured when the downward drainage reaches a value of 0.1 cm/day. Water content and soil water pressure at this point can be determined by plotting the data as a function of time.

The Soil Management CRSP team in Sitiung carried out several field tests to determine field capacity. Changes in the total water content and soil water pressure with time for one such study are presented in Figures 2 and 3. Data show that field capacity was reached less than 30 hours after irrigation stopped.

Table 8 presents field-measured values of field capacity and corresponding soil water pressures for three sites. Data show that field capacity for the surface few cm is around 39% of the soil volume. It generally increases with depth and ranges from about 46 to 53% at the 15-cm depth and 49 to 61% for the rest of the soil profile. Except for the soil's top 15 cm, field capacity values obtained by this procedure represent water-content values very close to saturation. Data in Table 8 also show that, in Sitiung soils, soil water pressures at which field capacity is reached range from about –30 to –50 cm in the surface 15 cm of the soil and –10 to –25 cm in the subsoil. These pressures are considerably higher than the –330 cm commonly used for laboratory estimation of field capacity.

Water Flow Rates

Except where a field has been deliberately puddled, Sitiung soils do not flood, even during torrential rains. They absorb and conduct water rapidly. Table 9 presents infiltration rates for a number of soils in

Table 7. Examples of laboratory-measured soil water retention values for Oxisols and Ultisols in Sitiung.

Soil Unit	Depth	Soil water pressure, –bar 0.01	0.10	0.33	15	Soil location and source
	cm	*Water content, cm³/cm³*				
AU-Bd-51	0–5	0.576	0.518	0.474	0.322	Sitiung-South Jujuhan area. Soil
	25–30	0.618	0.573	0.517	0.380	Research Institute (1979).
AU-Bd-21	0–5	0.577	0.528	0.487	0.350	
	20–25	0.588	0.538	0.491	0.364	
AU-Gd-71	0–5	0.600	0.554	0.506	0.367	
	15–20	0.566	0.522	0.472	0.348	
AC-Bd-31	0–5	0.608	0.562	0.519	0.345	
	20–25	0.595	0.549	0.495	0.366	
AC-Bd-51	5–10	0.589	0.549	0.504	0.352	
	25–30	0.612	0.560	0.519	0.382	
AC-Bd-31	13–15	0.532	0.488	0.449	0.327	
	30–35	0.565	0.513	0.467	0.326	
VU-Lo-31	0–5	0.456	0.399	0.366	0.268	
	10–15	0.504	0.462	0.423	0.320	
TU-Pc-51	0–5	0.532	0.486	0.448	0.329	
	10–15	0.585	0.535	0.496	0.377	
SBL1	0–15	0.606	0.546	0.485	0.334	Sitiung II E, Pusat
	43–76	0.620	0.566	0.505	0.336	PenelitianTanah (1984)
	76–99	0.611	0.554	0.500	0.355	
SBD5	0–13	0.594	0.524	0.468	0.287	Sitiung III B
	13–46	0.603	0.543	0.488	0.341	
	46–73	0.605	0.550	0.500	0.366	
	73–102	0.586	0.530	0.482	0.341	
SBD6	0–11	0.543	0.472	0.422	0.278	Sitiung IV B
	11–28	0.579	0.517	0.464	0.336	
	28–48	0.579	0.528	0.477	0.332	
	48–86	0.567	0.512	0.464	0.340	
86P124	0–13	—	—	0.464	0.340	Sitiung I, Suharta
	13–37	—	—	0.513	0.295	and Kimble (1986)
	37–68	—	—	0.532	0.290	
	68–100	—	—	0.531	0.283	
	100–127	—	—	0.511	0.271	
	127–170	—	—	0.477	0.273	
SP-5	0–10	—	0.562	0.486	0.316	Gunung Medan, Fakultas
	10–23	—	0.548	0.486	0.283	Pertanian, Universitas
	23–51	—	0.481	0.456	0.309	Andalas (1982)
	102–151	—	0.490	0.470	0.336	
SP-2	0–18	—	0.514	0.582	0.346	Gunung Medan
	18–34	—	0.600	0.588	0.360	
	34–67	—	0.544	0.497	0.358	
	67–104	—	0.600	0.573	0.342	
	104–130	—	0.618	0.584	0.366	
	Mean	0.578	0.534	0.489	0.332	

Table 8. Examples of field-measured values of field capacity and soil water pressures at which field capacity occurs in Oxisols and Ultisols in Sitiung.

Depth	I		II		III	
	Field capacity	Soil water pressure	Field capacity	Soil water pressure	Field capacity	Soil water pressure
cm	cm^3/cm^3	-cm H_2O	cm^3/cm^3	-cm H_2O	cm^3/cm^3	-cm H_2O
3.75	0.395	28	0.392	36	0.383	53
15	0.483	27	0.532	32	0.453	41
30	0.570	20	0.521	26	0.488	15
45	0.577	21	0.579	22	0.500	11
60	0.578	11	0.573	10	0.513	14
75	0.585	18	0.571	13	0.526	20
90	0.596	9	0.590	18	0.524	—
105	0.608	10	0.561	21	0.533	—

I—Sitiung 1A', Dierolf et al. (1991); II—Sitiung 1A', unpublished data, S. M. CRSP; III—Gunung Medan, unpublished data from Bujang Rusman's research, S. M. CRSP.

the Sitiung area. Measurements made by the Soil Research Institute (1979) in the Sitiung–South Jujuhan area show infiltration rates as high as 198 cm/hr. This study also reports several cases of low infiltration rates and attributes them to compaction caused by mechanical land clearing. Measurements made in other areas (Fakultas Pertanian, Universitas Andalas, 1982; Makarim, 1985; Winardi, 1988) also show high infiltration rates. These data suggest that all of the rainfall should be accepted by the soil, with little or no runoff. Some of the rates are extremely high (Winardi, 1988).

The infiltration measurements referred to above were made using double-ring infiltrometers in which a depth of water is ponded and infiltration is recorded as the drop in the height of the water surface. The method does not simulate rainfall or its acceptance by the field soil.

Measurements that best show how rainfall is accepted by the field soil are made in large erosion plots where rainfall and runoff are recorded separately and intake of rainfall is calculated as

Intake of rainfall = rainfall – runoff.

Table 10 shows rainfall, runoff, and field intake of rainfall for a bare plot in Sitiung IV. Data show rainfall intake rates ranging from 68 to 99% depending on the amount of rain and plot moisture prior to rainfall. For nine of the twelve months, intake rates

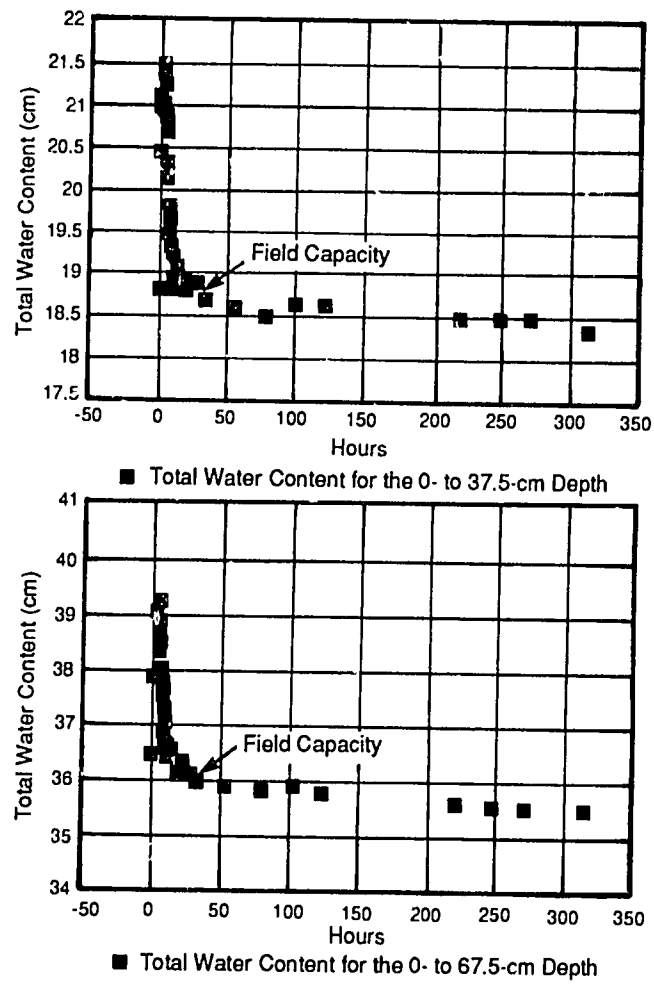


Figure 2. Total water content in an Ultisol irrigated to maximum field saturation and allowed to drain without evaporation, Sitiung 1A'.

were more than 90% of the rainfall. Intake rates fell below 80% only during October, November, and December. The total rainfall for the year was 3248 mm, while the intake was 2805 mm—or 86.4% of the rainfall.

The bare plot referred to above represents the worst case for runoff and erosion. It was not protected, and it was tilled frequently, up and down the slope. Normal field soils almost always have a certain amount of vegetation—crop, weeds, or decaying residue. Therefore, the intake of rainfall in normal field soils should be higher than in the bare plot.

A field trial on an Ultisol in Sitiung 1A' provided a more accurate estimate of water intake (Arya et al., 1992). A field plot was delineated to a depth of 120 cm and irrigated with constant-rate irrigation of a magnitude that supplied water for entry into the soil, maintained a ponding depth of 4.1 cm, and caused overflow. The plot was irrigated continuously for about 2.5 hours to ensure maximum saturation of the soil profile and the establishment of a steady state. Cumulative irrigation and overflow were recorded for the next 40 minutes. Data are presented in Figure 4. The rate of water intake was calculated as the difference between the irrigation and overflow rates. Data show that, at full saturation, water was entering the soil at the rate of 68 mm/hr. This rate exceeds commonly observed rainfall rates in Sitiung. Total rainfall amounts ranging from 20 to 50 mm per event, and even higher, can occur, but they are distributed over several hours and are generally received on surfaces that are not entirely saturated. Thus, most rainfalls are likely to be absorbed by the soil without producing any runoff.

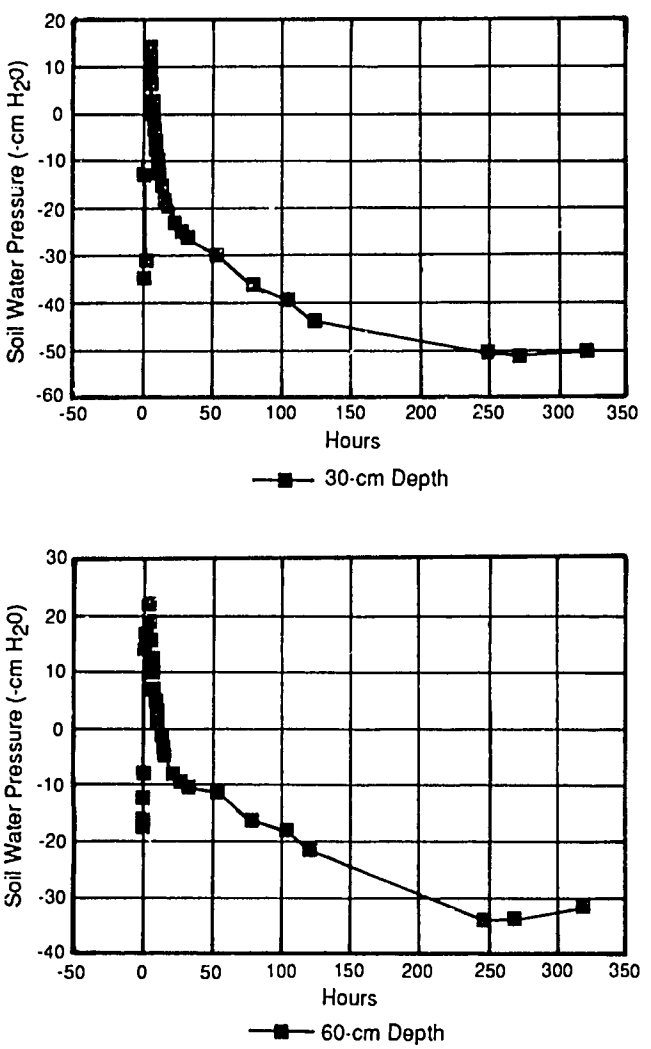


Figure 3. Soil water pressure in an Ultisol irrigated to maximum field saturation and allowed to drain without evaporation, Sitiung 1A'.

Internal Pore Structure

Rapid entry and rapid downward drainage of water in Sitiung soils (Figures 2, 4; Tables 9, 10) result from a pore structure that (under field conditions) has a large capacity and that remains stable even under saturated conditions. Field investigations (Arya, 1990; Dierolf et al., 1991; Arya et al., 1992) have revealed that a

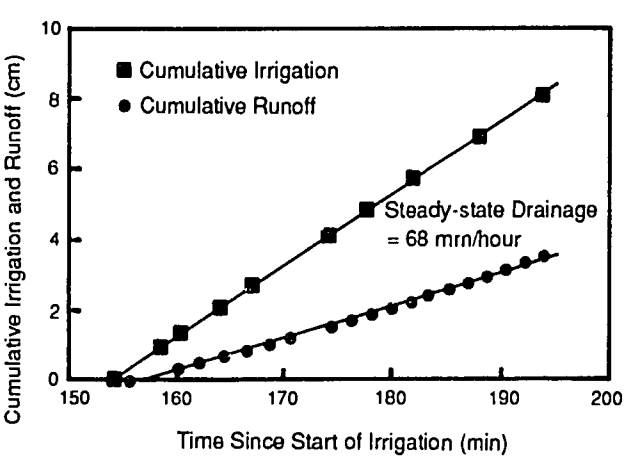


Figure 4. Cumulative irrigation and runoff during steady-state drainage in an Ultisol, Sitiung 1A'. Irrigation was maintained at a constant rate to supply water for entry into the soil, maintain a constant ponding depth, and cause overflow. Data from Arya et al. (1992).

fraction of the total pore space in Sitiung soils consists of large pores. Changes in total water content with time (Figure 2) show that, within 25 to 30 hours after irrigation stopped, the total water content dropped to a point beyond which further decreases in water content became negligible (0.02 to 0.05 cm per day). This point is defined as field capacity.

Here, then, one can identify two categories of pores: macropores and micropores. Macropores make up that portion of the pore volume that drains rapidly between maximum saturation and field capacity. Micropores constitute that portion of the pore volume that remains filled at field capacity. Water flow through the macropores is quite rapid; micropores conduct water very slowly. In Figure 2, for example, the 0- to 67.5-cm profile lost 3.35 cm of water during the first 29.2 hours, the time it took to reach field capacity. After field capacity was reached, it took 284 hours to drain off an additional 0.5 cm of water. The initial rapid drainage of water indicates the influence of macropores. The previous example also shows that soil water at field capacity is held tightly in fine pores.

Table 11 presents data on total porosity and relative distributions of macro- and micropores for two sites in Sitiung. Pore radii defining the lower limits of the macropore sizes are included in Table 11. Data show that macropores in the surface soil account for a significant portion of the total pore space, 25 to 39% for Site I and 29 to 45% for Site II. This percentage decreases sharply with depth, however. The fraction of the macropores in the subsoil shows a range of 4 to 8% for Site I and 8 to 17% for Site II. Pore space below the 30-cm depth appears to be made up largely of fine pores: they account for 92 to 96% of the total pore space for the 30- to 105-cm depth at Site I and 84 to 92% for the 30- to 75-cm depth at Site II.

Although the volume fraction of the macropores decreases with depth, the pore radii separating the

Table 9. Examples of infiltration rates (cm/hr) in Oxisols and Ultisols as measured by double-ring infiltrometers.

I		II		III	
Site I.D.	Infiltration	Site I.D.	Infiltration	Treatment	Infiltration
AU-Bd-51	0.34	SP-3	3.00	(a) Rice	31.76
AU-Bd-21	0.08	SP-3	2.04	Corn	37.88
AU-Gd-71	196.68	SP-4	3.59	(b) Rice	45.20
AC-Bd-31	32.36	SP-5	6.60	Corn	40.81
AC-Bd-51	4.98	SP-6	2.04	(c) Rice	40.81
AC-Bd-51	0.05	SP-6	0.90	Corn	59.06
AC-Bd-31	0.11	SP-7	5.04	(d) Rice	35.00
AC-Bd-51	0.04	SP-7	2.64	Corn	40.17
AU-Bd-21	0.10			(e) Rice	46.97
AU-Bd-51	1.41			Corn	48.36
AU-Bd-31	0.12			(f) Rice	50.22
VU-Lo-31	48.80			Corn	55.71
TU-Pc-51	0.11			(g) Rice	33.38
AU-Bd-21	0.03			Corn	37.12
				(h) Rice	41.77
				Corn	52.82
				(i) Rice	57.29
				Corn	58.31

I. Sitiung-South Jujuhan area, Soil Research Institute (1979).
II. Gunung Medan, Fakultas Pertanian, Universitas Andalas (1982).
III. Central Kalimantan, Winardi (1988). Letters a, b, c etc. stand for various combinations of nitrogen and green-manure treatments.

Table 10. Plot-scale measurement of runoff and intake of rainfall in a bare field soil (10 to 13.5% slope) in Sitiung IV (1985).[§]

Month	Rainfall	Runoff	Intake	
	mm	*mm*	*mm*	*% rainfall*
January	436	27	409	93.8
February	162	3	159	98.1
March	468	46	422	90.2
April	151	1	150	99.3
May	239	20	219	91.6
June	44	1	43	97.7
July	78	0	78	100.0
August	258	30	228	88.4
September	242	13	229	94.6
October	389	96	293	75.3
November	409	130	279	68.2
December	372	77	295	79.3
Total	3248	444	2804	
% of rainfall	100	13.7	86.3	

[§] Unpublished data from H. Suwardjo, Center for Soil and Agroclimate Research, Bogor.

macro- and micropores increase with depth. This is a very important feature of the pore structure in highly weathered soils. According to Poiseuille's law (e.g., Hillel, 1971, p. 81), volume flow is proportional to the fourth power of the pore radius. Therefore, a small increase in pore size can result in a significantly large increase in the volume flow. Thus, rapid transport of incoming water is ensured even though a large portion of the soil matrix remains filled with water (Tables 7 and 8).

Hydraulic Conductivity

Saturated hydraulic conductivity is a good indicator of the soil's ability to drain water. Table 12 presents field-saturated conductivity data for a Sitiung Ultisol. Data show a range of conductivity values from 2 to 4 cm/hr in the surface few cm of the soil to 4 to 9 cm/hr in the subsoil. Such high values are unexpected in soils with high clay contents. The occurrence of these high values in Sitiung soils confirms the presence of large pores. The higher saturated conductivity values in the subsoil are consistent with the observed increase in macropore size with depth.

Table 11. Total porosity (TP) and proportions of macro- and micropores for two sites in Sitiung.

	I				II			
Depth	Total porosity	Macro-pores[§]	Micro-pores[§]	Macropore radii lower limit[§§]	Total porosity	Macro-pores[§]	Micro-pores[¶]	Macropore radii lower limit[§§]
cm	*cm^3/cm^3*	*% TP*	*% TP*	*cm*	*cm^3/cm^3*	*% TP*	*% TP*	*cm*
3.75	0.650	39.2	60.8	0.00524	0.669	44.7	55.3	0.00277
15	0.646	25.2	74.8	0.00544	0.642	29.1	70.9	0.00358
30	0.601	5.2	94.8	0.00734	0.581	16.5	83.5	0.00980
45	0.615	6.2	93.8	0.00699	0.575	11.7	88.3	0.01340
60	0.623	7.2	92.8	0.01335	0.562	8.4	91.6	0.01050
75	0.634	7.7	92.3	0.00816	0.564	8.2	91.8	0.00735
90	0.630	5.4	94.6	0.01631	—	—	—	—
105	0.643	4.1	95.9	0.01468	—	—	—	—

I. Sitiung IA', data from Dierolf et al. (1991).
II. Gunung Medan, unpublished data from Bujang Rusman's Ph.D. research. S. M. CRSP Project, Sitiung.
[§] Macropores, %TP = ([TP-water content at field capacity]/TP)100. See Table 8 for field capacity values.
[§§] Lower limits of macropore radii calculated from h = 2s cos a/dgr, where h is the soil water pressure at field capacity (–cm H_2O, see Table 8 for values), s is the surface tension of water (72 dynes/cm), a is the contact angle (0 degree for soil), d is the density of water (1.0 g/cm^3), g is the acceleration due to gravity (980 cm/sec^2), and r is the radius of the soil pore (cm).
[¶] Micropores, %TP = ([Water content at field capacity]/TP)100.

Except in the surface few cm of soil, macropores account for a very small fraction of the total pore volume (Table 11). Much of the water in the subsoil is held in micropores, which conduct water quite slowly. The implication is that water movement in Sitiung soils is rapid only during application. It decreases rapidly as soon as the macropores are empty. This shift has been confirmed in another field measurement by Dierolf et al. (1991). Their data showing conductivity as a function of time are presented in Figure 5. Saturated conductivities were similar to the data presented in Table 12. However, they dropped by three to four orders of magnitude within 25 hours after irrigation stopped, while pore saturation values remained between 75 to 95%.

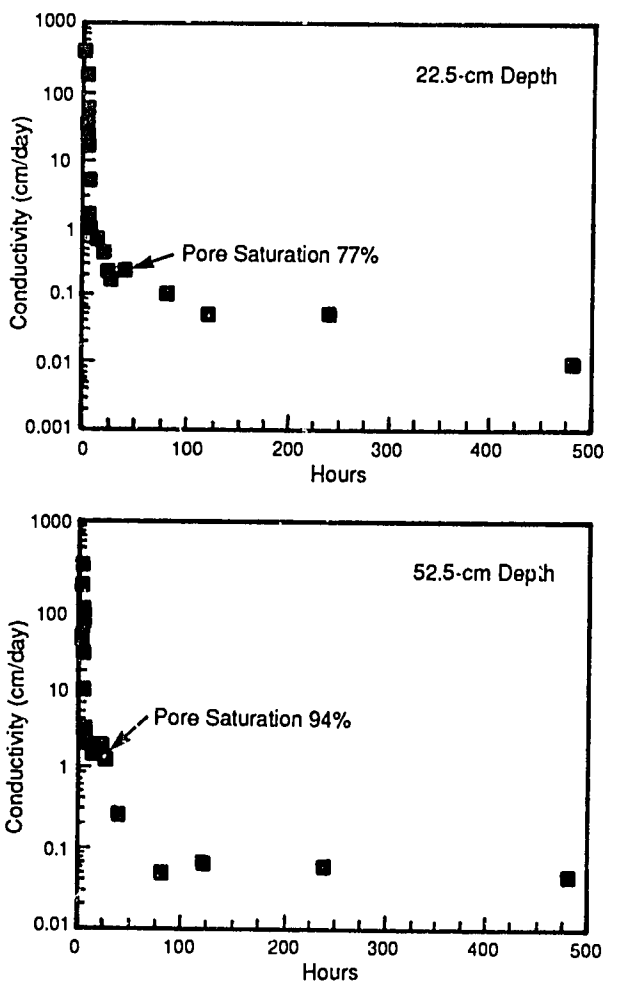


Figure 5. Hydraulic conductivity in an Ultisol irrigated to maximum field saturation and allowed to drain without evaporation. Unpublished data from T. S Dierolf, Soil Management CRSP Project.

These data show that Ultisols and Oxisols in Sitiung (i) retain large volumes of water and (ii) rapidly transmit large volumes of water.

Table 12. Field-measured saturated hydraulic conductivities in an Ultisol in Sitiung.[§]

Depth	Cycle I[¶]	Cycle II[¶]	Mean
cm		*cm/hr*	
0–2.75	4.24	3.54	3.89
2.75–4.6	2.57	2.31	2.44
4.6–10.3	6.96	6.40	6.68
10.3–20.2	9.84	8.63	9.24
20.2–29.2	9.24	8.10	8.67
29.2–39.6	6.48	5.52	6.00
39.6–49.9	7.01	5.86	6.44
49.9–69.6	8.73	8.68	8.71
69.6–78.8	6.90	5.78	6.34
78.8–85.2	3.99	3.38	3.69
85.2–96.5	4.26	3.88	4.07
96.5–110.6	5.44	4.70	5.07

[§] Data from Arya et al. (1992).
[¶] Conductivities were measured in the same plot over two cycles of irrigation.

Field Water Regime

Frequent rainfall (Table 1), high soil water retention (Tables 7, 8; Figure 2), and low evaporative demand (Table 1) suggest that Sitiung soils remain wet most of the year. Measurements of soil water content with depth and time provide a picture of how soil water is depleted, how is it distributed in the soil profile, and what potential supplies exist. Data in Table 8 show that, at field capacity, water contents held in Sitiung soils range from 0.37 to 0.48 cm^3/cm^3 in the surface soil and 0.49 to 0.61 cm^3/cm^3 in the subsoil. These values indicate the amount of water the soil can potentially retain. Actual field wetness, on the other hand, is a function of the balance between recharge and depletion. Rainfall increases the water content; gravity-drainage, evaporation, and plant uptake deplete it. Thus, the field water status should fluctuate.

Figures 6 and 7 present daily rainfall and volumetric water contents for several depths in an Ultisol planted to cowpea and corn. Data show that water content was affected primarily in the top 25 to 30 cm. Water contents in this layer increased with rainfall and decreased without it. As expected, the amplitude of the fluctuations in water content decreased with depth. Even with no rainfall, very little change occurred in the water content at depths below 30 cm Data also indicate that water contents at all depths remained close to field capacity, even during the long rainless periods.

For cowpea (Figure 6), a dry period occurred from 28 July to 4 September, with only one exception: 8 mm of rainfall on 15 August. Water contents in the 0- to 25-cm depth declined with time, reflecting the absence of rainfall. However, water contents in the 30- to 60-cm depth declined negligibly with time and remained slightly below field capacity at all times.

For corn (Figure 6), the rainfall events were much more evenly distributed, with two dry spells of six to nine days and a few heavier showers near the end of the growing season. Water contents in the 0- to 25-cm layer fluctuated with time, but showed a slight tendency to increase. Overall, water contents in this layer tended to remain above field capacity. This surplus could have resulted from the frequent and more evenly distributed rainfall events. Unlike water contents for cowpea, water contents for corn in the 30- to 60-cm depth showed the effect of the two dry spells indicated above. For the rest of the season, however, they remained virtually stable and near field capacity.

Water contents for the 0- to 25-cm depth were measured by gravimetric sampling, and those for the 30- to 60-cm depth were measured by a neutron probe. The effects of spatial variability in gravimetric samples and temporal variability in neutron-probe standards undoubtedly have contributed to the variability in water contents reported in Figures 5 and 6. The overall trends in the field water regime, however, are consistent with the rainfall patterns and soil water-retention properties discussed earlier.

There are no objective criteria to quantify the wetness of a field moisture regime. However, since field capacity represents the maximum wetness after free drainage, it can serve as a reference. The field wetness can be expressed relative to this reference. Data reported in Figures 6 and 7 show that field wetness in the surface 20- to 25-cm depth stays around field capacity; field wetness remains slightly below field capacity in the 30- to 60-cm depth.

It may appear unusual that field water contents in the 30- to 60-cm depth never rose above field capacity, which, for this soil, was measured in a plot approximately 75 m from the cowpea and corn plots. Large spatial variability is very common in Sitiung (Trangmar et al., 1984). Thus, field capaci-

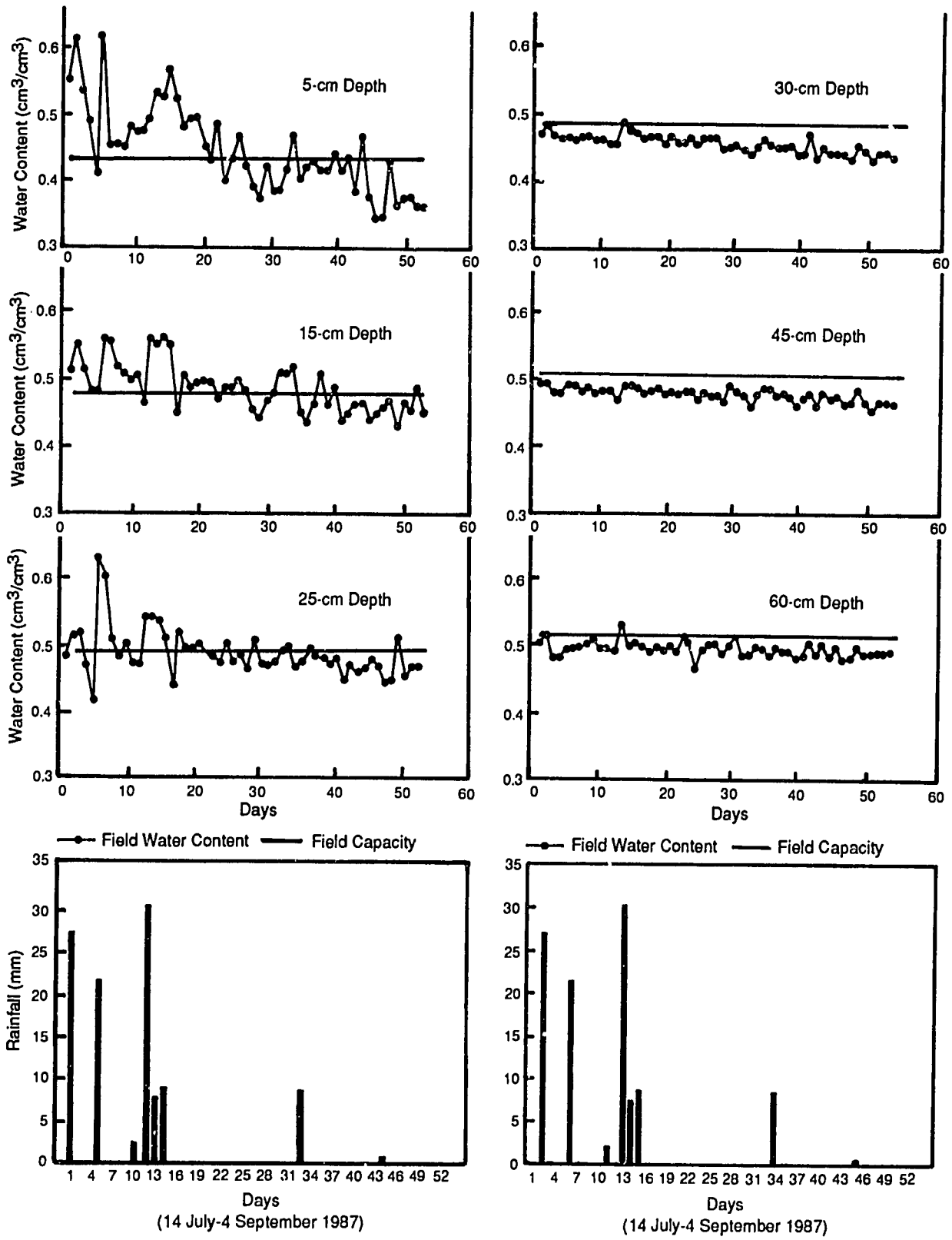
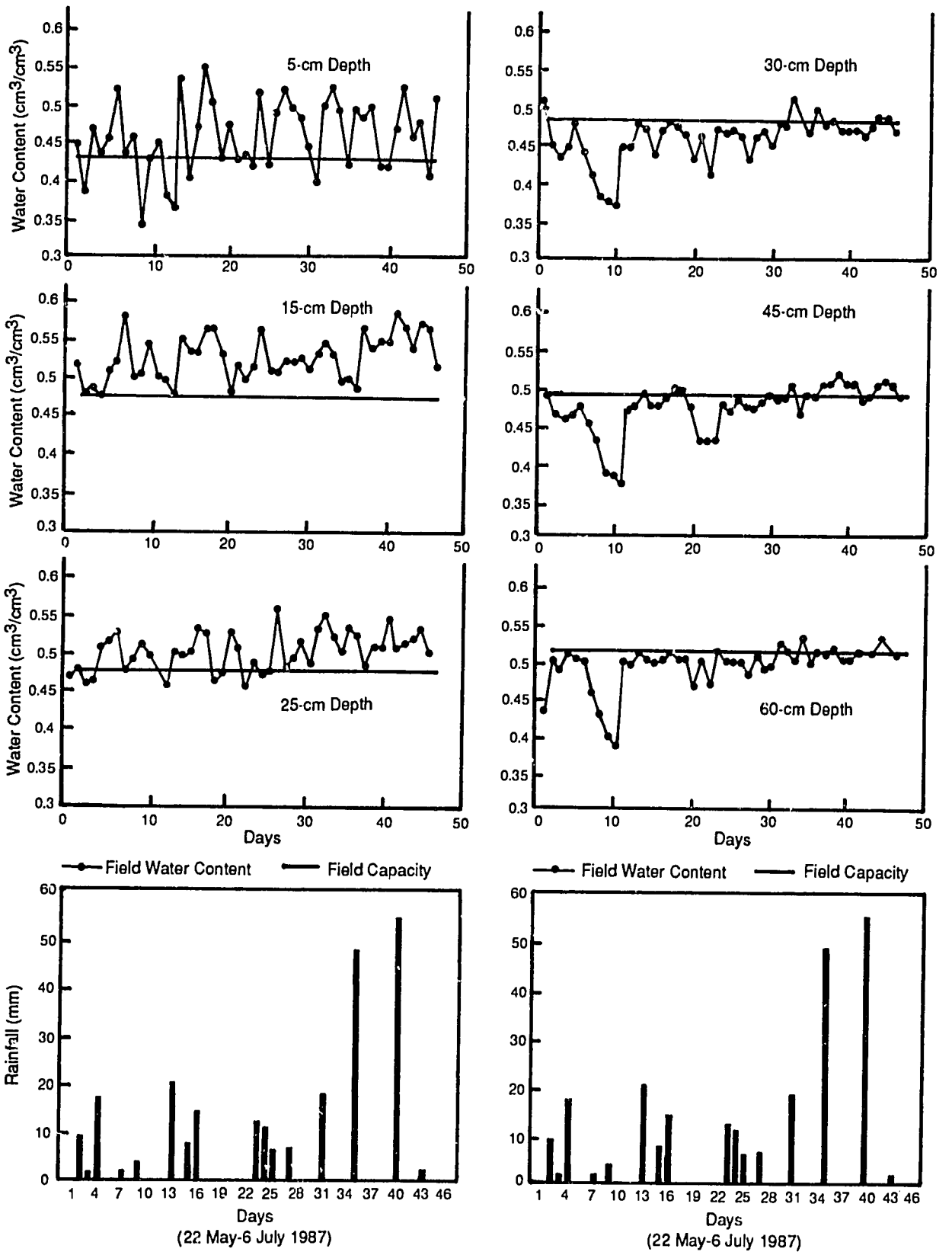


Figure 6. Daily rainfall and field water content in an Ultisol planted to cowpea, Gunung Medan.



gure 7. Daily rainfall and field water content in an Ultisol planted to corn, Gunung Medan.

ties for the corn and cowpea plots could have differed slightly from those some distance away.

In addition, measuring field capacity in Sitiung requires prolonged and thorough wetting to ensure potential saturation in all parts of the soil profile, a circumstance that does not occur under normal field conditions. Based on results from field-drainage experiments, we speculate that rainwater received in the surface soil interacts with a wider range of pores and thus moves more slowly than it does in the subsoil. Water drained from the surface layer most likely finds its way into discrete macropore channels in the subsoil and descends rapidly, without much interaction with the surrounding microporous soil, especially if the subsoil water content is already high. Thus, subsoil water contents are unlikely to be measured at levels above field capacity. A water content higher than field capacity can be detected if the measurements are made during or very soon after a heavy rainfall. Water contents reported in Figures 6 and 7 were measured 12 to 18 hours after the rainfall events.

Limitations to Crop Water Use

Despite high rainfall, low evaporative demand, and an abundance of stored soil water, crop water stresses are common in Sitiung. The most commonly observed symptom of water stress is wilting foliage. No other measure of water stress is available, and a quantitative assessment of crop losses due to water stress has not been made.

Although it rains frequently, rainless periods of several days are common. Dry periods of several weeks may also occur during certain times of the year. Examples of rainless periods are shown in Table 1 and Figures 6 and 7. Crops unable to extract water from the subsoil suffer from water stress during these periods, primarily because most are sensitive to acidity and aluminum toxicity. Their root systems remain confined to the surface 20 to 30 cm of the soil. As a result, they are unable to extract available water from the subsoil. Data in Figures 6 and 7 demonstrate that food crop plants such as cowpea and corn affect soil water content mainly in the surface layers. The reservoir of water below a depth of 30 cm remains largely unaffected. Unsaturated movement of water in Sitiung Ultisols and Oxisols is too slow (Figure 5) to meet crop water needs simply by moving to points of absorption. Plant roots have to make contact with the extractable water.

Acidity and Aluminum Saturation

Almost all data on chemical analysis show that Sitiung soils are acid and aluminum toxic (e.g., Soil Research Institute, 1979; Fakultas Pertanian, Universitas Andalas, 1982; Subagjo, 1988; Wade et al., 1988; Adiningsih et al., 1988). Commonly reported pH values range from under 4 to 5, and aluminum saturation can be as high as 90 to 100% (Table 13).

Effect of Aluminum Toxicity on Root Growth and Plant Production

Arya et al. (1987, 1988 I, II), Rusman and Arya (1988), and Rusman et al. (1989) present data showing that plants which grow well in the acid, aluminum-toxic soils of Sitiung invariably have a deep root system. Such systems provide a larger volume of soil from which plants can obtain water and nutrients. Native plant species such as local grasses, forage legumes, trees, and bushes grow wel and almost never show symptoms of water stress. Food crop plants, on the other hand, are quite sensitive to high levels of aluminum saturation. Their root-zone depths are generally quite shallow, and they frequently exhibit symptoms of water stress and nutrient deficiency. Most commonly observed root-zone depths for food crops and nonfood vegetation are summarized in Table 14.

Figure 8 illustrates the sensitivity of soybean roots to aluminum saturation in the topsoil. Data show a steep drop in root growth as aluminum saturation exceeds 45%. Maximum root growth occurred when aluminum saturation was under 10%. Figure 9 shows the effect of deep liming on corn root growth. Without lime, corn roots did not grow beyond a depth of 15 cm or so. Where lime was deep-incorporated, roots were found as deep as the lime was incorporated.

Table 15 shows that good plant growth is generally associated with dense, deep root systems. For food crops, data indicate a marked correlation of biomass with rooting depth and density. A deeper root system may be a result of natural adaptation, or it can be achieved by soil management. Rooting depth for corn, for example, increased when lime was deeply incorporated to neutralize subsoil aluminum. *Desmodium ovalifolium* (a forage

Table 13. Typical soil chemical characteristics in Sitiung.[§]

Depth	Org. C	Free Fe	Exchangeable Ca	Mg	K	Al	ECEC	Al sat.	pH H_2O
A. An Ultisol, Sitiung IVD									
cm	%	%	*cmol*					%	
0–5	4.6	3.6	0.6	0.2	0.1	4.3	5.2	83	3.6
5–20	1.5	4.4	0.1	t[¶]	t	3.3	3.4	97	4.3
20–48	1.1	4.8	t	t	t	2.8	2.8	100	4.7
48–102	0.6	4.7	t	t	t	2.4	2.4	100	4.6
102–157	0.4	5.4	0.1	t	t	2.0	2.1	95	4.4
157–194	0.3	5.2	0.1	0.1	t	1.6	1.8	89	4.6
B. An Oxisol, Sitiung IA									
cm	%	%	*cmol*					%	
0–13	3.0	3.4	0.3	0.1	0.2	5.0	5.6	89	4.1
13–37	1.0	4.2	0.1	t	0.1	2.9	3.4	85	4.9
37–68	0.5	3.8	t	t	t	2.7	2.7	100	5.0
68–100	0.3	4.2	t	t	t	2.9	2.9	100	4.9
100–127	0.3	4.1	t	t	t	3.3	3.3	100	5.1
127–170	0.3	4.1	t	t	t	3.3	3.3	100	5.2

[§] Data from Wade et al. (1988). [¶] t = trace.

legume) and natural forages (local weeds), on the other hand, rooted deeply without any soil amendment.

Data presented in Figure 9 and Table 15 show that roots tend to concentrate in the surface and that their densities decrease progressively with depth. One might think that very small root densities in the subsoil would contribute little to growth. However, evidence suggests that subsoil roots, no matter how small the density, probably play a significant role in supplying water and, possibly, nutrients to the crop plant. Figure 10 shows the relationship between corn biomass and root mass in the topsoil and subsoil. Although the root mass in the topsoil was several times that in the subsoil, the aboveground biomass production did not have a discernible relationship to the root mass in the topsoil. On the other hand, top growth was clearly related to the root mass in the subsoil.

These observations do not imply that aboveground biomass is solely determined by root growth. Rather, the two are interdependent. In principle, good top growth can be supported by limited root growth if water and essential nutrients remain nonlimiting in the root zone. However, a nonlimiting environment seldom (if ever) occurs under field conditions. Limitations to root growth in Sitiung's acid soils place a corresponding limit on

Table 14. Commonly observed root-zone depths for food crops and nonfood vegetation in the acid soils of Sitiung.[§]

Crop	Root-zone depth: Poor plant growth	Good plant growth	Deep liming[¶] (variable depth)
	cm	*cm*	*cm*
Corn	<30	40–50	d+
Soybean	<25	35–40	d+
Cowpea	<35	55–60	—
Mungbean	<20	30–35	—
Peanut	<30	40–45	—
Desmodium ovalifolium	—	100+	—
Local forages	—	120+	—
Alley-crop trees	—	150+	—

[§] Data from Arya et al. (1988 II).
[¶] Roots were found 5 to 10 cm below the depth of liming (d).

the soil volume from which water and nutrients can be extracted. Liming and fertilization of the topsoil generally assure increased early growth, thus increasing the water requirement. However, since the root systems of acid-sensitive plants remain concentrated near the surface, the aboveground vegetation experiences stress as soon as the extractable water in the surface zone is depleted. Poorly growing plants with low water requirements can live on a poor root system, but they produce very little. Recognition of these limitations offers an opportunity for exploring soil-management technologies that would lead to a more efficient use of soil water resources.

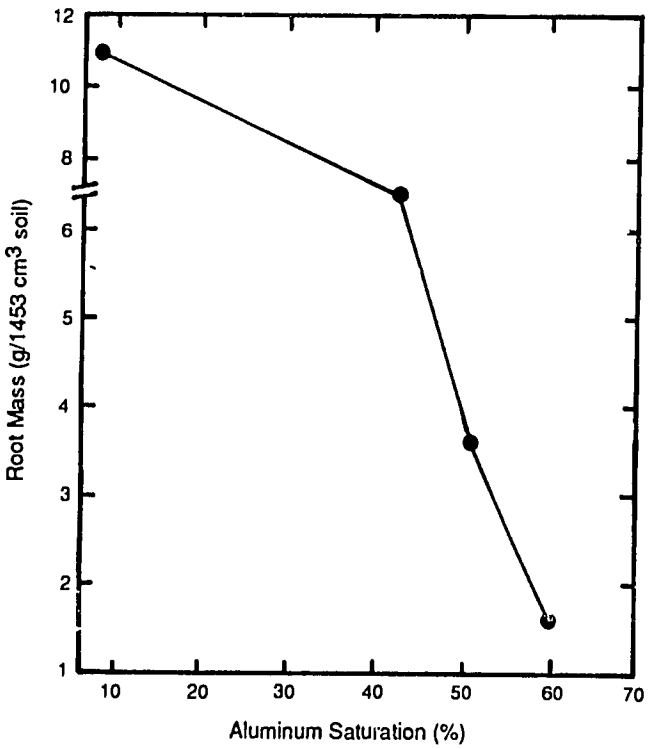
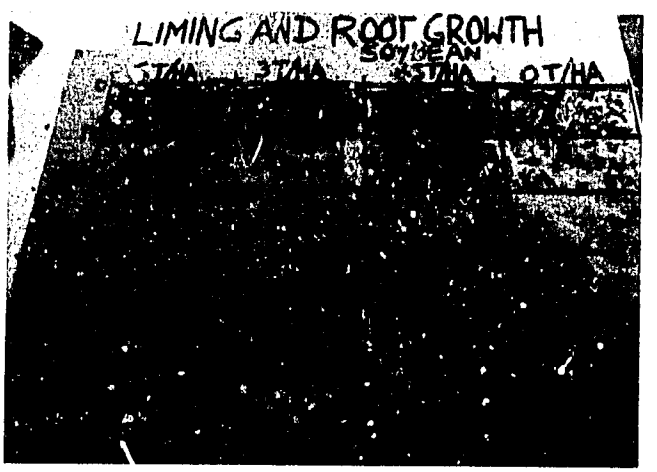


Figure 8. Effect of aluminum saturation on soybean root growth in the top 0 to 12 cm in an Oxisol, Sitiung 1A. Data from Arya et al. (1987).



A comparison of soybean root-growth response to applications of lime in the surface soil. From left, treatments received lime at the rate of 6 t/ha, 3 t/ha, 1.5 t/ha, and 0 t/ha, respectively.

Root Growth, Plant Production, and Water-depletion Patterns

Direct estimates of plant water uptake were not possible in Sitiung, in part because facilities were lacking. Also, spatial variability in the soil and poor control over experimental conditions raised doubts about the success of such efforts. Several indirect observations were made, however, to evaluate the role of root growth and crop production in water use and soil water-depletion patterns.

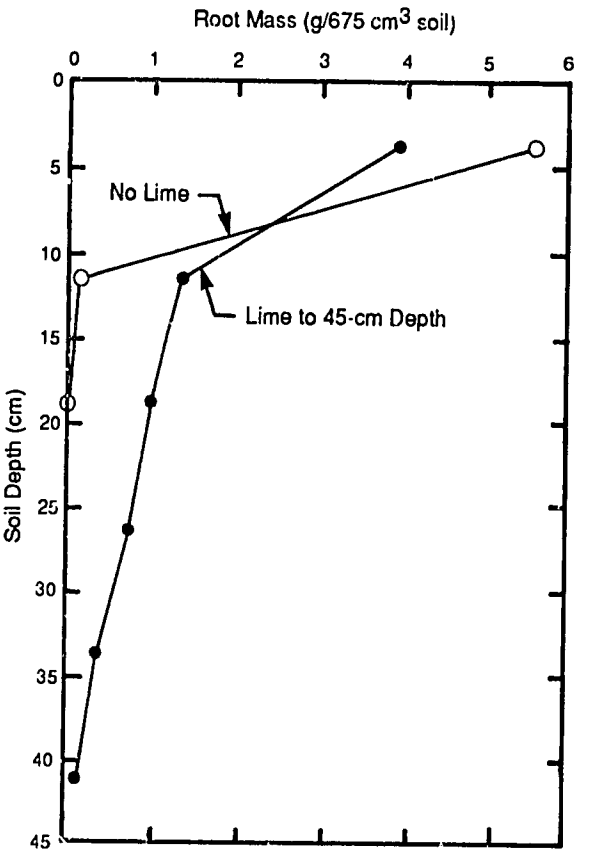


Figure 9. Effect of deep lime placement on corn root growth in an Ultisol. Rusman and Arya (1988).

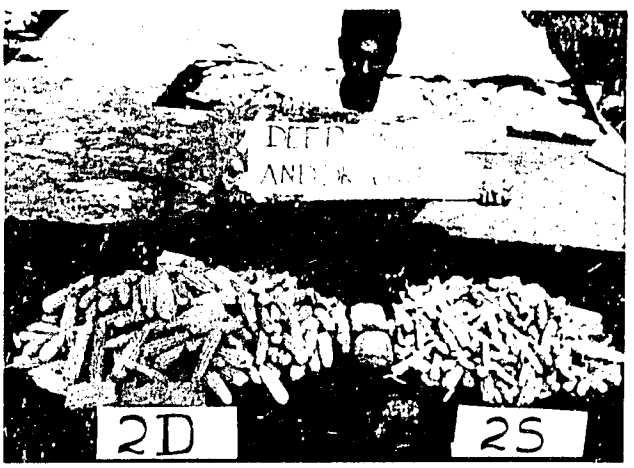
Limitations to Crop Water Use

One of the Soil Management CRSP's field experiments consisted of monitoring soil water pressure and soil water content as a function of depth and time in plots where variable rooting depths were induced by incorporating lime to various depths. Lime neutralizes toxic aluminum. Deep incorporation of lime thus allows aluminum-sensitive plants to increase root growth in the subsoil. It was expected that both the water-depletion and soil water-pressure values would reflect the effects of differences in the crop growth and rooting patterns.

Liming Depth and Soil Water-pressure Patterns

Soil water pressure is often used as an indicator of water-absorbing activity of the roots. The more negative the soil water pressure, the drier the soil. Given the same soil moisture characteristics and rainfall regime, a drier soil indicates a greater water absorption by plants.

Soil water pressures were recorded as a function of depth and time for three depth-of-liming treatments planted to corn. The treatments included: (i) no lime, (ii) lime to 20-cm depth, and (iii) lime to 50-cm depth. Data are reported in Figures 11, 12, and 13. Early-season soil water pressures had low negative values and were very similar for the three treatments. Differences began to appear about 40 to



Note the difference in yield for corn where 2 t/ha of lime was deep-incorporated (2D) as compared with corn where 2 t/ha of lime was incorporated in the surface soil (2S).

Table 15. Root growth and aboveground biomass for food crops and forage plants in acid soils of Sitiung, Indonesia.[§]

	Corn		Soybean		Mungbean		*Desmodium ovalifolium*	Local forages
Depth	0 lime	lime to 50 cm	0 lime	lime to 10 cm	0 lime	lime + GM to 10 cm	0 lime	0 lime
cm	*Fresh root mass (g/liter)*							
0–10	19.03	20.86	1.11	7.52	1.06	4.88	3.22	4.64
10–20	0.93	3.48	0.39	0.20	0.05	0.30	1.15	1.38
20–30	0.09	1.95	0.04	0.07	0.01	0.03	0.43	1.15
30–40	0.00	1.01	0.02	0.02	0.00	0.01	0.28	0.61
40–50		0.30	0.00	0.01		0.00	0.13	0.38
50–60		0.10		0.00			0.11	0.21
60–70		0.00					0.08	0.18
70–80							0.07	0.20
80–90							0.05	0.10
90–100							nd[¶]	0.11
100–110							nd	0.05
110–120							nd	0.03
	kg/ha							
Biomass	4332	13195	779	3052	390	2147	5078	7637

[§] Data from Arya et al. (1988 II).
[¶] Not determined.
GM = green manure.

45 days after planting. Thereafter, soil water pressures became more negative and varied in accordance with the differences in the aboveground vegetative growth and the expected variations in the rooting depth.

For example, at the depth of 22.5 cm (Figure 11), soil water pressures were least negative for the treatment with no lime. They indicated very little root activity. Those for the 20- and 50-cm depth-of-liming treatments showed significantly more negative values, indicating the presence of active roots.

At the 37.5-cm depth (Figure 12), soil water pressures for the no-lime and 20-cm depth-of-liming

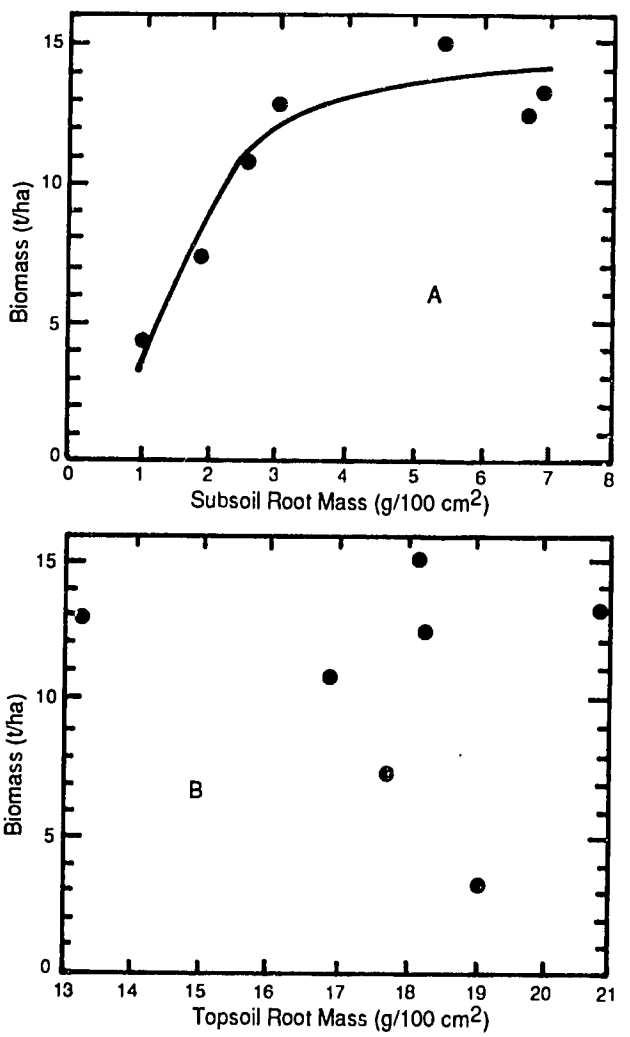


Figure 10. Relationship between corn biomass and root growth: (A) subsoil root mass, (B) topsoil root mass, Gunung Medan. Data from Rusman et al. (1989).

Note the difference in yield for corn where 2 and 4 t/ha of lime were deep-incorporated (2D, 4D) as compared with corn where 2 and 4 t/ha of lime were incorporated in the surface soil (2S, 4S).

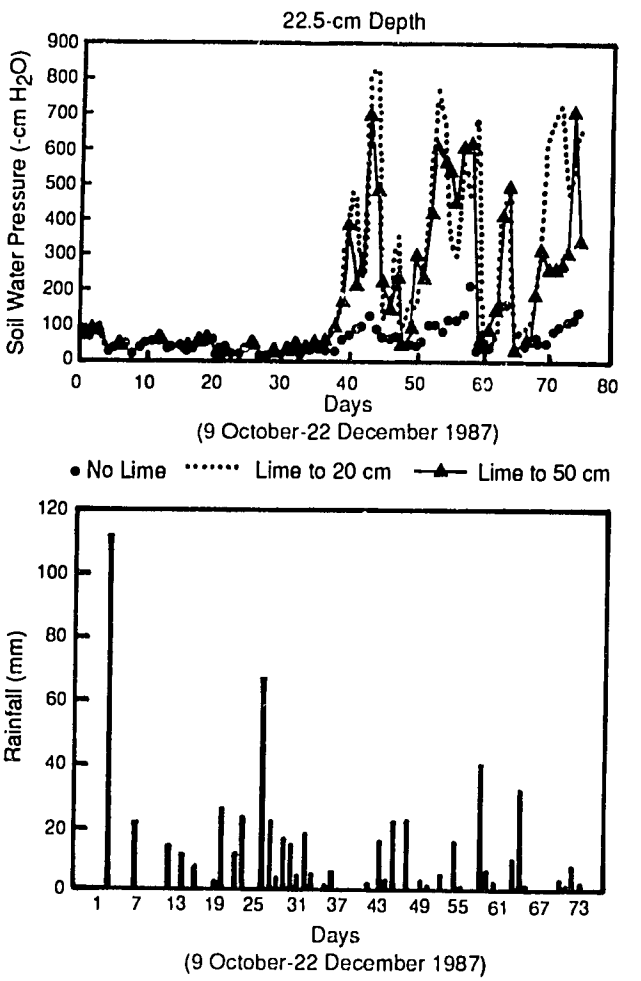


Figure 11. Daily rainfall and soil water pressure at a depth of 22.5 cm for three depth-of-liming treatments (0, 2 t/ha/10 cm to a 20-cm depth, and 2 t/ha/10 cm to a 50-cm depth) planted to corn, Gunung Medan. Data from Rusman (1990).

treatments were similar: both had very low negative values. Pressures at this depth were significantly more negative for the 50-cm depth-of-liming treatment. Data indicate an increase in root activity only where lime was present. Apparently, liming to a 20-cm depth did not affect water absorption at the 37.5-cm depth because movement of lime is extremely slow. The lime neutralized aluminum only where it was applied.

Data for the 52.5-cm depth (Figure 13) show a pattern similar to that for the 37.5-cm depth. They suggest that liming to 50 cm allowed more roots to grow at that depth.

Liming Depth and Crop Use of Soil Water

In addition to soil water pressure, total water contents in the root zone were recorded as a function of depth and time. The three depth-of-liming treatments referred to previously and several other crops planted elsewhere during the succeeding seasons were monitored.

Figure 14 presents total water content in the 0- to 67.5-cm depth for corn in both the unlimed and the 50-cm depth-of-liming treatments referred to earlier. Data show that total water content for the unlimed plot was always higher than for the deep-limed plot. The differences were small during the early part of the growing season, but they became

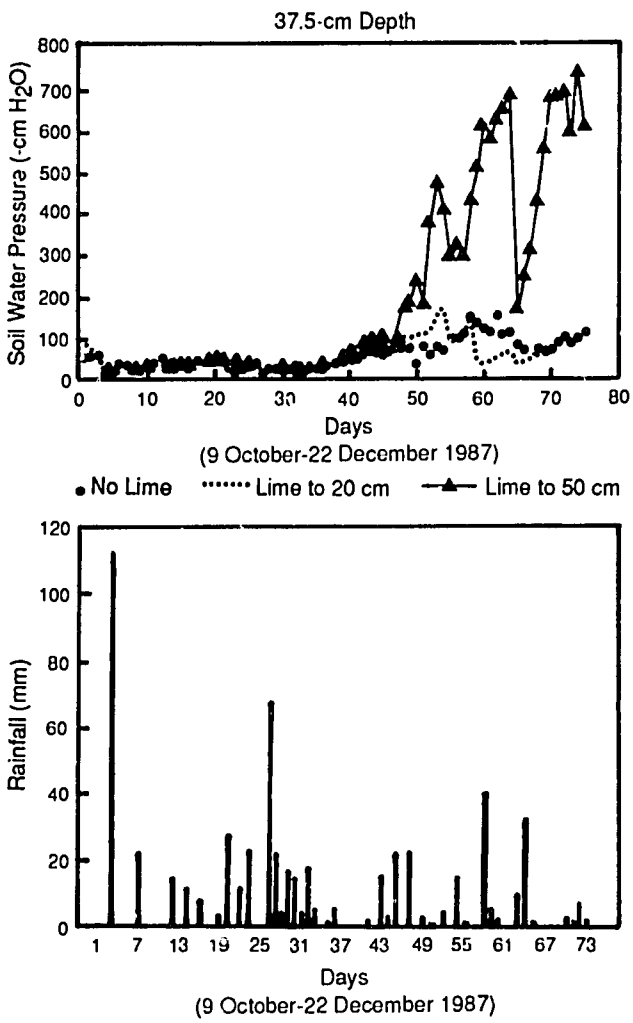


Figure 12. Daily rainfall and soil water pressure at a depth of 37.5 cm for three depth-of-liming treatments (0, 2 t/ha/10 cm to a 20-cm depth, and 2 t/ha/10 cm to a 50-cm depth) planted to corn, Gunung Medan. Data from Rusman (1990).

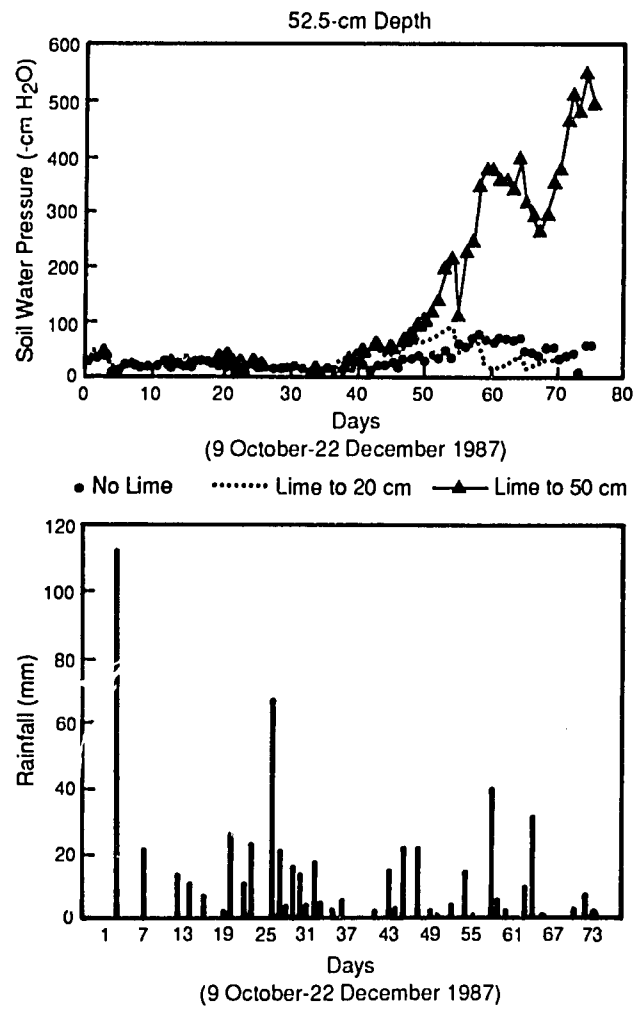


Figure 13. Daily rainfall and soil water pressure at a depth of 52.5 cm for three depth-of-liming treatments (0, 2 t/ha/10 cm to a 20-cm depth, and 2 t/ha/10 cm to a 50-cm depth) planted to corn, Gunung Medan. Data from Rusman (1990).

progressively more pronounced as the season went on and the demand for water increased. Lower water contents in the deep-limed plot indicate an increased water use by the plants. Plants in this treatment had vigorous vegetative growth and an increased water demand. The increase in the rooting depth and density enabled the plants in the deep-limed plot to absorb water efficiently. Plants growing in the unlimed plot had very shallow root systems. They produced low biomass yields and were unable to use the available soil water. As a result, the soil profile was wetter.

A comparison of total water contents for the 20- and 50-cm depth-of-liming treatments is presented in Figure 15. Data show that both treatments had similar water contents through much of the season—except during the later stages of growth, when the 50-cm treatment showed consistently lower water contents for about three weeks. This period coincided with the reproductive stage of growth. Availability of water during this stage can have a marked effect on yield. Production data show that the deeper liming treatment produced 17% more grain and 25% more biomass (Rusman, 1990).

Crop water use for the 20- and 50-cm depth-of-liming treatments was probably similar during the period when the root-zone total water contents for the

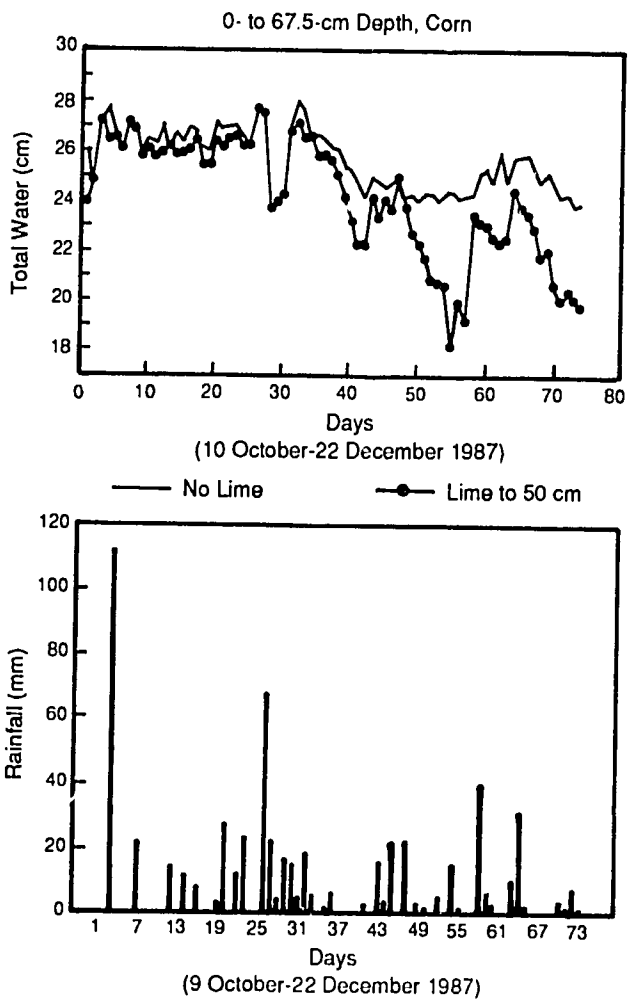


Figure 14. Daily rainfall and total water content in the 0- to 67.5-cm depth for two depth-of-liming treatments (0 and 2 t/ha/10 cm to a 50-cm depth) planted to corn, Gunung Medan. Data from Rusman (1990).

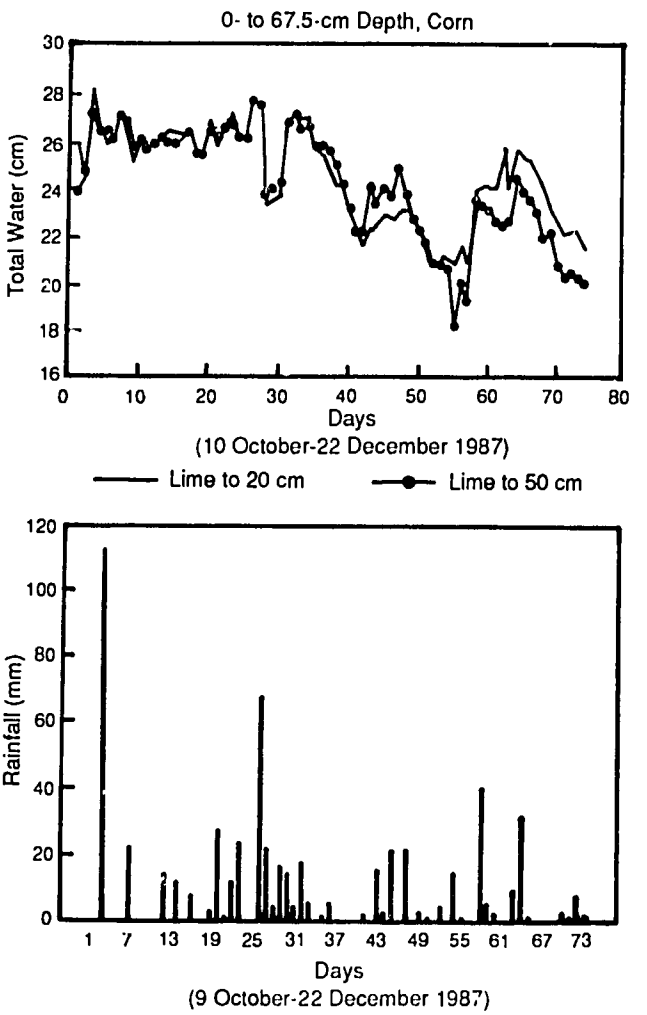


Figure 15. Daily rainfall and total water content in the 0- to 67.5-cm depth-of-liming treatments (2 t/ha/10 cm to a 20-cm depth and 2 t/ha/10 cm to a 50-cm depth) planted to corn, Gunung Medan. Data from Rusman (1990).

two treatments were similar. Soil water-pressure data (Figures 11, 12, and 13), on the other hand, indicate that the 20-cm treatment did not have much influence on water absorption below a depth of 20 to 25 cm. Plants in the 20-cm treatment seem to have met their water requirement, probably by a more thorough absorption of water in that zone. Water absorption for the plants in the 50-cm treatment was more spread out, as illustrated by the distribution of soil water pressures with depth (Figure 16). Data show that soil water pressures in the surface zone were more negative for the 20-cm treatment as compared to those for the 50-cm treatment. Soil water pressures in the deeper layers of the soil profile were more negative for the 50-cm treatment. Thus, the plants in the deeper liming treatment did not have to meet their water requirement (Figure 14) entirely from the surface zone. Evidently, these plants were able to extract water from depths that were inaccessible to plants in the no-lime or the 20-cm depth-of-liming treatments.

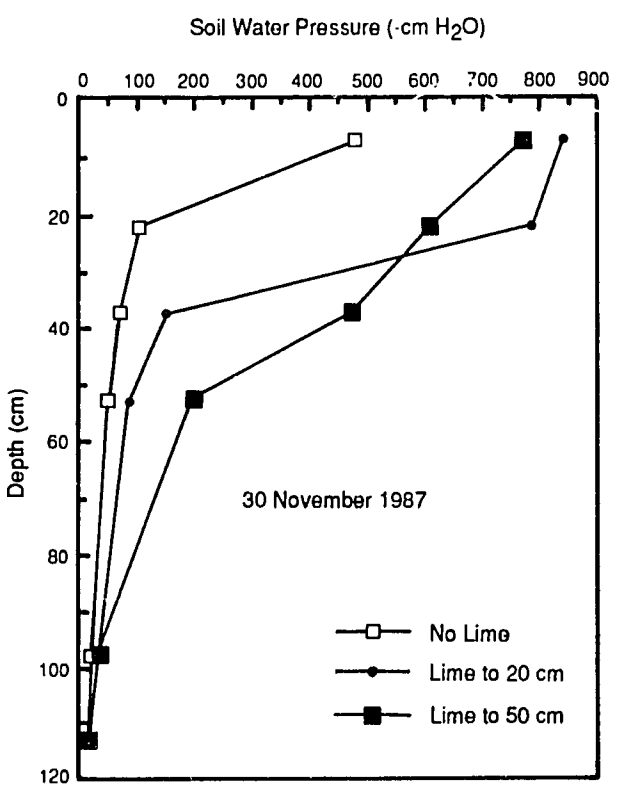


Figure 16. Distribution of soil water pressure with depth for three depth-of-liming treatments (0, 2 t/ha/10 cm to a 20-cm depth, and 2 t/ha/10 cm to a 50-cm depth) planted to corn, Gunung Medan. Data were taken one month prior to harvest by Rusman et al. (1989).

Rooting Depth and the Effect of Drought

The above observations indicate that a deep root system is important for efficient water absorption and sustained plant growth. As we have seen, deeper rooting can be induced by deep incorporation of lime. In one field trial, we applied various amounts of lime such that a given amount was either all applied in the surface or distributed to various depths. Distributing a given amount of lime over a depth reduced the concentration of lime per unit depth. Corn was planted as the test crop. Visual observations indicated that early vegetative growth was more vigorous in the treatments where all of the lime was applied in the surface as compared to treatments where the same amount of lime was

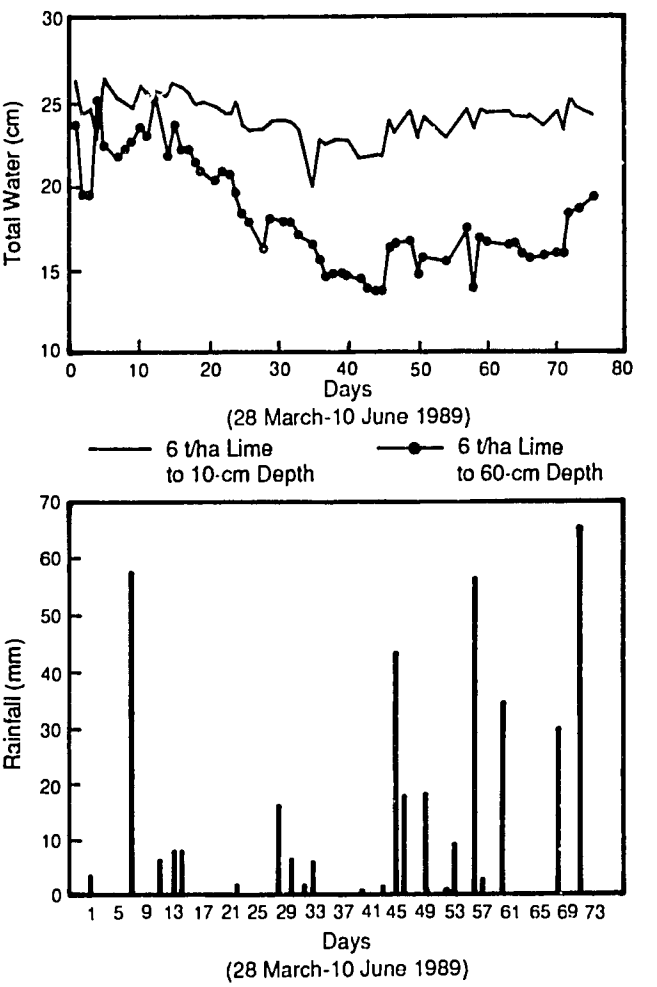


Figure 17. Daily rainfall and total water content in the 7.5- to 67.5-cm depth for liming treatments of 6 t/ha/10 cm to a 10-cm depth and 6 t/ha/10 cm to a 60-cm depth planted to corn, Gunung Medan.

distributed over a depth. However, the deep incorporation of lime produced significantly larger grain yields (Arya et al., 1990). Plants in the treatments where all of the lime was applied in the surface frequently wilted during rainless periods.

Figure 17 presents total water content in the 7.5- to 67.5-cm depth for treatments where (i) 6 t/ha lime was all applied in the surface 10 cm of the soil and (ii) 6 t/ha lime was distributed to a 60-cm depth. Data show that the soil profile was significantly drier where lime was distributed to a 60-cm depth. The difference in the water content for the two treatments was small early in the season when the crop's demand for water was low. However, pronounced differences appeared as the season progressed and the demand for water increased. During a dry spell of about 38 days (broken only by several very light showers), both treatments showed a decrease in the total water content. However, the rate of decrease for the liming to a 60-cm depth was much greater, an indication that plants in this treatment were withdrawing water at a much faster rate than those in the treatment where all of the lime was applied in the surface. Data clearly indicate the relationship between rooting depth and crop water availability.

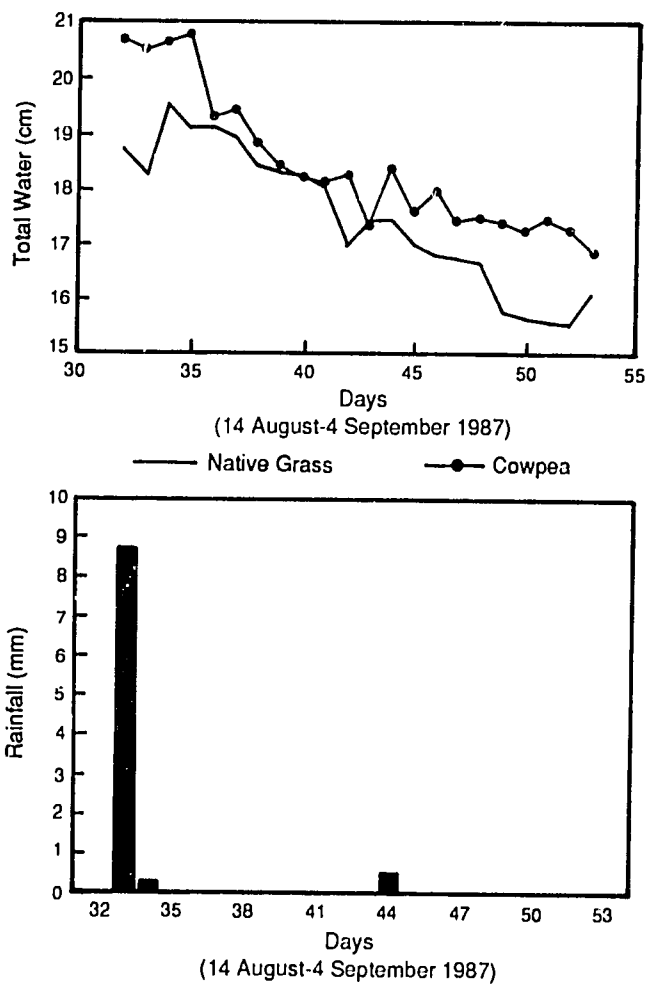
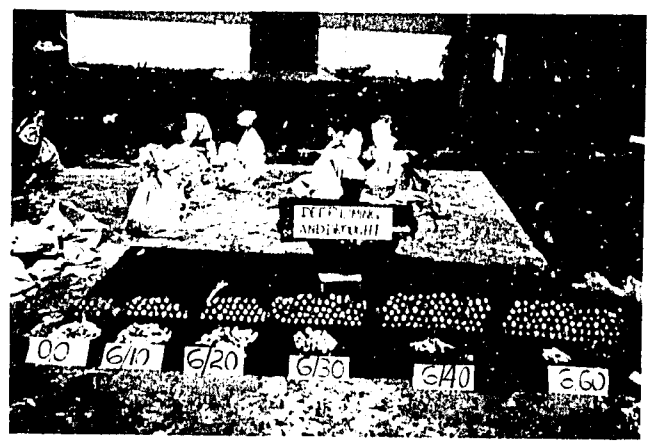


Figure 18. Daily rainfall and total water content in the 7.5- to 67.5-cm depth for cowpea and a native grass (mowed paspalum), Gunung Medan.

Local Forages vs. Food Crops

Local plant species are naturally adapted to the acid soil conditions. Their deep root systems enable them to withdraw water from soil depths normally inaccessible to shallow-rooted food plants; consequently, they are less likely to exhibit symptoms of water stress. Figure 18 shows total water content in the 7.5- to 67.5-cm depth for a native grass (a mowed paspalum) and cowpea. Observations were made during a rainless period of 21 days. Data show that the soil profile under the native grass always had a lower water content than the soil profile under the cowpea. Both showed a decrease in water content with time. The rate of decrease, however, was faster under the native grass. These differences could also relate to differences in aboveground biomass. In cowpea, which seemed to have a larger biomass, wilting was quite evident, whereas the native grass remained turgid.



Note the difference in yield for corn that received (from left) no lime and lime at 6 t/ha to 10-, 20-, 30-, 40-, and 60-cm depths.

Note the difference in aboveground biomass for corn where 4 t/ha of lime was deep-incorporated (4D) as compared with corn where 4 t/ha of lime was incorporated in the surface soil (4S).

Field Water Balance

Where does all the rainfall go? How much water is used in evapotranspiration? What amounts are lost through runoff and deep drainage? These questions must be answered before we can design strategies to cope with the water problems in Sitiung's Ultisols and Oxisols.

The most common approach to determining how a given water supply is disposed of is to conduct water-balance measurements over long periods. The water balance for a given depth of soil can be calculated from

$$S_{(t2)} = S_{(t1)} + R_{(t1-t2)} - Ro_{(t1-t2)} - ET_{(t1-t2)} - D_{(t1-t2)}$$

where $S_{(t2)}$ is the water storage in a given soil depth at a future time t2, $S_{(t1)}$ is the water storage for the same soil depth at an earlier time t1, $R_{(t1-t2)}$ is the total rainfall between times t1 and t2, $Ro_{(t1-t2)}$ is the total surface runoff between times t1 and t2, $ET_{(t1-t2)}$ is the total evapotranspiration between times t1 and t2, and $D_{(t1-t2)}$ is the total deep drainage between times t1 and t2.

Unfortunately, estimates of water balance for Sitiung and most areas in Indonesia are unavailable. A simple balancing of rainfall and potential evapotranspiration has been attempted (e.g., Team IUTP, 1977), but such balancing provides no information on the magnitude of the actual evapotranspiration, runoff, or drainage. It tells only the balance between total rainfall and the atmospheric demand.

Despite incomplete information, it should be possible to obtain an approximate partitioning of the rainfall into the various components of the water balance. First, we will attempt to compute a very general annual water balance for the Sitiung region. Then, a few specific cases of seasonal water balance will be presented with the help of field data collected by the Soil Management CRSP Project.

Annual Water Balance for Sitiung

A very general (and somewhat crude) estimate of the water balance for Sitiung can be made if the following conditions are applicable on an annual basis.

$S_{(t2)}-S_{(t1)}$	= 0 on an annual basis.
$R_{(t1-t2)}$	= 3000 mm (Table 1).
$Ro_{(t1-t2)}$	= 15% of rainfall (Table 10).
$ET_{(t1-t2)}$	= 80% of potential evapotranspiration (PET).
PET	= Pan evaporation = 3.73 mm/day (Table 1).

With these assumptions, the annual loss of water through evapotranspiration is 1361 mm. The remaining amount of rainfall is disposed of through runoff and deep drainage. If runoff does not exceed 15% of the rainfall, deep drainage would account for 1189 mm, or 40% of the rainfall—a large amount for internal drainage through the soil profile. However, internal drainage is much safer than runoff in disposing of excess rainfall. An increase in the surface runoff would increase erosion and other forces destructive to the land surface. Internal drainage of this magnitude, however, also has a negative effect: it leaches nutrients from the soil. Leaching of nutrient bases contributes to infertility and acidity.

Seasonal Water Balance

The Soil Management CRSP Project in Sitiung has carried out daily measurements of soil water storage for several crop seasons. Data were collected to characterize the field moisture regime and to evaluate the effects of soil management practices on crop water availability. These data along with daily rainfall data were used to compute seasonal water balances for several crops. Computations were

carried out using daily time intervals. Rainfall was measured daily. Changes in the soil water storage were obtained from the measured daily values. Runoff and internal drainage were estimated using an empirical procedure developed for the Sitiung soil and rainfall conditions. These values were substituted in the water-balance equation to obtain ET estimates. Daily measurements of pan evaporation provided an estimate of PET for the weather conditions in Sitiung.

Daily ET values were noisy because of variations in the measured values of soil water storage. However, when summed over the season, the resulting ET values appeared quite realistic in relation to the evaporative conditions in Sitiung.

Estimation of Drainage and Runoff

Procedure of Black et al. 1969

Estimates of internal drainage were attempted using a procedure outlined by Black et al. (1969). This procedure has been modified by Ritchie (1981) to determine drainage and upper drained limits for soils. The procedure relates downward drainage at a given depth to the total water stored in the soil profile above that depth. Data were obtained from Bujang Rusman's research plot, where drainage and soil water storage were measured as a function of depth and time after the plot had been thoroughly saturated and allowed to drain while being covered on the surface to prevent evaporation. An example of the relationship between drainage at the 67.5-cm depth and the stored water in the 0- to 67.5-cm depth is shown in Figure 19. Data show that downward drainage virtually stopped when the stored water was 32 cm—the value of field capacity for the 0- to 67.5-cm depth in this soil. Values for field-measured soil water storage, on the other hand, never exceeded 28 to 29 cm. The procedure, therefore, indicated zero drainage even after the heaviest of the rainfall events.

This finding is highly implausible. As discussed (in the section on the field water regime), wetness and drainage patterns obtained in a plot saturated by excessive water application and drained in absence of evapotranspiration will probably not apply to normal field conditions. Based on water-flow rates (Tables 9, 10, 12; Figure 4), one would suspect that a fair amount of water is probably disposed of during and soon after the rainfall. Thus, one would probably not detect the maximum wetness of the soil if the measurements are made 15 to 20 hours after the rainfall. An assumption inherent in the approach of Black et al. and Ritchie is that all of the drainage water is detectable as the matrix water. This assumption may be true for small amounts of rain that do not result in rapid downward flow. But when rainfall results in rapid downward flow, not all of the rain may be detectable as part of the soil water. Black et al. (1970) have discussed the problem of rapid drainage and recognize the need for a more frequent measurement of soil water during the period when rapid drainage is expected. Even then, it would seem that rainwater that passes through the soil profile without altering the wetness would not be detectable as part of the soil water.

An Alternative Procedure

We reasoned that a balancing of the water-supply and retention-capacity factors should provide an estimate of the combined drainage and runoff. The supply factor is actually a sum of the existing water storage and the rainfall; the retention-capacity factor is the maximum observable field water storage during the time when plant influence on water depletion is minimal. A balance of these factors can be expressed as

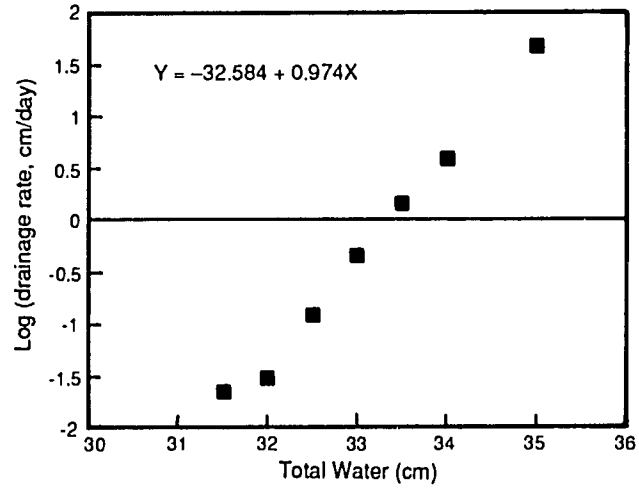


Figure 19. Relationship between the rate of drainage at the 67.5-cm depth and total water content in the 0- to 67.5-cm soil profile, Gunung Medan. Data from Rusman (1990).

$$D = (R - Ro) + Sc - Sm$$
$$\text{or } (D + Ro) = R + Sc - Sm; \quad \text{for } (R + Sc) > Sm$$

where D is the drainage, R is the rainfall, Ro is the runoff, Sc is the water storage immediately before the rainfall event, and Sm is the maximum observed field water storage. This relationship is valid only for positive values of (D + Ro). Negative values of (D + Ro) are set equal to zero.

For Soil Management CRSP field plots in Sitiung, R and Sc were measured daily. Sm was estimated from measured field water storage 24 to 36 hours after a heavy rainfall during the early stages of plant growth. Accurate and site-specific estimates of runoff were unavailable. Estimates for bare plots at a slope of 10 to 13% in Sitiung IV (Table 10) suggest that runoff would not exceed 15% of the rainfall on an annual basis. Soil Management CRSP field plots were not bare, and they were situated on slopes not exceeding 5%. Runoff was generally not observed. It probably occurred only during the heaviest rainfall events—if it occurred at all. Therefore we have considered runoff as equal to zero Where accurate estimates of runoff are available, they can be applied to improve the estimates for drainage.

Examples of drainage values calculated by the procedure of Black et al. (1969) and the alternative procedure proposed above are presented in Table 16.

Table 16. A comparison of drainage calculated by the procedure of Black et al. (1969) and the alternative procedure proposed in this report.[§]

		Drainage at 67.5-cm depth		
Day	Rainfall	Current total water	Black et al.	Alternative procedure
	cm			
1	0.00	23.96	0.00	0.00
2	11.23	24.86	0.00	9.09
3	0.00	27.68	0.00	0.68
4	0.00	26.83	0.00	0.00
5	0.00	26.88	0.00	0.00
6	2.24	26.40	0.00	1.64
7	0.00	27.58	0.00	0.58
8	0.00	27.27	0.00	0.27
9	0.00	26.05	0.00	0.00
10	0.00	26.37	0.00	0.00
11	1.42	25.97	0.00	0.39
12	0.00	26.23	0.00	0.00
Total	14.89	—	0.00	12.65

[§] Soil profile depth: 67.5 cm; Maximum observed field water storage (Sm): 27.0 cm.

Water Balance

Water balance data for corn, soybean, and a native grass are presented in Table 17. Results show that components of the water balance varied with the vegetation type, the amount of biomass, and the amount of rainfall. Corn and soybean were planted in plots which had been limed to varying depths to induce varying depths of rooting. These liming treatments resulted in varying levels of growth. Corn planted in the unlimed plot had low biomass yield. All of the corn plots were kept free of weeds because of plans to measure root growth. Soybean was weeded only once, during the early stages of growth. Thereafter, weeds grew freely and filled whatever space was available. Weed growth was most vigorous in the unlimed soybean plot, which produced very little soybean biomass. Deep-limed soybean plots had little weed growth because of the soybean's vigor. The native grass was a mowed paspalum. It did not receive any lime or fertilizer.

Soil water storage shows a net gain in some cases and a net loss in others. With the exception of the unlimed corn plot, the net loss appears to be associated with the higher values of evapotranspiration. The soil profile shows a net gain in storage where evapotranspiration values were lower.

Evapotranspiration and deep drainage appear to be the major components of the water balance in the Sitiung region. Total water available for evapotranspiration and deep drainage is the sum of the rainfall and the net change in the storage. The sums of the evapotranspiration and drainage are less than the rainfall where the change in the soil water storage is positive. They are more than the rainfall where the change in the soil water storage is negative. Data show that for the short-growing native grass with full cover, evapotranspiration and drainage components were 62 and 27% of the rainfall, respectively. The remainder (11%) was accounted for by the increase in the soil water storage. In the case of corn, the change in the soil water storage was negative. This means that evapotranspiration and

drainage used more water than was available from the rainfall. After adjusting for the change in the soil water storage, we see that evapotranspiration in the unlimed corn plot, where plant growth was very poor, accounted for only 14% of the rainfall. Drainage in this case accounted for 86% of the rainfall. For the deep-limed corn, evapotranspiration and drainage were 46 to 49% and 51 to 54% of the rainfall, respectively.

Unlimed soybean plots differed sharply from the unlimed corn plots. Weeds seem to have been the active user of water in the unlimed soybean plot, where evapotranspiration and drainage accounted for 72 and 28% of the rainfall, respectively. Evapotranspiration and drainage in the deep-limed soybean plots accounted for 60 and 37% of the rainfall, respectively. The remaining rainfall was accounted for by the increase in the soil water storage.

If we take an average of all the observations, we find that evapotranspiration and drainage account for 52 and 46% of the rainfall, respectively. Only 2% of the rainfall is actually accounted for by the changes in the soil water storage.

Evapotranspiration values for the weed-covered soybean plot indicate that locally adapted species are efficient in using water under acid soil conditions. Food crops, too, do not have a problem in extracting water, provided that their root zones are increased by deep liming. Water availability is restricted, however, for acid-sensitive plants with a shallow root system—a category that includes most food crops.

The magnitudes of the evapotranspiration values appear to be quite reasonable. Taking pan evaporation as a measure of the potential evapotranspiration, we see that native grasses and short crops such as soybean evapotranspire at the rate of 80 to 90% of the potential evapotranspiration rate. These ratios of crop evapotranspiration to pan evaporation are consistent with the ratios published in the literature. For tall-growing corn and highly efficient weeds, slightly higher evapotranspiration than pan evaporation is not surprising. Chang (1968) quotes several examples of data showing crop potential evapotranspiration 5 to 24% higher than pan evaporation. He attributes these higher values to the increased canopy roughness usually associated with tall crops.

Table 17. Water balance for corn, soybean, and a native grass in Sitlung.[§]

Dates, crop, & treatment	Observation period	Rainfall (R)	S2–S1[¶]	Drainage (D)	ET[‖]	PE[¶¶]	Ratios[#] D/R	ET/PE	ET/R
	days	*cm*	*cm*	*cm*	*cm*	*cm*			
1987: 8/14–10/26									
Mowed grass—no lime	74	37.34	+4.19	10.03	23.11	26.24	0.269	0.881	0.619
1988: 10/10–12/22									
Corn—no lime	74	58.85	–2.44	52.70	8.59	26.97	0.860	0.319	0.140
Corn—lime to 20 cm	74	58.85	–5.45	34.92	29.39	26.97	0.543	1.090	0.457
Corn—lime to 50 cm	74	58.85	–4.70	32.19	31.36	26.97	0.507	1.163	0.493
1989: 3/28–6/8									
Soybean + weeds—no lime	73	39.80	–3.09	11.99	30.90	30.04	0.280	1.029	0.720
Soybean—lime to 20 cm	73	39.80	+1.69	14.62	23.49	30.04	0.367	0.782	0.590
Soybean—lime to 50 cm	73	39.80	+0.95	14.51	24.34	30.04	0.365	0.810	0.612

[§] Soil profile depth is 67.5 cm for corn and soybean and 112.5 cm for native grass.
[¶] Net change in soil water storage.
[‖] Evapotranspiration.
[¶¶] Pan evaporation.
[#] Ratios D/R and ET/R have been adjusted for the change in the soil water storage (S2 – S1).

Implications of Rapid Drainage for Soil Fertility and the Environment

The rapid water intake and downward flow through the soil profile in Sitiung Ultisols and Oxisols allow them to accommodate the region's large and intense storms. The soils' pore structure facilitates rapid infiltration and percolation. Water balance data in Table 17 show that, on average, 46% of the nearly 3000 mm of annual rainfall is disposed of via internal drainage. Depending upon the amount of rainfall and antecedent field water status, some rainfall events can result in much larger amounts of drainage.

Rapid drainage of large amounts of water has important implications for nutrient retention and transport. Given that the soils' ability to retain nutrients is low (Table 13), one would expect substantial downward movement of more mobile nutrients such as nitrogen and potassium. Others, such as added calcium (from lime) and phosphorus, are not likely to be affected because of their reaction with the surface soil and relatively low mobility. Data on the distribution and relative amounts of macro- and micropores (Table 11), hydraulic conductivity (Table 12 and Figure 5), and field water regime (Figures 6 and 7) suggest that water interacts with the surface soil and then moves downward primarily through macropores. The downward-moving, nutrient-carrying water most likely does not adequately mix with or displace the subsoil water. This result is expected because the subsoil remains quite wet through most of the year, especially on lands devoted to food cropping. There are three reasons for this high subsoil moisture: first, the subsoil clay contents are generally high; second, the overall evaporative demand is low; and third, the aluminum-sensitive shallow-rooted crops are unable to extract water from the subsoil.

Given the high probability of inadequate exchange between the drainage water and the resident subsoil water, one would expect that downward-moving nutrients would probably not accumulate in the subsoil. Thus one might also expect the following:

- Difficulty in building and maintaining soil fertility.
- Low fertilizer-use efficiency for some nutrients.
- Probable release of fertilizer nutrients and readily soluble crop-protection chemicals into the groundwater. A humid tropical environment, the Sitiung area exhibits a high incidence of pests and diseases. As a result, the use of crop-protection chemicals is increasing. Although there are no data on the fate of these chemicals, rainfall levels and soil water-flow characteristics suggest that much of the washed-down chemicals probably end up in the groundwater.

Water moving through macropores may not necessarily transport significant amounts of solutes over short periods, however. In a field trial, potassium fertilizer (KCl) was mixed in the surface 2 cm of an unamended, bare Ultisol at the rate of 80 kg K/ha. Although a total of 43 cm of rain fell during the two-week period after fertilizer application, all of the applied fertilizer was recovered from the surface 40 cm. Even after another 34 cm of rainfall (cumulative 77 cm) during the next month, only 13% of the applied K was unaccounted for in the surface 40 cm. After another three months and 86 cm of rainfall (cumulative 163 cm), 44% of the applied K was not recovered in the surface 40 cm. So although the applied K may eventually be lost to leaching, significant losses due to frequent and intense rainfall may not be a common occurrence. The applied K that was not recovered in the surface 40 cm was presumably leached below the 80-cm sampling

depth as there was no indication of any subsoil accumulation.

Accumulation of K was monitored in a field trial in which three rates of K were applied over six cropping seasons: 70 and 250 kg/ha K applied as a one-time application at the start of the cropping cycle and 600 kg/ha K in five doses of 120 kg each applied at the start of each crop, except one. Distributions of soil K with depth at the end of the sixth crop are presented in Figure 20. Data show that one-time applications of 70 and 250 kg/ha K did not result in an increase in the soil K over what was initially present. The 600 kg rate increased soil K, but only in the top 30 cm. An estimate of K removed by the crop plants is not yet available, and thus it is not yet possible to estimate the loss of applied K. Based on the data presented in the previous paragraph, downward movement of K should be expected. However, data presented in Figure 20 show no change in the K levels below a depth of 30 cm. Thus, the K that moved downward probably did not accumulate in the subsoil.

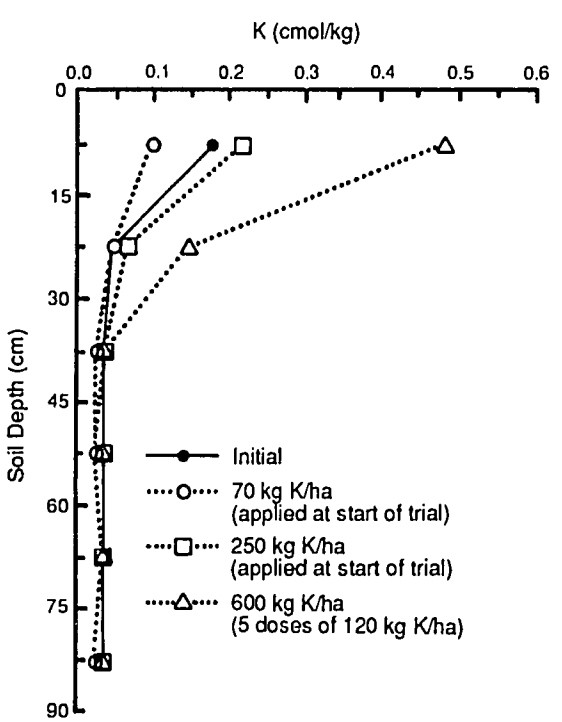


Figure 20. Soil distribution of extractable K in an Ultisol after six cropping seasons at three K rates, Sitiung IA'. Unpublished data from Dierolf, Soil Management CRSP Project.

Data presented in Figure 20 indicate the difficulty in improving and maintaining K levels in Sitiung Ultisols and Oxisols. Similar difficulties may exist for other nutrients. A stable medium for plant growth must have a large sustained capacity to retain and supply water and nutrients. Moreover, plants should be able to explore a large volume of the medium. This kind of medium can be produced if acid soils in Sitiung and similar soils elsewhere are ameliorated to subsoil depths.

Analyses presented in this report show that although Sitiung soils have a large capacity to hold water, acid-sensitive plants are able to extract water only from shallow depths that have been amended to reduce aluminum toxicity. In addition, a larger volume of the soil cannot be made fertile because structural conditions in the subsoil micropores are not conducive to permeation and accumulation of nutrients. We have seen that more than 90% of the pore volume in the subsoil consists of micropores (Table 11). Water movement in these pores is extremely slow (Figures 5, 6, and 7). One would think that if nutrients could get into these pores, they might stay there and be available for absorption by a growing root. The difficulty is that nutrients are unlikely to get into these pores in significant amounts by moving through the soil matrix. The absence of base cations results in an increase in the aluminum saturation, which inhibits penetration of food crop roots into the subsoil. Thus, a preponderance of infertile, acid subsoils should be expected, despite the incorporation of fertilizers and amendments into the surface soil. To incorporate nutrients and other amendments deep into the subsoil by physical means is not feasible, especially for resource-poor farmers.

On the other hand, there are indications that fertility of both the top- and the subsoil is reasonably good at the time of land clearing. It declines as the land is brought under cultivation with food crops (e.g., Driessen et al., 1976). Table 18 presents an example of the decline in soil fertility with cultivation, especially levels of organic carbon, nitrogen, and potassium. Use of triple superphosphate and lime helped maintain the available phosphorus and calcium levels in the topsoil. Topsoil volume, however, is probably too small to sustain plant growth. Except for available phosphorus, fertility in the subsoil generally deteriorated with time. Data show a progressive

increase in aluminum saturation, worsening the restrictive effects of aluminum toxicity on root growth.

Nothing appears to explain how natural vegetation improves and maintains subsoil fertility. Nutrients available in the surface probably move to the subsoil regions via root systems of species that are well-adapted to the local soil conditions. This advantage is lost when natural vegetation is removed and the land is planted to aluminum-sensitive, shallow-rooted vegetation.

Thus, including naturally adapted, deep-rooted vegetation in the cropping system may improve subsoil fertility. Deep-rooted vegetation would transport nutrients to the more protective microporous regions they cannot reach by moving through the soil matrix. Natural vegetation can be adapted in the food cropping system by rotation, mixed cropping, or intercropping. The subsoil can be improved if the natural vegetation is fertilized to increase the amount of nutrients available for downward transport. The proper choice of base cations may eventually reduce acidity and aluminum toxicity in the subsoil. The natural vegetation must be acid-tolerant and naturally deep-rooted, however. Local forage legumes and grasses have these characteristics (Tables 14 and 15). They grow well and produce substantial biomass year round (Arya et al., 1990).

Table 18. The effect of land clearing and cultivation on fertility in an Ultisol/ Oxisol in Sitiung.

Characteristics	Rubber, forest, or other natural vegetation (a)	Cultivation	
		4 years (b)	12 years[1] (c)
	Topsoil (variable depth, 0–5 cm to 0–23 cm)		
Organic C (%)	6.84	2.40	1.79
Total N (%)	0.39	0.16	0.12
Avail P (Bray II) (ppm)	8.82	10.45	9.50
Exch. Ca (me/100 g)	2.00	0.97	2.83
Exch. Mg (me/100 g)	0.24	0.24	0.33
Exch. K (me/100 g)	0.22	0.19	0.10
Exch. Na (me/100 g)	0.08	0.05	0.01
Exch. Al (me/100 g)	1.78	2.45	2.67
pH (H_2O)	5.26	4.58	4.90
ECEC (me/100 g)	4.32	3.90	5.94
Al sat (%)	41.20	62.80	44.90
	Subsoil (variable depth, 5–20 cm to 5–50 cm)		
Organic C (%)	3.09	1.11	0.74
Total N (%)	0.24	0.08	0.07
Avail P (Bray II) (ppm)	5.39	5.00	8.80
Exch. Ca (me/100 g)	1.46	0.53	0.77
Exch. Mg (me/100 g)	0.29	0.12	0.19
Exch. K (me/100 g)	0.25	0.22	0.06
Exch. Na (me/100 g)	0.09	0.04	0.01
Exch. Al (me/100 g)	1.78	2.23	3.97
pH (H_2O)	5.33	4.74	5.20
ECEC (me/100 g)	3.87	3.14	5.00
Al sat (%)	46.00	71.00	79.40

(a) Balittan/Sitiung—data from Fakultas Pertanian, Universitas Andalas (1982); (b) Balittan/Sitiung—average of unpublished data from Iswandi H. Basri and of data from Arief and Zubaidah (1989); (c) Nearby farmer's field/Sitiung—unpublished data from Iswandi H. Basri, Sukarami Research Institute for Food Crops.

[1] Initial liming and regular use of triple superphosphate.

Conclusions and Implications for Research

Conclusions

- Ultisols and Oxisols retain and transmit large amounts of water. They remain quite wet below a depth of about 30 cm.
- Soil structure plays a major role in determining the hydrologic and chemical environment in these soils.
- Root systems of the aluminum-sensitive food plants remain confined to the surface soil. Thus, they are unable to use the large reservoir of available subsoil water.
- Deep-rooted plant species use soil water efficiently.
- Soil management practices that improve crop rooting depth alleviate the effects of water stress.

Implications for Research

Amelioration of the subsoil is necessary to create a soil medium of sufficient capacity to retain and supply water and nutrients for sustained plant growth. Such a medium already exists for plant species able to root deeply and explore a large volume of the soil. Management strategies are needed for those species unable to grow roots in the aluminum-toxic subsoil.

The following ideas are suggested for research and evaluation:

- Soil Management CRSP research has shown substantial improvement in the subsoil environment by deep incorporation of lime. A depth of 25 to 30 cm appears to be quite adequate. A technology for deep incorporation of lime and fertilizers is needed.
- Surface-applied lime moves downward very slowly. Methods to leach lime into the subsoil may be more cost-effective than deep incorporation.
- Breeding and selecting crop cultivars for their ability to root deeply in the aluminum-toxic subsoil should receive emphasis.
- Nutrients lost from the surface soil probably do not accumulate in the subsoil. Thus, applying fertilizers to the surface soil may be an ineffective enrichment strategy. Naturally adapted plant species that root deeply may transport nutrients into the more protective regions in the subsoil. Their role in fertility management needs to be evaluated and the mechanisms involved need to be clarified.
- How fertilizer is applied may be significant. Surface-applied fertilizers are vulnerable to leaching. Nutrients may be better protected if they are mixed in the soil or deep-incorporated. Dry-season application may be more conservation-effective than wet-season application. Slow-release fertilizers may also be beneficial.
- Soil fertility problems could be more clearly articulated if researchers had quantitative information on the movement and fate of applied nutrients. To get that information, we need to set new research directions. Such research would also better assess the risk of groundwater contamination from agricultural chemicals.

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