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SIGNIFICANCE OF MACROPOROSITY AND HYDROLOGY FOR SOIL MANAGEMENT AND SUSTAINABILITY OF AGRICULTURAL PRODUCTION IN A HUMID-TROPICAL ENVIRONMENT

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Abstract

This paper analyzes soil-related agronomic constraints in the Sitiung region of Indonesia that are directly related to low nutrient-holding capacity, macroporosity, and rainfall regime. This region receives 2500 to 3000 mm of rainfall per year, but nearly 50% of the rainfall is disposed of rapidly via internal drainage. Although rapid internal drainage reduces the risks of erosion, it leads to infertility, acidity, and Al toxicity. The physical structure of the soils is characterized by stable aggregates, with numerous macropores in the surface and a predominantly microporous subsoil matrix interspersed with a few larger macropores. Macropores account for about 29% of porosity in the surface and between 3 and 6% in the subsoil. The saturated hydraulic conductivity of the matrix containing macropores averages about 300 to 400 cm/day, whereas that of the microporous matrix is generally <1 cm/day. The structure facilitates rapid infiltration and leaching of rainfall. However, little opportunity exists for nutrients moving downward with drainage water to accumulate in the subsoil. The main reason for this seems to be the low hydraulic conductivity and the preponderance of excessive wetness in the subsoil. Drying seems to be essential for movement of nutrients into the subsoil matrix. However, most of the agronomic crops are sensitive to Al toxicity and fail to grow roots deeper than 10 to 15 cm. Thus, they suffer from water stress, despite heavy and frequent rainfall, and fail to cause drying of the subsoil. Problems of acidity, Al toxicity, and infertility worsen progressively where agricultural production consists mainly of Al-sensitive crops. Although liming with calcium carbonate improves the soil chemical environment, downward movement of lime is very slow. Deep liming is effective in improving rooting depth, crop water availability, and drying of the subsoil, but the technology is cost- and labor-intensive. Native vegetation, on the other hand, is able to grow roots to considerable depths and causes significant drying of the subsoil, even without soil amendments. Thus, production systems in which locally adapted vegetation of economic value is the main focus seem to be more sustainable and conducive to improving soil conditions.

Humid tropical soils are generally highly weathered (e.g., Uehara and Gillman 1981). They are characterized by low-activity clays and large, water-stable aggregates. The resulting pores are relatively large and conduct water rapidly (e.g., Anderson and Bouma 1977; Arya et al. 1998). Because of the high intensity of weathering, high rainfall, and leaching, humid tropical soils are generally less fertile and exhibit varying degrees of subsoil toxicities, usually low pH and high levels of exchangeable Al, Fe, and Mn (e.g., Subagjo 1988). Macropore flow allows drainage water to move downward without significantly mixing with or displacing the resident subsoil water (e.g., Beven and Germann 1982), thus presenting little opportunity for nutrients to accumulate in the subsoil. The process leads to rapid loss of applied nutrients and the persistence of an unfavorable chemical environment in the subsoil (e.g., Dierolf et al. 1997). Because of the low hydraulic conductivity of micropores, nutrient cations contained in the microporous subsoil matrix may be better protected from leaching. Replenishing nutrients in micropores, however, is more difficult. Depending on the dryness of the microporous matrix, solutes may move from saturated macropores into unsaturated micropores, but saturated micropores are likely to be bypassed (e.g., Youngs and Leeds-Harrison 1990). Therefore, although occasional or intermittent drying of the subsoil seems to be desirable, plant species sensitive to soil toxicities fail to grow roots in the subsoil, and, thus, they fail to effect significant drying (e.g., Arya et al. 1992). Only vegetation that is adapted to soil and climatic conditions can grow deeper roots, cause drying of the subsoil, and possibly facilitate nutrient recycling.

Thus, improving and maintaining productivity of humid tropical soils is challenging, especially when agricultural systems are based on crops that are sensitive to the chemical environment of the soil (e.g., Sanchez 1982). In many humid tropical areas, however, population pressure has caused large areas of fragile lands to be brought into crop production. Research reported in this paper was undertaken to explore possible interrelationships between soil structure, water flow rates, field water regime, soil chemical environment, root growth, and crop water availability problems in Ultisols and Oxisols of Sitiung, Indonesia. Sitiung is one of several transmigrant sites established by the Government of Indonesia during the 1970s for relocating and settling farm families from the heavily populated island of Java. In the early 1980s, the Soil Management Collaborative Research Support Project (SM-CRSP) established a research site in Sitiung with the objective of developing sustainable soil/crop management systems for the region. Sitiung represents a microcosm for many similar environments in the humid tropical world. Our diagnostic analysis should be useful to researchers and decision-makers in other, similar regions.

Studies of soil structure and hydrologic processes were prompted by several observations: (i) despite frequent and heavy rainfall and high clay contents in the soil, food crop plants exhibited symptoms of severe water stress during rainless periods exceeding 2 to 3 days, (ii) agricultural fields seldom, if ever, showed symptoms of flooding, with the soil surface remaining friable and tillable soon after a rainfall, (iii) growth of agronomic crops was sparse and extremely poor if the soil was not limed, irrespective of fertilizer application, and (iv) native vegetation surrounding agronomic crop fields showed luxuriant growth. In this paper we report and interpret the results of these investigations and examine their implications for soil management and sustainability of agricultural production.

SITE DESCRIPTION AND METHODS

The Physical Environment

Climate

Sitiung is located on the island of Sumatra, approximately 102° E and 1° S. The climate is humid tropical, with average rainfall ranging from 2500 to 3000 mm per year (e.g., Soil Research Institute 1979; Arya et al. 1992; Dierolf 1992). The rainy season extends from September to May; June to August is considered relatively dry even though rainfall averages 130 to 180 mm per month. It rains frequently during the rainy season, with 20- to 50-mm rainstorms being common (Dierolf 1992). The total number of rainy days varies from 150 to 175. Relative humidity is usually high (70-80%), and hours of sunshine are short (4-6 h/day). Minimum and maximum temperatures range from 22 °C to 31.5 °C. Potential evaporative demand is quite low, usually 3.5 to 4.0 mm per day.

Soils

Soils in the Sitiung region are primarily Ultisols and Oxisols (Soil Research Institute 1979; Suharta and Kimble 1986; Subagjo 1988). Most of the experimental sites are classified as clayey, kaolinitic, isohyperthermic, Typic Kanhapludults. Data on soil texture show that soils are generally clayey, with clay contents ranging from 50 to 80%. Clay content generally increases with depth. The surface 15- to 20-cm depth consists of highly stable aggregates ranging in size from 1 to 5 mm. The subsoil, on the other hand, is massive, with few root channels and little differentiation into discrete peds. The soil material is generally nonsticky because of the dominance of kaolinitic minerals in the clay fraction (e.g., Suharta and Kimble 1986; Subagjo 1988). Mechanical impedance is low throughout the soil profile, ranging from 0.5 to 6 kg/cm^2, whereas bulk densities seldom exceed 1.2 g/cm^3 (Soil Research Institute 1979; Arya et al. 1992).

Soil acidity, aluminum toxicity, and low fertility are considered the main agronomic constraints to food production (Wade et al. 1988; Adiningsih et al. 1988). Commonly reported soil pH values range from 3.5 to 5, with Al saturation sometimes as high as 90 to 100%. Topsoil layers generally have slightly higher pH and lower Al saturation compared with subsoil layers. The effective cation exchange capacity (ECEC) seldom exceeds 3 to 4 me/100 g. Nutrient bases are generally quite low, whereas trace elements are reported to be nonlimiting (e.g., Subagjo 1988). The soils are essentially devoid of weatherable primary minerals.

Soil Structure and Hydrologic Studies

Our studies were largely diagnostic in nature. The purpose was to develop broad conclusions and to obtain a basis for land use decisions and integrated soil/crop management strategies in relation to soil characteristics, plant species, and climatic conditions. Our methods consisted of standard field and laboratory procedures used in soil/crop research but modified, as necessitated, by objectives and the availability of equipment and material.

Macroporosity and Soil Water Flow Rates

Macroporosity was inferred from bulk and particle densities, water flow rates, and field water retention data. Although attempts have been made to define macropores in terms of specific pore radii (e.g., Luxmoore 1981; Luxmoore et al. 1990), no agreement exists on a strict definition. Our purpose was to delineate and quantify that portion of soil porosity that contributes to rapid water movement. Water flow was measured in field plots that were delineated to a depth of 120 cm. The soil monoliths were sealed on the sides with plastic to prevent lateral flow of water. The plots were instrumented with neutron-probe access tubes and tensiometers at various depths. Large tin-roofed sheds protected the plots from uncontrolled wetting by rainfall. The plots were first irrigated heavily and then allowed to drain, with surface evaporation prevented by straw mulch and plastic covers. Changes in water content and pressure head were monitored as a function of depth and time. One of the sites was also used for measuring the field-saturated (i.e., satiated) hydraulic conductivity before monitoring postinfiltration changes in the water content and pressure head. A detailed description of this test, including measurement of the field-saturated hydraulic conductivity, is given in Arya et al. (1998). Field water intake measurements under natural rainfall were part of an erosion study and were conducted in standard erosion plots. Rainfall and runoff were measured for each rainfall event.

Field Water Regime and Water Balance

The field water regime was monitored on a daily basis for several vegetation types, including corn, cowpea, soybean, mungbean, and a native grass/weed mixture. Neutron-probe access tubes were installed in each treatment of interest, and readings were obtained at 15-cm depth increments down to a depth of 120 cm or more. The surface 15-cm depth was sampled gravimetrically on a regular basis.

Bulk and particle densities were measured as a function of depth in all fields where the field water regime was monitored. These data provided an estimate of porosity. Daily rainfall and pan evaporation data were obtained on test sites in Gunung Medan and Sitiung 1A'. The rainfall recorder was a tipping bucket rain-gauge connected to an automatic data logger. The pan evaporimeter was a standard USDA evaporation tank equipped with a hook gauge.

Crop water use was computed using the following water balance equation: Equation (1) or Equation (2) where S_{t2} is water storage in the root zone at a certain time t_2, S_{t1} is water storage at an earlier time t_1, and *R, Ro, Et, Dd,* and *Du* are the totals of rainfall, runoff, evapotranspiration, downward drainage, and upward flow of water into the root zone, respectively, for the observation period, (t_1 -> t_2). In our investigations S_{t1}, S_{t2}, and *R* were obtained from daily measurements. Fields being monitored were flat, and no surface runoff was ever observed; hence *Ro* was set to zero. Because of generally wet conditions and the restricted root growth, upward flow of water into the root zone, *Du,* at depths exceeding 0.6 m was considered inconsequential. Downward drainage, *Dd* was estimated from the summation of drainage, *Dd*', associated with daily rainfall events, using an empirical method proposed by Arya et al., (1992): Equation (3) where *R* is the amount of any 24-hour rainfall, S_c is the current water storage measured the previous day, and S_m is the maximum observable field water storage determined from field drainage tests and field monitoring of water storage for a range of wetness conditions. Drainage occurred only when ($R + S_c$) exceeded S_m. Since *R* and S_c were measured on a daily basis, Eq. (3) leads directly to estimates of *Dd.*

$$S_{t_2} = S_{t_1} + R - Ro - Et - Dd + Du$$

Equation 1

$$Et = S_{t_1} - S_{t_2} + R - Ro - Dd + Du$$

Equation 2

$$Dd' = (R + S_c) - S_m$$

Equation 3

Root Growth Measurements

We postulated that the crop water availability problems were related to restricted root growth as a result of Al toxicity (e.g., Ritchey et al. 1980) and obtained field data for a range of vegetation and soil conditions. The measurements generally involved opening a soil pit along the rows of a fully developed crop, removing soil cores (11 cm diameter by 10 cm height) from various depths, washing the soil, and recovering the roots on a 0.5-mm sieve. Recovered roots were spread on absorbent paper towels and dried free of imbibed moisture. Fresh roots were weighed. Above-ground plant biomass was measured on all sites where root growth measurements were obtained. Plant biomass was dried in convection ovens and weighed.

Liming Rate and Depth

There was ample evidence of positive crop response to liming (Wade et al. 1988; Adiningsih et al. 1988). Liming rate and depth of application were, therefore, combined with measurements of root growth and water depletion for the purpose of quantifying the effects of lime on root growth and soil hydrologic processes. Treatments included limed versus unlimed plots and shallow versus deep-limed plots for the same rates of application. The liming material consisted of finely ground agricultural limestone.

Leaching Losses of Nutrients

Several studies were undertaken to monitor the transport and leaching of nutrients (e.g., Gill 1988; Dierolf 1992). These studies produced estimates of the initial distribution of a nutrient in the root zone, amounts applied as treatments, amounts removed by crops, and final distribution after the cropping cycle. A nutrient balance was performed to determine the amount that could not be accounted for. Our main interest was to quantify nutrient accumulation in the subsoil. In particular, we followed K^+ because of its high vulnerability to leaching.

RESULTS AND DISCUSSION

Soil Structure and Hydrology

Macroporosity and Water Flow Rates

Figure 1 presents an example of changes in total water stored in the 0- to 67.5-cm depth while the soil surface was protected against evaporation and lateral movement of water was prevented. Similar data were obtained for different soil layers at 15-cm depth increments down to a depth of 112.5 cm. Results show a rapid decrease in stored water caused by gravity drainage. However, within the first 25 to 30 h, the rate of decrease in water content reached a point beyond which further decreases in the water content became very small. For example, the 0- to 67.5-cm profile lost 3.17 cm of water during the first 27 h, but only 0.75 cm during the next 286 h. Similar sharp changes in water storage were obtained for other profile depths.

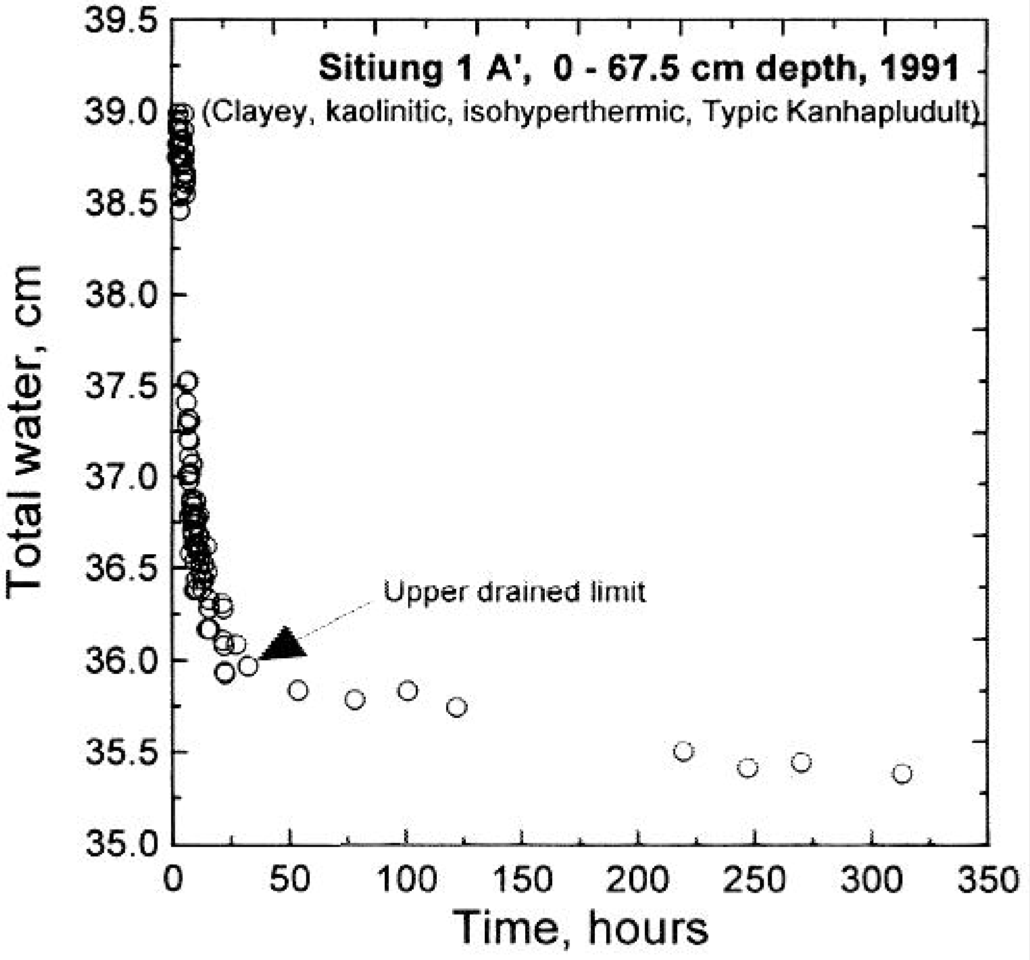
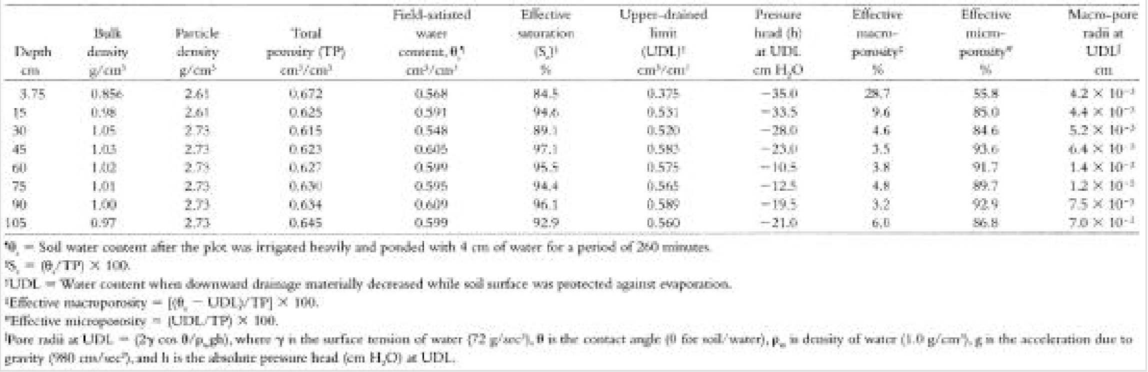


Fig. 1. Total water content in the 0- to 67.5-cm depth in an Ultisol irrigated to maximum field saturation and allowed to drain while being protected from surface evaporation and lateral movement.

The point at which a sharp change in the rate of decrease in water content occurs is defined as the upper drained limit (UDL), a term first suggested by Ritchie (1981). One can identify two categories of pores at the sharp breaking point in the drainage rate: macropores and micropores. Macropores make up that portion of the pore volume that drains rapidly between maximum saturation and the UDL, and micropores constitute the remaining portion that remains saturated at the UDL. Values of macro- and microporosities and their relative abundance in the soil profile were obtained using measurements of total porosity, field-satiated water content (i.e., the soil water content after prolonged ponding), and the water content at UDL. Results are presented in Table 1. The data show that the maximum measured water content never approached total porosity, thus reflecting the presence of entrapped air (Hillel 1980; Bruce and Luxmoore 1986). Effective field saturation ranged from 85% in the surface to 97% in the subsoil. Effective macroporosity (i.e., the pore volume between maximum water content and UDL as a percent of total porosity) decreased with depth from about 29% in the surface to between 3 and 6% in the subsoil. Effective microporosity, on the other hand, constituted about 56% of porosity in the surface layer and 85 to 94% in the subsoil.



Depth cm	Bulk density g/cm³	Particle density g/cm³	Total porosity (TP) cm³/cm³	Field-satiated water content, θ_s* cm³/cm³	Effective saturation (S_e)† %	Upper-drained limit (UDL)‡ cm³/cm³	Pressure head (h) at UDL cm H_2O	Effective macro-porosity§ %	Effective micro-porosity¶ %	Macro-pore radii at UDL‖ cm
3.75	0.856	2.61	0.672	0.568	84.5	0.375	−35.0	28.7	55.8	4.2×10^{-3}
15	0.98	2.61	0.625	0.591	94.6	0.531	−33.5	9.6	85.0	4.4×10^{-3}
30	1.05	2.73	0.615	0.548	89.1	0.520	−28.0	4.6	84.6	5.2×10^{-3}
45	1.03	2.73	0.623	0.605	97.1	0.583	−23.0	3.5	93.6	6.4×10^{-3}
60	1.02	2.73	0.627	0.599	95.5	0.575	−10.5	3.8	91.7	1.4×10^{-2}
75	1.01	2.73	0.630	0.595	94.4	0.565	−12.5	4.8	89.7	1.2×10^{-2}
90	1.00	2.73	0.634	0.609	96.1	0.589	−19.5	3.2	92.9	7.5×10^{-3}
105	0.97	2.73	0.645	0.599	92.9	0.560	−21.0	6.0	86.8	7.0×10^{-3}

*θ_s = Soil water content after the plot was irrigated heavily and ponded with 4 cm of water for a period of 260 minutes.
†$S_e = (\theta_s/TP) \times 100$.
‡UDL = Water content when downward drainage materially decreased while soil surface was protected against evaporation.
§Effective macroporosity = $[(\theta_s - UDL)/TP] \times 100$.
¶Effective microporosity = $(UDL/TP) \times 100$.
‖Pore radii at UDL = $(2\gamma \cos \theta/\rho_w gh)$, where γ is the surface tension of water (72 g/sec²), θ is the contact angle (0 for soil/water), ρ_w is density of water (1.0 g/cm³), g is the acceleration due to gravity (980 cm/sec²), and h is the absolute pressure head (cm H_2O) at UDL.

TABLE 1 Bulk and particle density, total porosity, field saturation, upper drained limit, proportions of macro- and micropores, and lower size limit of macropores for an experimental site in Sitiung 1A', Indonesia

Values of the pore radius separating the macropores from the micropores was obtained by determining the average radii of water-filled pores at the UDL. Tensiometric measurements of the pressure head corresponding to the UDL were converted to equivalent pore radii using the capillary equation. An example of changes in the pressure head with time for the 30- and 60-cm depths is presented in Fig. 2. The results in Table 1 show that the lower limit of the macropores ranged from about 0.0042 to 0.014 cm. Similar values were found for all test sites in Sitiung. The UDL occurred at pressure heads ranging from -35 cm in the surface to -11 cm in the subsoil. Similar pressures for UDL have been reported by Rusman (1990) and Dierolf (1992). These results show that laboratory estimation of the field capacity (or UDL) at -100 or -330 cm pressure head, as is usual, would be in considerable error. Our field results are consistent with the effect of macropores on water flow.

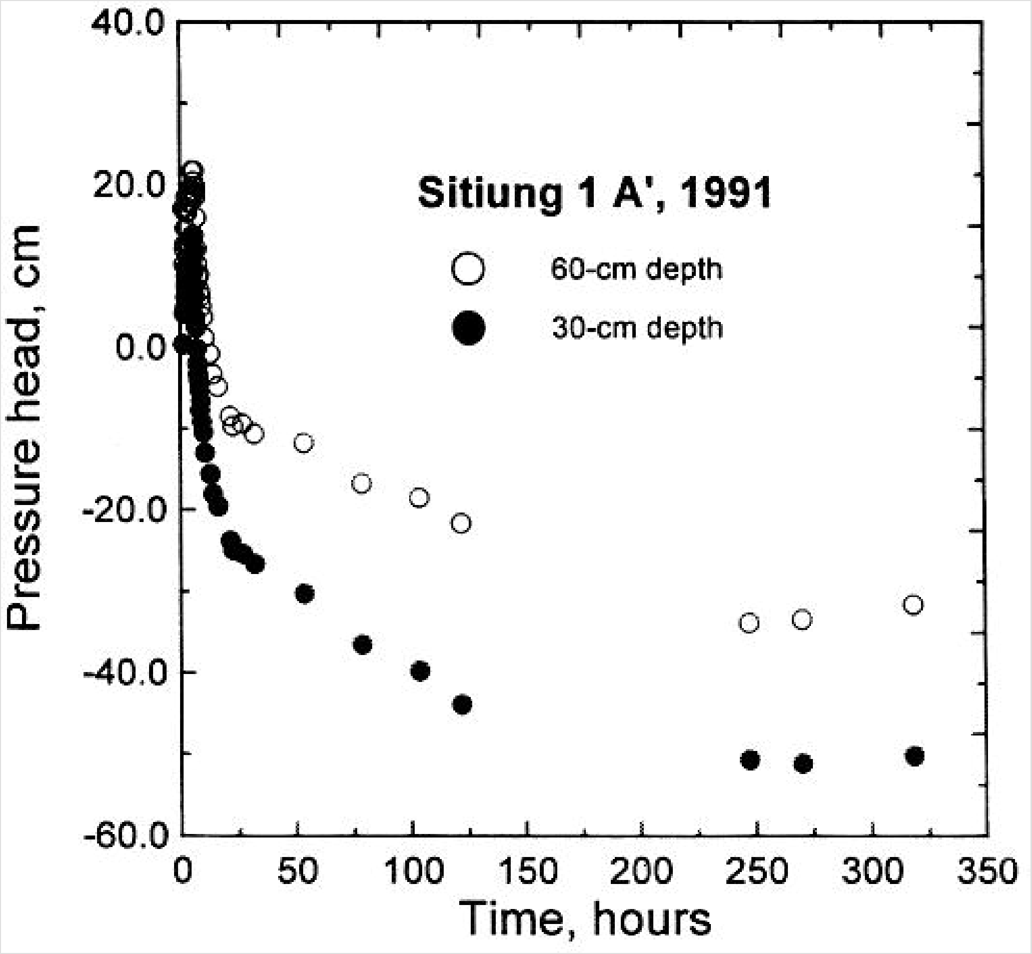


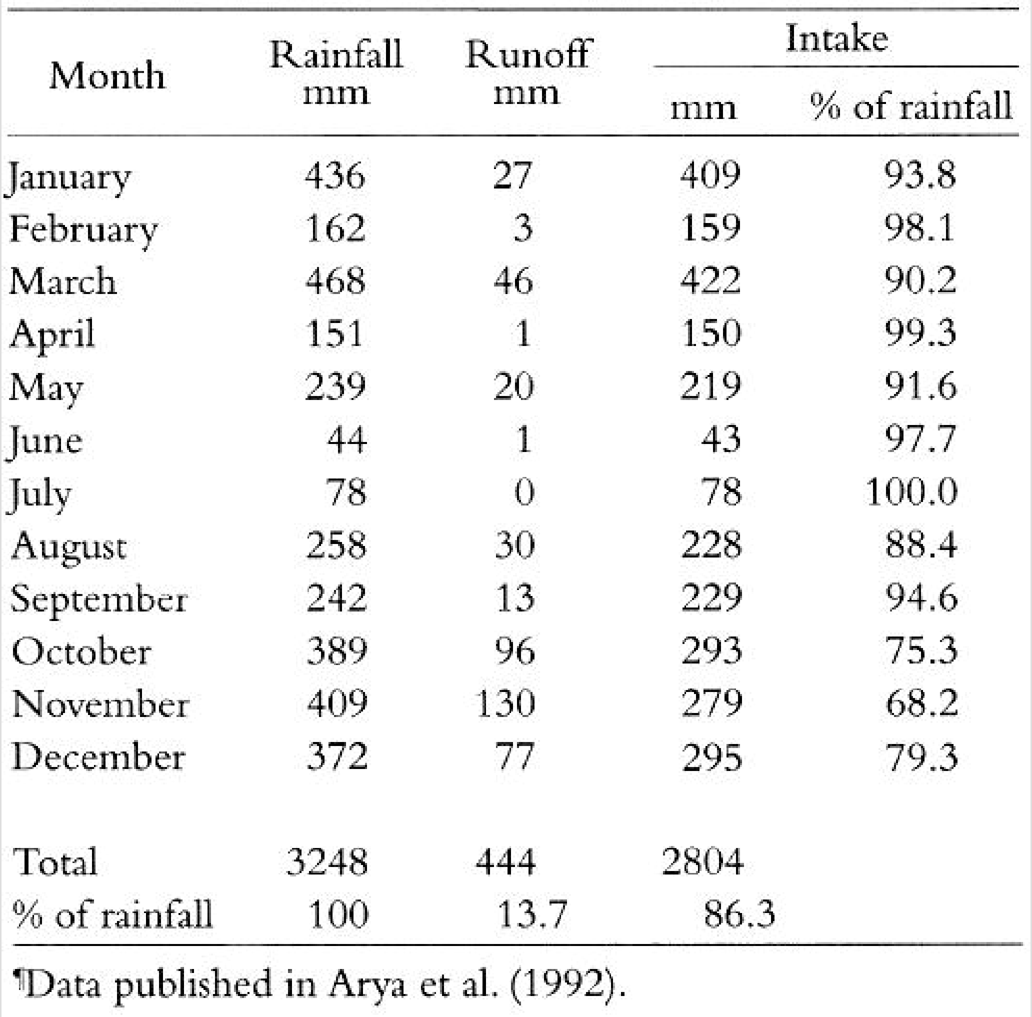
Fig. 2. Pressure heads at two depths in an Ultisol irrigated to maximum field saturation and allowed to drain while being protected from surface evaporation.

Results in Table 1 also show that whereas macroporosity decreases with depth, the average size of the macropores increases. This is an important feature of the pore structure in Sitiung soils. According to Poiseiulle's law (*cf.* Hillel 1971, p. 81), the volumetric flow rate is proportional to the fourth power of the pore radius. Therefore, a small increase in pore size can lead to large increases in the flow rate. The subsoil macropore radii in Table 1 are roughly twice those in the surface soil, indicating that subsoil macropore flow rates can be 16 times those in the surface layer. Thus, rapid transport of downward draining water is assured even though 95% of the subsoil matrix is microporous.

High flow rates in Ultisols and Oxisols of Sitiung have been measured by Rusman (1990), Dierolf et al., (1997), and Arya et al. (1998). Dierolf et al. found that 100% of 72.5-mm irrigation water, applied to a bare plot over a period of 100 minutes, had drained past a depth of 112.5 cm in 24 h. Arya et al. measured a steady-state flux of 6.8 cm/hour in a field plot under ponded conditions. These flow rates are high and exceed commonly observed rainfall rates in the region. Thus, most of the rain is likely absorbed by the soils without producing surface runoff.

Field Intake of Rainfall

The observations of rapid water flow in Sitiung soils were confirmed quantitatively by the results of rainfall/runoff measurements. Table 2 presents monthly rainfall and runoff data for a bare erosion plot. Data show that the rainfall intake rate ranges from 68 to 99% of the rainfall, depending on the amount of rainfall, rainfall intensity, and plot water contents before rainfall. For 9 of the 12 months, intake rates were more than 90% of the rainfall. Intake rates fell below 80% during October, November, and December. The total rainfall for the year was 3249 mm, whereas the intake was 2805 mm, or 86.4% of the rainfall. Field soils are almost always covered by certain amount of vegetation. Therefore, the intake rate in normal field soils should be even higher. Thus, the risk of erosion is minimal in Sitiung soils unless they are compacted by machinery, as in cases where land clearing was done by heavy bulldozers.



Month	Rainfall mm	Runoff mm	Intake	
			mm	% of 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	

¶Data published in Arya et al. (1992).

TABLE 2 Field plot-scale measurement of runoff and intake of rainfall in a bare soil (10 to 13.5% slope), Sitiung IV (1985)¶

Hydraulic Conductivity

Except for a few centimeters of the surface soil, macropores account for a very small fraction of the total pore volume (Table 1). Much of the water is held in micropores, which conduct water quite slowly. An example of changes in the hydraulic conductivity as a function of the pressure head is presented in Fig. 3. Results indicate high conductivities only during the rapid flow phase. Values decreased by three to four orders of magnitude at pressure heads of -10 to -15 cm, whereas pore saturation remained between 90 and 95%. These pressure heads correspond to the UDL which, for most depths, occurred within the first 25 to 30 h after cessation of surface ponding. These results imply that water flow in Sitiung soils is rapid only during application. The flow rates decrease rapidly as soon as the macropores are empty. Results also suggest that no significant drying of the soil profile should be expected from gravity drainage alone.

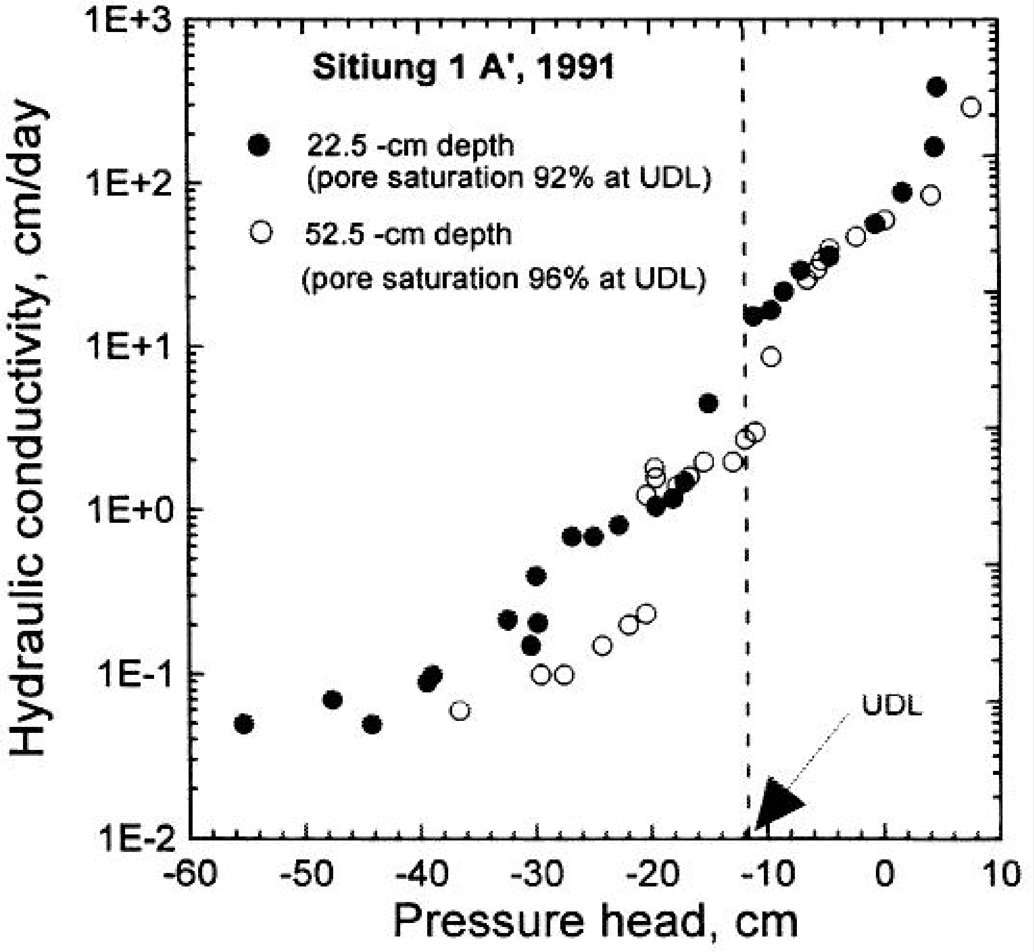


Fig. 3. Hydraulic conductivity at two depths in an Ultisol as a function of pressure head.

The data in Fig. 3 show a rapid decline in the hydraulic conductivity with decreasing pressure heads, even for positive pressure heads. The occurrence of both positive and negative pressures during ponding, and for a short time after the cessation of ponding, has been reported and discussed by Arya et al. (1998). They attribute these observations to incomplete and variable saturation caused by the presence of entrapped air and differences in field-satiated hydraulic conductivities with depth. Changes in the volume of entrapped air and/or progressive sealing of pores can lead to changes in K even under positive pressures (Faybishenko 1995). The results in Fig. 3 also confirm the presence of a dual-porosity soil medium (e.g., Gerke and van Genuchten 1993; Mohanty et al. 1997). Note the sharp changes in the hydraulic conductivity at about -12- and -30-cm pressure heads. These results imply that capillary, flow-based, unimodal, soil hydraulic functions may be inadequate to simulate water flow in macroporous soils of the type that occur in Sitiung.

Field Water Regimen

Figure 4 presents daily rainfall and volumetric water contents for several depths in an Ultisol planted to cowpea. Similar data were obtained for corn, soybean, and a native grass (Arya et al. 1992). The data in Fig. 4 show that the water content was affected primarily in the top 15 cm. Water contents in this layer increased with rainfall and decreased when there was no rainfall. As expected, the amplitude of fluctuations in water content decreased with depth. Notice the dry period from July 28 to September 4 (38 days), except for an 8-mm rain on August 15. Although water contents in the 0- to 25-cm layer declined with time during this period, those in the 30- to 60-cm depth decreased only negligibly and remained at or slightly below UDL.

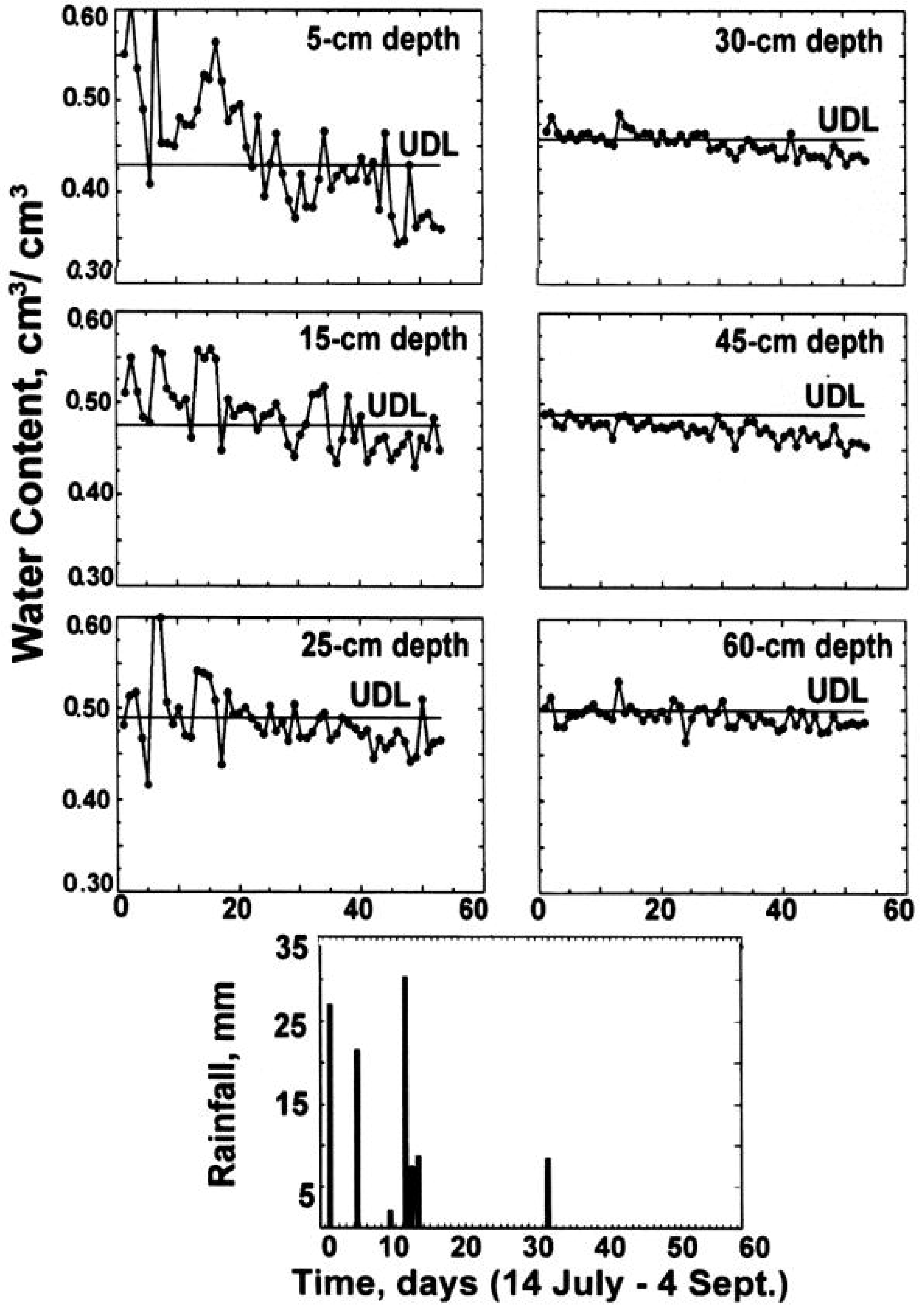


Fig. 4. Daily rainfall and field water content at several depths under a cowpea crop during the 1987 cropping season. Gunung Medan, Sitiung.

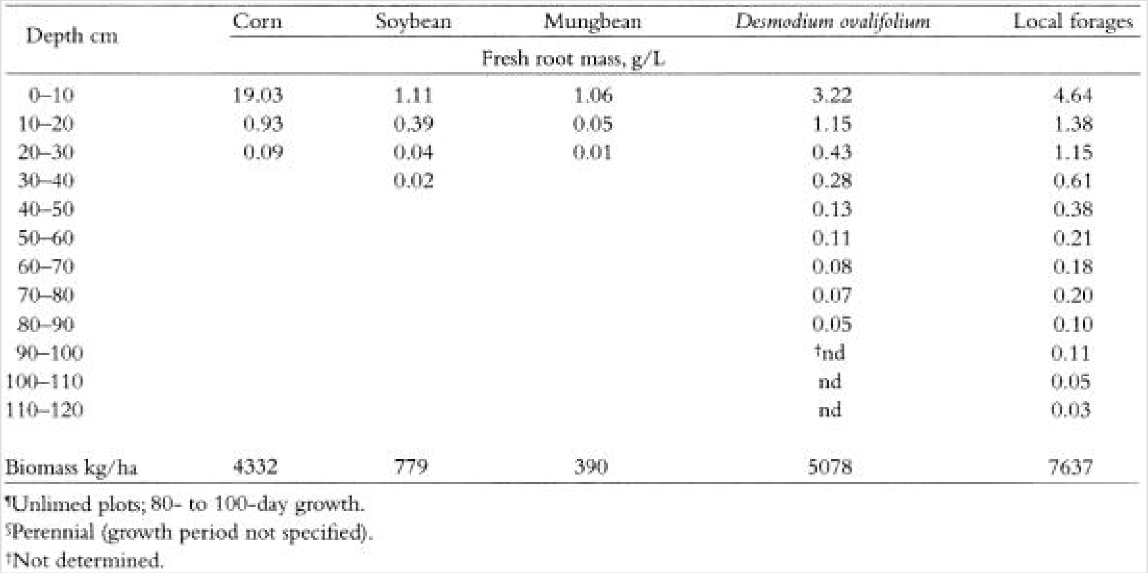
Water contents of the 0- to 15-cm depth were measured by gravimetric sampling, whereas those of the 15- to 60-cm depth were measured with a neutron probe. Spatial variability in gravimetric samples and temporal variability in the neutron probe standards undoubtedly made some contribution to the variability in water content data reported in Fig. 4. However, our interest was only to follow the overall wetness of the field soils; the data serve that purpose clearly. Note that although the water contents in the 30- to 60-cm depth remained high, they only occasionally rose above the UDL. This may be the result of spatial variability in the soil hydraulic properties (e.g., Trangmar et al. 1984) because the UDL was measured in a plot about 75 m from the cowpea field. In addition, accurate estimation of the UDL requires prolonged and thorough wetting to ensure maximum possible saturation of all parts of the soil profile, a situation that normally does not occur under field conditions, especially in subsoil layers. Thus, subsoil water contents under field conditions are unlikely to remain above UDL.

Limitations to Crop Water Use

Root Growth

Root growth is of paramount importance to plants' ability to absorb water and nutrients from a soil. High mechanical impedance can restrict root growth. Available data (e.g., Soil Research Institute 1979; Arya et al. 1987) show mechanical impedances of the Sitiung Ultisols and Oxisols in the range of 3 to 7 kg/cm^2. An obvious preliminary conclusion is that no soil physical barriers exist to root growth. Mechanical impedances have to be in the range of 12 to 18 kg/cm^2 in order to substantially affect seedling emergence and root growth of common field crops (e.g. Taylor and Klepper 1978).

Nevertheless, available data on root growth (Arya et al. 1987, 1988, I and II; Rusman and Arya 1988; Rusman et al. 1989) show vast differences in root density and rooting depth between agronomic plants and locally-adapted native vegetation. A comparison of the rooting depths for several food crop plants, along with aboveground plant biomass production, is presented in Table 3. For the food crop plants, most of the roots were confined to the top 10 cm of the profile, whereas local forages and legumes showed rooting depths up to and beyond 100-cm depth. Investigations of alley-crop tree roots, such as those of calliandra (*Calliandra calothyrsus*), leucaena (*Leucaena leucocephala*), and albizzia (*Paraserianthes falcataria*), showed rooting depths exceeding 150 cm (Dierolf et al. 1989). Deeper root systems provide a larger volume of soil from which plants can obtain water and nutrients. The effect of rooting depth on plant growth is clearly reflected in the biomass production data in Table 3. The data do not imply that aboveground biomass is determined solely by root growth. Rather, the two are interdependent. In principle, good shoot 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 places a corresponding limit on the soil volume from which water and nutrients can be extracted.



Depth cm	Corn	Soybean	Mungbean	*Desmodium ovalifolium*	Local forages
			Fresh root mass, g/L		
0–10	19.03	1.11	1.06	3.22	4.64
10–20	0.93	0.39	0.05	1.15	1.38
20–30	0.09	0.04	0.01	0.43	1.15
30–40		0.02		0.28	0.61
40–50				0.13	0.38
50–60				0.11	0.21
60–70				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
Biomass kg/ha	4332	779	390	5078	7637

¶Unlimed plots; 80- to 100-day growth.
§Perennial (growth period not specified).
†Not determined.

TABLE 3 Root growth and aboveground biomass for food crops¶ and non-food vegetation§ in upland acid soils of Sitiung

Acidity, Al Toxicity, and Root Growth

Root growth investigations in limed and unlimed treatments confirmed the serious limitations to root growth caused by Al toxicity. Fig. 5 shows root growth patterns for a soybean crop under four liming treatments. The liming treatments had been applied two and a half years before sampling. Results showed a dramatic response of root density to liming. However, >95% of the root mass was confined to the top 10 cm of soil, i.e., the depth of liming. Liming increased rooting density but not the rooting depth. Chemical analyses of the soil (data not presented) showed that root growth patterns were consistent with the distribution of exchangeable Ca and Al. Lime apparently did not move below the depth of application since no changes in either the Ca or Al concentration were observed below the depth of liming.

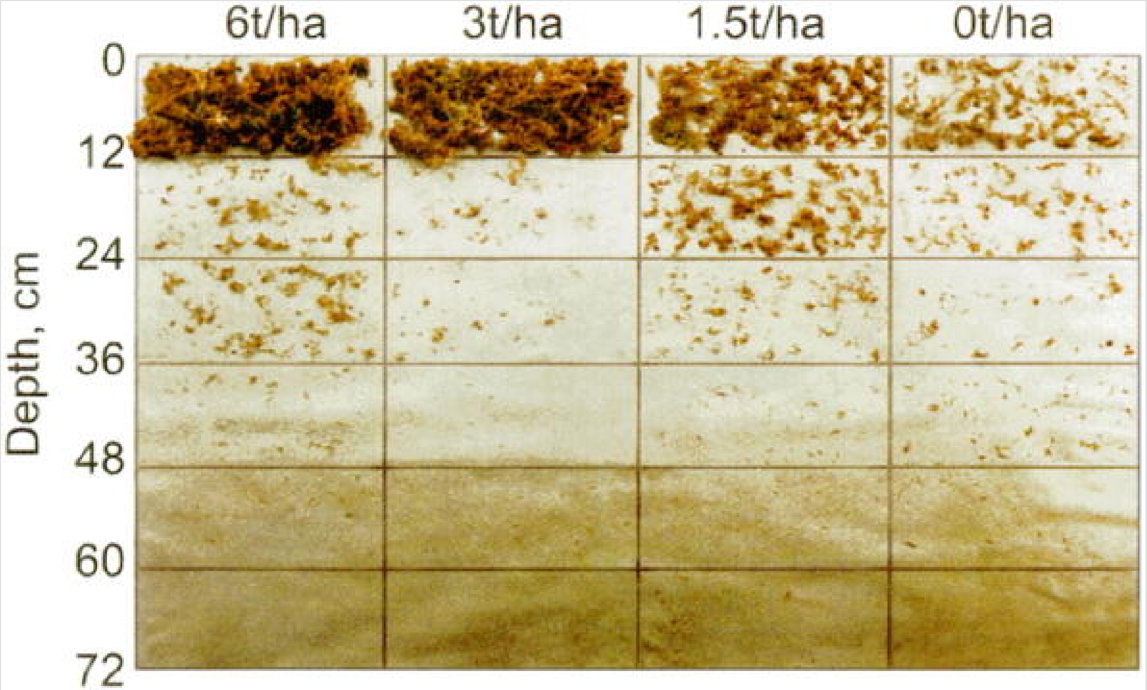


Fig. 5. Effect of liming rate on root growth and distribution of a soybean crop in an Al-toxic soil, two and a half years after the liming treatments. All of the lime was applied in the surface and mixed by hoeing.

Effect of Deep Placement of Lime on Rooting Depth and Crop Water Use

The results presented in Fig. 5 prompted studies of the effects of deep liming on crop rooting depth, water use, and production. Fig. 6 presents temporal patterns of the soil water pressure head at a depth of 37.5 cm under a corn crop subjected to three liming treatments: no lime, lime to 20 cm depth, and lime to 50 cm depth. The liming rate was 1 t/ha/10 cm depth. Although we found distinct differences in vegetative growth, pressure heads for the three treatments were almost identical for the first 45 days of growth. Thereafter, pressure heads for the deepest liming treatment became much more negative, reaching values of -750 cm, while those for the other two treatments did not decrease below -100 cm and remained comparable in magnitude. Higher negative pressure heads reflect more water being absorbed by the roots. Apparently, liming to 20-cm depth did not induce root activity at the 37.5-cm depth. However, at a shallower depth of 22.5 cm (data not shown), pressure heads for the 20- and 50-cm depths of liming treatments were similar, with both exhibiting high negative values. Grain yields for the 0, 20-cm, and 50-cm depths of liming treatments were 1911, 4745, and 5830 kg/ha, respectively. These results corroborate the assertion that rooting depth is crucial to water and nutrient availability. Data in Figs. 5 and 6 again suggest that the rate of downward movement of lime is negligible for the soil and climatic conditions in Sitiung.

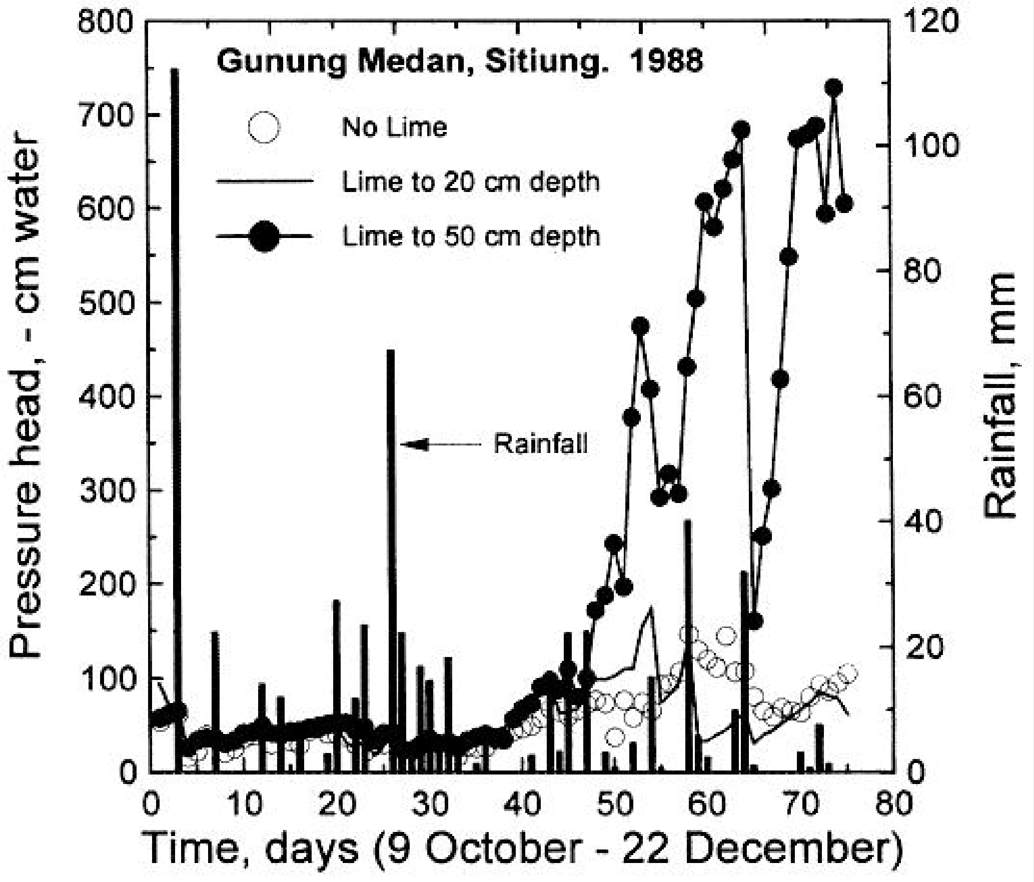


Fig. 6. Daily rainfall and pressure heads at a depth 37.5 cm under a corn crop planted to three depth-of-liming treatments.

A more dramatic effect of liming depth on crop water use and production was observed during the 1989 cropping season, which was characterized by a significant drought. Fig. 7 presents daily rainfall and total water in the 7.5- to 67.5-cm depth as a function of time for a corn crop with 6 t/ha lime applied evenly in the top 10- or 60-cm depth. Distributing the same amount of lime over a six times greater depth resulted in a proportionately reduced neutralization of Al toxicity per unit depth. The long dry spell was interrupted only by several very light showers. Both treatments responded to the rainfall patterns. However, the total amount of water in the soil profile remained significantly lower for the deeper liming treatment, thus indicating that plants in this treatment were withdrawing water at a much faster rate than when all of the lime was applied to the surface 10-cm layer. The difference in profile water storage between the two treatments was about 3 to 4 cm during the initial stages of growth when the crops' demand for water was small, but it increased to 10 to 12 cm as the season progressed and the demand for water increased. Grain yields for the shallow and deep liming treatments were 1550 and 3200 kg/ha, respectively. We attribute these effects to increased rooting depth achieved by deep placement of lime. The deeper liming treatment caused significant drying of the soil profile even though Al toxicity in this treatment was reduced only minimally compared with the shallow liming treatment. Similar data comparing changes in water storage in the root zones of cowpea and a native grass (Arya et al. 1992) showed that even without lime, native grass caused significantly more drying of the soil profile.

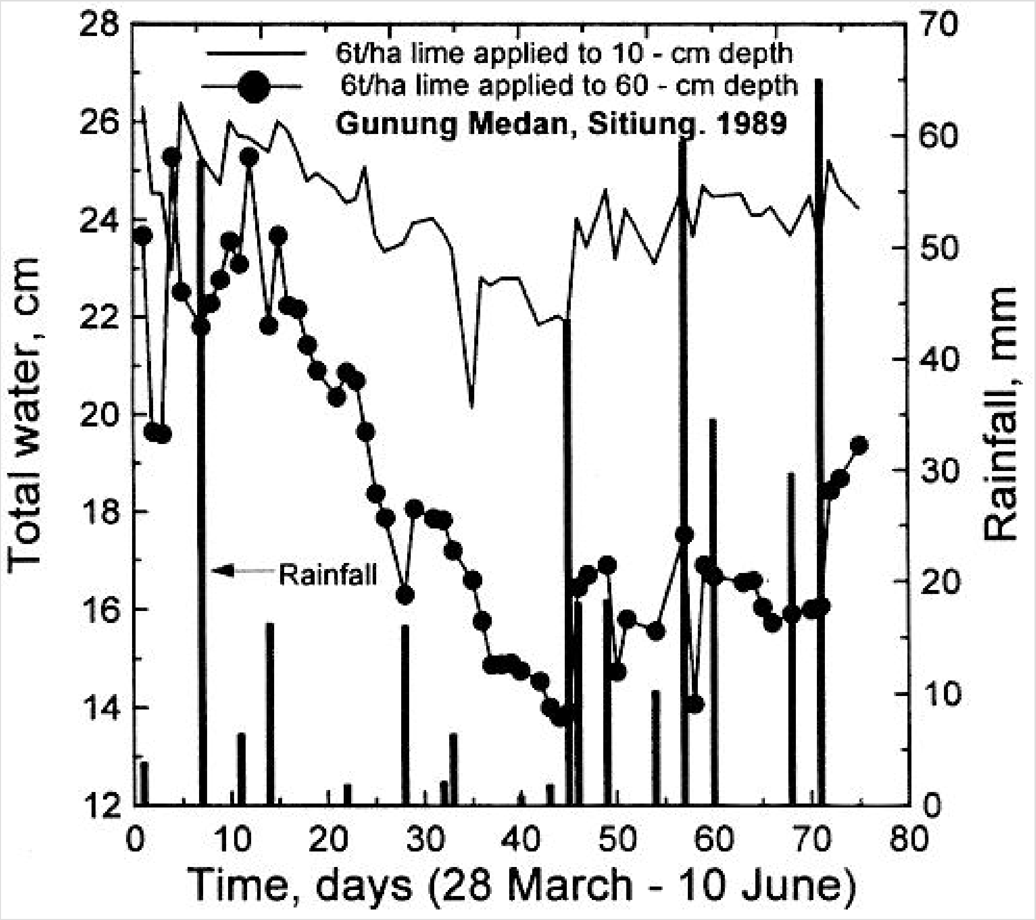
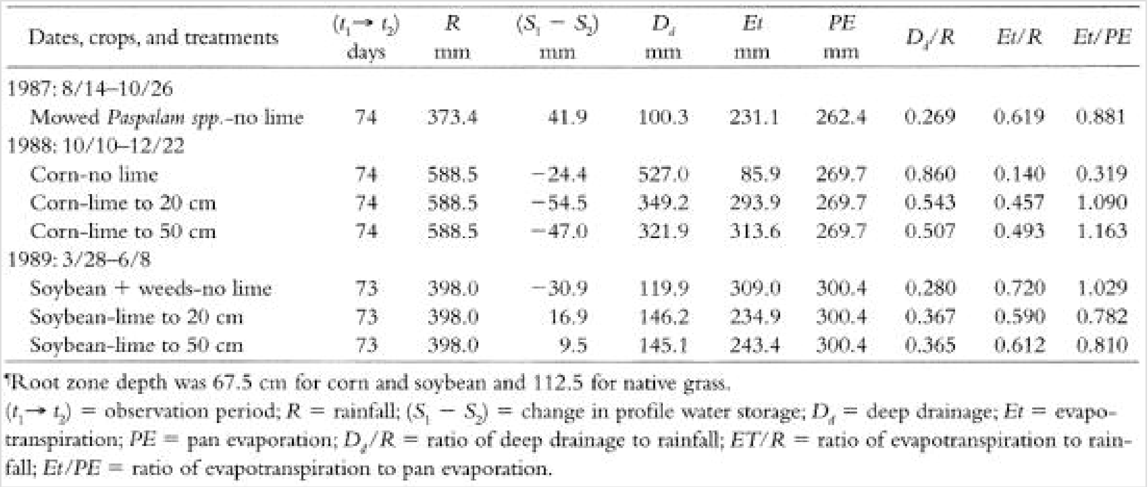


Fig. 7. Daily rainfall and total water content in the 7.5- to 67.5-cm depth under a corn crop for two liming treatments: 6 t/ha distributed to a 10-cm depth and 6 t/ha distributed to a 60-cm depth.

Surface application of lime is the standard practice in Sitiung. Early crop growth is usually robust if sufficient fertilizer is applied and the crop's need for water is met. However, the increased crop growth also means increased demand for water. If the root system is restricted (as is usually the case with no lime or shallow incorporated lime), crops with more vegetative growth are expected to experience greater stress during subsequent rainless periods. Although the amount of rainfall in Sitiung is high, the distribution is often erratic, and rainless periods of a few to several days are not uncommon. Despite the high water-holding capacity of the soils and high water storage in the subsoil (Table 1 and Fig. 4), crops often fail because of intermittent drought. Critical Al saturation and optimum liming rates for various crops and soil conditions were determined by, for example, Wade et al. (1988). However, the recommendations failed to take into account the important role of root growth in water availability and crop production, as demonstrated by our results in Fig. 7.

Field Water Balance

Table 4 presents seasonal water balances for several agronomic crops and a native grass vegetation. Results show that components of the water balance varied with vegetation type, liming treatment, and amount of rainfall. Corn and soybean were planted in plots that had been limed to various depths to induce different depths of rooting. The liming treatments resulted in varying levels of vegetative growth. All of the corn plots were kept free of weeds. The soybean crop was weeded only once, i.e., during the early stages of growth. Thereafter, weeds grew freely and filled whatever space was available. Weed growth was most vigorous in the unlimed treatments, which produced little soybean biomass. The deep-limed soybean plots had little weed growth because of the vigorous growth of the crop. The native grass was a *Paspalam spp.,* which was mowed several times.



Dates, crops, and treatments	$(t_1 \rightarrow t_2)$ days	R mm	$(S_1 - S_2)$ mm	D_d mm	Et mm	PE mm	D_d/R	Et/R	Et/PE
1987: 8/14–10/26									
Mowed *Paspalam spp.*-no lime	74	373.4	41.9	100.3	231.1	262.4	0.269	0.619	0.881
1988: 10/10–12/22									
Corn-no lime	74	588.5	−24.4	527.0	85.9	269.7	0.860	0.140	0.319
Corn-lime to 20 cm	74	588.5	−54.5	349.2	293.9	269.7	0.543	0.457	1.090
Corn-lime to 50 cm	74	588.5	−47.0	321.9	313.6	269.7	0.507	0.493	1.163
1989: 3/28–6/8									
Soybean + weeds-no lime	73	398.0	−30.9	119.9	309.0	300.4	0.280	0.720	1.029
Soybean-lime to 20 cm	73	398.0	16.9	146.2	234.9	300.4	0.367	0.590	0.782
Soybean-lime to 50 cm	73	398.0	9.5	145.1	243.4	300.4	0.365	0.612	0.810

[¶] Root zone depth was 67.5 cm for corn and soybean and 112.5 for native grass.

$(t_1 \rightarrow t_2)$ = observation period; R = rainfall; $(S_1 - S_2)$ = change in profile water storage; D_d = deep drainage; Et = evapotranspiration; PE = pan evaporation; D_d/R = ratio of deep drainage to rainfall; ET/R = ratio of evapotranspiration to rainfall; Et/PE = ratio of evapotranspiration to pan evaporation.

TABLE 4 Seasonal water balance[¶] for corn, soybean, and a native grass in Sitiung, Indonesia

Soil water storage showed a net increase in some cases and a net decrease in others. A net decrease implies that evapotranspiration and drainage combined used more water than was available from the season's rainfall. The additional water came from storage present before the measurements started. Therefore, in expressing drainage and evapotranspiration as percentages of rainfall, it became necessary to make proportional adjustments to evapotranspiration and drainage to eliminate the effect of the net loss in soil water storage.

As elsewhere, evapotranspiration and deep drainage are the major components of the water balance in the Sitiung region. Data show that, for the native grass, the evapotranspiration and drainage components were 62 and 27% of the rainfall, respectively. The remaining 11% was accounted for by increased soil water storage. In the case of corn, the change in soil water storage was negative. For the unlimed corn treatment, where plant growth was very poor, evapotranspiration and drainage accounted for 14 and 86% of the rainfall, respectively. For the deep-limed corn, on the other hand, evapotranspiration and drainage accounted for 47.5 and 52.5% of the rainfall, respectively. Liming to 20-cm depth was nearly as good as liming to 50-cm depth. For the unlimed soybean, where weed growth was vigorous, evapotranspiration and drainage accounted for 72 and 28% of the rainfall, respectively, indicating that locally adapted weed species were far more effective in extracting water and drying the soil. For the case of deep-limed soybean, where weed population was minimal, evapotranspiration and drainage accounted for 60 and 37% of the rainfall, respectively. Again, liming to 20-cm depth was as good as liming to 50-cm depth. These results indicate that while deep liming improves crop water extraction, local vegetation is far more effective in extracting water, even when the soil is not amended with lime.

The computed values of evapotranspiration in Table 4 appear to be quite reasonable for the Sitiung region. Taking pan evaporation as a measure of potential evapotranspiration, we observe 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 ratios published in the literature. Slightly higher evapotranspiration than pan evaporation should be expected for tall-growing corn and highly efficient weeds. Chang (1968) quotes several examples of data showing crop potential evapotranspiration 5 to 24% higher than pan evaporation. He attributes these higher values to high leaf area index (LAI) and the increased canopy roughness usually associated with tall crops.

Retention and Leaching of Nutrients

Systematic studies of nutrient retention and movement in Sitiung soils have not been made. Data on soil fertility (e.g., Wade et al. 1988; Adiningsih et al. 1988; Gill and Kamprath 1990) indicate low residual value of several fertilizer nutrients. A rapid decline in soil fertility with cultivation, especially the levels of organic carbon, nitrogen, and potassium, have been observed by some researchers (e.g., Fakultas Pertanian, Universitas Andalas 1982; Arief and Zubaidah 1989). These studies report high residual values of phosphorus when applied as triple superphosphate. Similar observations were made with calcium applied as limestone (e.g., Arya 1990).

However, because of rapid downward movement of large volumes of water (Fig. 1, Table 2), restricted root growth (Fig. 5), and the generally wet subsoil moisture regime (Fig. 4), the probability of significant exchange between downward moving drainage water and resident subsoil water is quite low. Therefore, it is not likely that readily soluble nutrients will accumulate in the subsoil in any significant amount.

Although water moving through macropores may not transport significant amounts of solutes over short periods, significant losses are likely over a season or several seasons. In a field trial (Dierolf 1992), potassium fertilizer (as 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 430 mm of rain fell during the 2-week period after fertilizer application, all of the applied fertilizer was recovered from the surface 40 cm of soil. Even after another 340-mm rainfall (cumulative amount 770 mm) during the next month, only about 13% of the applied K was unaccounted for in the surface 40 cm. However, after another 3 months and 860 mm additional rainfall (cumulative amount 1630 mm), 44% of the applied K was not recovered in the surface 40 cm, and there was no indication that any of the fertilizer had accumulated in the 40- to 80-cm depth.

Long-term subsoil accumulation of K was monitored in a field trial (Dierolf 1992) 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. The distributions of soil K with depth at the end of the sixth crop are presented in Fig. 8. Data show that one-time applications of 70 and 250 kg/ha K did not cause increases in soil K over what was initially present. The 600 kg/ha K in five split applications increased soil K only in the top 30 cm. After accounting for crop removal of K, only about 1% of the K applied as fertilizer was found to have accumulated in the 30-to 90-cm depth, whereas 33% was lost to depths below 90 cm (Dierolf et al. 1997).

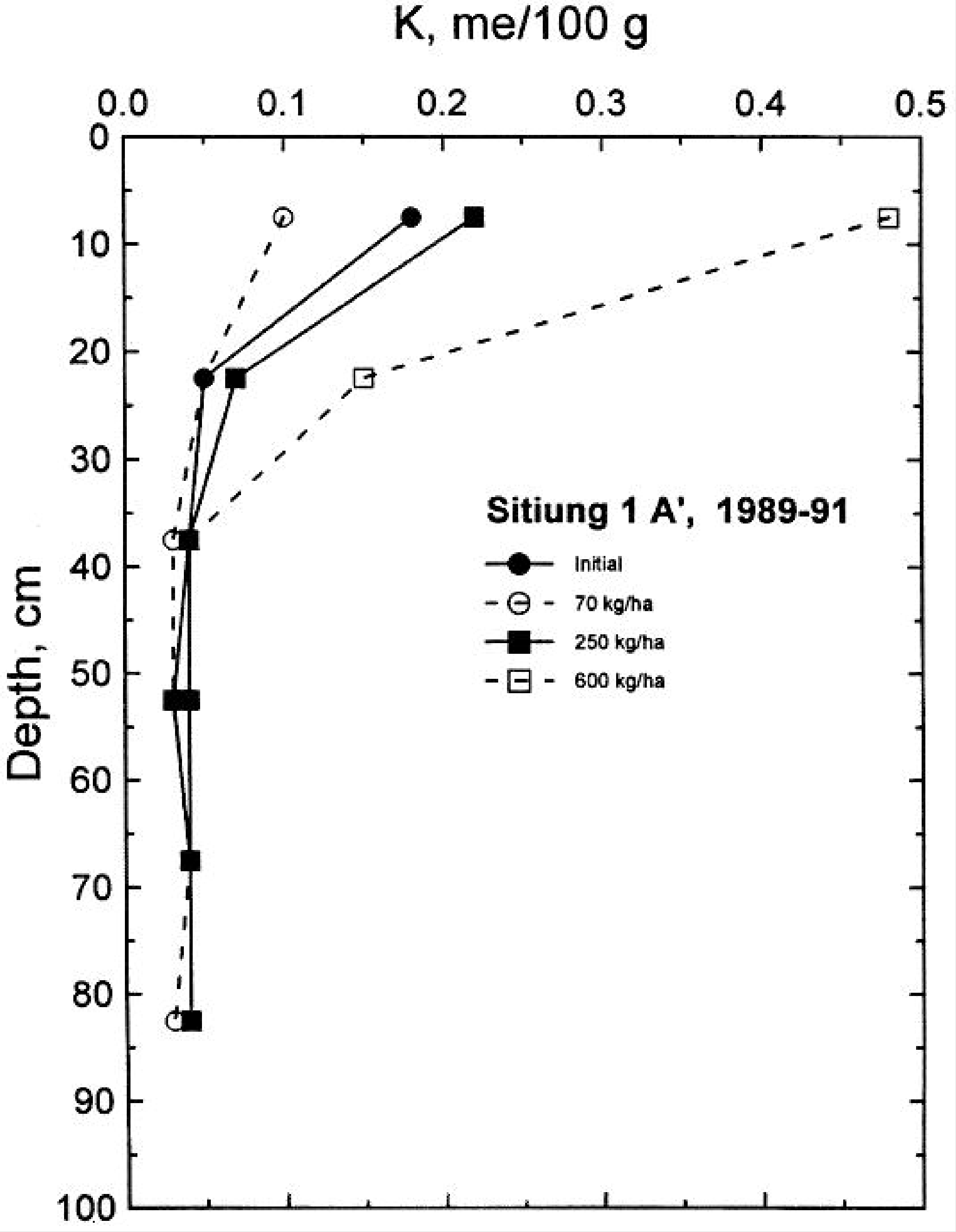


Fig. 8. Soil distribution of extractable K in an Ultisol, after six cropping seasons, at three rates of K application.

SUMMARY AND RECOMMENDATIONS

Rainfall and soil structure play major roles in soil hydrologic processes. These processes, in turn, greatly influence the soil's chemical environment. The physical structure of Sitiung soils is characterized by large and highly stable aggregates, with numerous macropores in the surface and a predominantly microporous subsoil interspersed with a few larger macropores (Table 1). This structure facilitates rapid downward movement of large volumes of water supplied by frequent torrential rainfall events in the area (Tables 2 and 4). Rapid leaching of rainwater via internal drainage reduces the risks of erosion. However, the process contributes to the persistence of infertility and toxicity in subsoil horizons.

Water in the surface horizon interacts with a wide range of pores (Table 1) and, thus, with a relatively large volume of soil from which it can pick up readily soluble nutrients. However, as water moves downward, it flows primarily through a few relatively large macropores, thereby bypassing the wet microporous matrix. The result is that readily soluble fertilizer nutrients do not accumulate in the subsoil but are leached further downward (Fig. 8). The subsoil toxicity prevails and the risk of groundwater pollution increases with continued use of fertilizer inputs.

Because the subsoil environment is toxic, root systems of a variety of agronomic crop plants remain restricted to the surface layers (Table 3, Fig. 5). Crops suffer from water stress while the subsoil remains excessively wet (Fig. 4). Root systems of locally adapted vegetation, on the other hand, are able to penetrate the subsoil more readily (Table 3), extract soil water, and promote drying.

Data presented in this paper show that more than 90% of the subsoil matrix is microporous (Table 1), and through this, water movement is extremely slow (Fig. 3). This implies that nutrient bases sequestered in micropores can also be relatively protected against the leaching action of rainwater. Applied base cations can, at the same time, lead to some neutralization of toxic Al. However, delivery of nutrients to subsoil micropores is difficult in a cropping system with Al-sensitive plants. Drying of the subsoil is essential to promote more effective interaction between nutrient-carrying drainage water and the subsoil matrix. This can be accomplished only by deep rooting vegetation. Deep rooting plant species not only cause drying of the subsoil, but they probably also transport nutrients to the subsoil matrix, as is evidenced by the generally better subsoil chemical environment found before land is cleared (Arief and Zubaidah 1989). Lambert and Arnason (1980) compared nutrient content of corn and weeds on a high rainfall site in Belize, Central America. For conditions of a comparable biomass, total nutrient content in the weeds was 3.76 times higher than in the corn. These studies demonstrate that adapted vegetation is able to explore a relatively large soil volume.

Research reported in this paper has shown that lime is an effective neutralizer of exchangeable Al and, hence, a good promoter of root growth. However, downward movement of lime is extremely slow. Deep placement of lime is effective in providing an improved environment for crop root growth (Figs. 6 and 7), but the technology is cost- and labor-intensive.

We conclude that traditional farming for food crop production is not likely to succeed in Sitiung and other regions with similar soil and climate conditions. A better option may be to shift from food crop production to one in which locally adapted vegetation of economic value is integrated in the cropping system. As we have shown, a variety of locally adapted grasses and forage legumes are available for this purpose. They provide an opportunity for developing a forage-live-stock-based production system. Alternatively, forage and food crops can be included in a mixed or rotational system. Tree crops adapted to local conditions offer another opportunity. Other strategies for improving soil conditions may include fertilization of deep rooted vegetation, deep incorporation of lime and fertilizer, and fertilizer application during periods of low rainfall. Breeding and selection of crop varieties for acid-tolerance offer additional opportunities for improving crop production in the Sitiung region.

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REFERENCES

Adiningsih, J. S., M. Sudjadi, and S. Setyorini. 1988. Overcoming soil fertility constraints in acid upland soils for food crop-based farming systems in Indonesia. Indones. Agric. Res. Dev. J. 10:49-58. [Context Link]

Anderson, J. L., and J. Bouma. 1977. Water movement through pedal soils: I. Saturated flow. Soil Sci. Soc. Am. J. 41:413-418. [Context Link]

Arief, A., and Y. Zubaidah. 1989. Preliminary Report on the Second International Trial on Soil Fertility of Acid Upland Soils for Rice. 1989 INSURF Workshop and Planning Meeting. Bangkok, Thailand, August 30-September 1, 1989. [Context Link]

Arya, L. M. 1990. Properties and processes in upland acid soils in Sumatra and their management for crop production, Applied Agricultural Research Project-Phase II. Sukarami Research Institute for Food Crops, Padang, Indonesia. Report prepared for Winrock International Institute for Agricultural Development, Morrilton, Arkansas. [Context Link]

Arya, L. M., T. S Dierolf, A. Sofyan, and I. P. G. Widjaja-Adhi. 1992. Soil structure effects on hydrologic processes and crop water availability in Ultisols and Oxisols of Sitiung, Indonesia. Soil Management CRSP Bull. 92-03. North Carolina

State University, Raleigh, NC. [Context Link]

Arya, L. M., T. S Dierolf, A. Sofyan, I. P. G. Widjaja-Adhi, and M. Th. van Genuchten. 1998. Field measurement of the saturated hydraulic conductivity of a macroporous soil with unstable subsoil structure. Soil Sci. 163:841-852. Ovid Full Text | [Context Link]

Arya, L. M., R. F. Guyton, B. Rusman, and I. P. G. Widjaja-Adhi. 1988. I. Spatial variation in soil properties and corn root and top growth in an acid Ultisol in Sitiung, West Sumatra, Indonesia. Research Report, TropSoils Project, Center for Soil Research, Bogor, and University of Hawaii, Honolulu, HI.

Arya, L. M., B. Rusman, Kasli, R. F. Guyton, I. Amien, I. P. G. Widjaja-Adhi, Sholeh, and O. Soepandi. 1988. II. Rooting patterns and plant production for food crops and non-food vegetation in the upland acid soils of Sitiung, West Sumatra, Indonesia. Research Report, TropSoils Project, Center for Soil Research, Bogor, and University of Hawaii, Honolulu, HI. [Context Link]

Arya, L. M., B. Rusman, R. F. Guyton, Sholeh, and E. Hidayat. 1987. Root growth problems in Sitiung soils and their implications for soil management and crop productivity. Paper presented at Rapat Teknis, Pusat Penelitian Tanah, Bogor. June 18-20, 1987. [Context Link]

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18: 1311-1325. [Context Link]

Bruce, R. R., and R. J. Luxmoore. 1986. Water retention: Field methods. *In.* Methods of soil Analysis, Part I.A. Klute (ed.). Agronomy No. 9. ASA, Madison, WI, pp. 663-686. [Context Link]

Chang, J. H. 1968. Climate and Agriculture: An Ecological Survey. Aldine Publishing Company, Chicago, pp. 186-187. [Context Link]

Dierolf, T. S. 1992. Cation movement and management in an Indonesian Ultisol. PhD thesis, University of Hawaii, Honolulu, HI. [Context Link]

Dierolf, T. S, L. M. Arya, and R. S. Yost. 1989. Root distribution in an alley-cropping system. Nitrogen Fixing Tree Research Reports. 7:9-11. [Context Link]

Dierolf, T. S, L. M. Arya, and R. S. Yost. 1997. Water and cation movement in an Indonesian Ultisol. Agron. J. 89:572-579. [Context Link]

Fakultas Pertanian, Universitas Andalas. 1982. Survey tanah dan kesesuaian lahan, Balai Penelitian Tanaman Pangan Sukarami. Lokasi: Sitiung, Sumatra Barat, Sumatra Agriculture Research Project No. 497-0263. [Context Link]

Faybishenko, B. A. 1995. Hydraulic behavior of quasi-saturated soils in presence of entrapped air: Laboratory experiments. Water Resour. Res. 31:2421-2435. [Context Link]

Gerke, H. H., and M. Th. van Genuchten. 1993. A dual porosity model for simulating the preferential movement of water and solute in structured porous media. Water Resour. Res. 29:305-319. [Context Link]

Gill, D. W. 1988. Response of upland crops to potassium at three levels of aluminum saturation in the humid tropics of West Sumatra. Ph.D. thesis. North Carolina State University, Raleigh, NC. [Context Link]

Gill, D. W., and E. J. Kamprath. 1990. Potassium uptake and recovery by an upland rice-soybean rotation on an Oxisol. Soil Sci. Am. J. 82:329-333. [Context Link]

Hillel, D. 1971. Soil and Water: Physical Principles and Processes. Academic Press, New York, pp. 80-81. [Context Link]

Hillel, D. 1980. Applications of Soil Physics. Academic Press, New York, p. 20. [Context Link]

Lambert, J. D. H., and J. T. Arnason. 1980. Nutrient levels in corn and competing weed species in a first year milpa, Indian Church, Belize, C.A. Plant Soil 55:415-427. [Context Link]

Luxmoore, R. J. 1981. Micro-, meso-, and macroporosity of soil. Soil Sci. Soc. Am. J. 45:671-672. [Context Link]

Luxmoore, R.J., P.M. Jardine, G.V. Wilson, J. R. Jones, and L. W. Zelazny. 1990. Physical and chemical controls of preferred path flow through a forested hillslope. *In.* Transport of Water and Solutes in Macropores. M. Th. van Genuchten et al. (eds.). Geoderma (Spec. Issue), vol. 46, pp. 139-154. [Context Link]

Mohanty, B. P., R. S. Bowman, J. M. H. Hendrickx, and M. Th. van Genuchten. 1997. New piecewise-continuous hydraulic functions for modeling preferential flow in an intermittent-flood-irrigated field. Water Resour. Res. 33:2049-2063. [Context Link]

Ritchey, K. D., D. M. G. Souza, E. Lobato, and O. Correa. 1980. Calcium leaching to increase rooting depth in a Brazilian savannah Oxisol. Agron. J. 72:40-44. [Context Link]

Ritchie, J. T. 1981. Soil water availability. Plant Soil 58:327-338. [Context Link]

Rusman, B. 1990. Perbaikan beberapa sifat kimia dan kandungan air tanah podsolik merah kuning Sitiung dengan pemberian kapur pada berbagai kedalaman serta efeknya terhadap perakaran dan hasil jagung. PhD Thesis, Universitas Padjadjaran, Bandung, Indonesia. [Context Link]

Rusman, B., and L. M. Arya. 1988. Observations of corn root growth as affected by subsoil liming and moisture regime. Research Report, TropSoils Project. Center for Soil Research, Bogor, and University of Hawaii, Honolulu, HI. [Context Link]

Rusman, B., L. M. Arya, I. P. G. Widjaja-Adhi, A. Sofyan, and T. S Dierolf. 1989. Effect of deep placement of lime on soil properties, root growth, water availability, and corn production in acid upland soils of Sitiung, West Sumatra, Indonesia. Paper presented at Rapat Teknis, Pusat Penelitian Tanah, Bogor, Indonesia, August 22-24, 1989. [Context Link]

Sanchez, P. 1982. A legume-based pasture production strategy for acid infertile soils of Tropical America. *In* Soil Erosion and Conservation in the Tropics. W. Kussow, et al. (eds.). ASA Spec. Publ. No. 43. ASA, Madison, WI, pp. 97-120. [Context Link]

Soil Research Institute. 1979. Soil survey of the irrigation project area, Sitiung-South Jujuhan (West Sumatra). Agency for Agricultural Research and Development, Ministry of Agriculture, Jakarta, Indonesia. [Context Link]

Subagjo, H. 1988. Volcanic ash influence and characterization of soils on the eastern plain of the Barisan Range between Sitiung-Kotabaru and Bangko, Sumatra. Ph.D. Thesis, North Carolina State University, Raleigh, NC. [Context Link]

Suharta, N., and J. Kimble. 1986. Characterization of selected pedons in Sitiung (West Sumatra) and Kuamang Kuning (Jambi). Mimeo report, Center for Soil Research, Bogor, and National Soil Survey Laboratory, Lincoln, NE. [Context Link]

Taylor, H. M., and B. Klepper. 1978. The role of rooting characteristics in supply of water to plants. Adv. Agron. 30:99-128. [Context Link]

Trangmar, B. B., R. S. Yost, M. Sudjadi, M. Soekardi, and G. Uehara. 1984. Regional variation of selected topsoil properties in Sitiung, West Sumatra, Indonesia. Research Series 026: TropSoils Tech. Rep. No. 1. HITAHR, College of

Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI. [Context Link]

Youngs, E. G., and P. B. Leeds-Harrison, 1990. Aspects of transport processes in aggregated soils. J. Soil Sci. 41:665-675. [Context Link]

Uehara, G., and G. Gillman. 1981. The Mineralogy, Chemistry, and Physics of Tropical Soils with Variable Charge Clays. Westview Press, Boulder, CO, pp. 101-102. [Context Link]

Wade, M. K., D. W. Gill, H. Subagjo, M. Sudjadi, and P. Sanchez. 1988. Overcoming soil fertility constraints in a transmigration area of Indonesia. TropSoils Bull. 88-01: North Carolina State University, Raleigh, NC. [Context Link]

Key words: Humid tropics; soil quality; macroporosity; hydrology; soil management; sustainability of agriculture production

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IMAGE GALLERY

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$$S_{t_2} = S_{t_1} + R - Ro - Et - Dd + Du$$

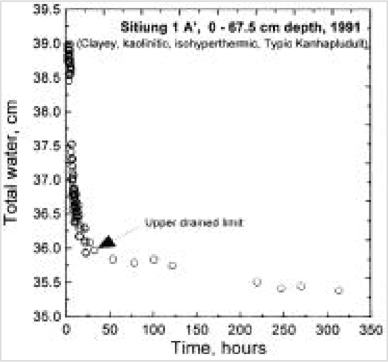
☐ Equation 1

$$Et = S_{t_1} - S_{t_2} + R - Ro - Dd + Du$$

☐ Equation 2

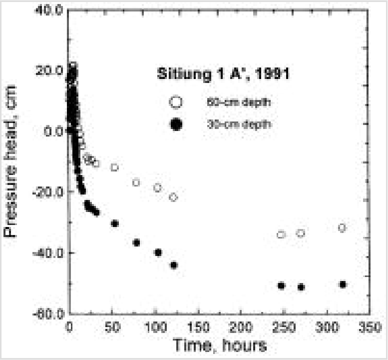
$$Dd' = (R + S_i) - S_m$$

☐ Equation 3

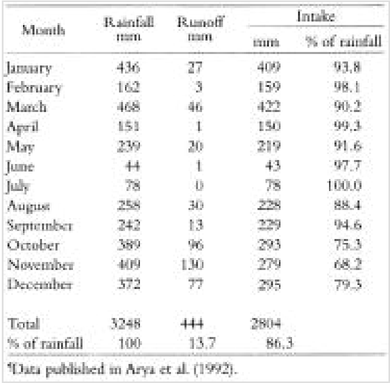


☐ Fig. 1

☐ Table 1



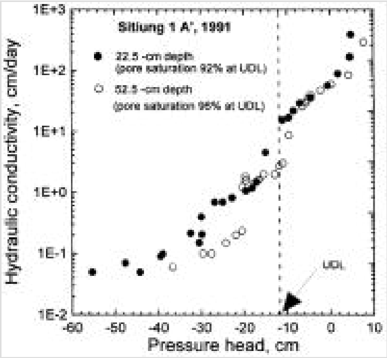
☐ Fig. 2



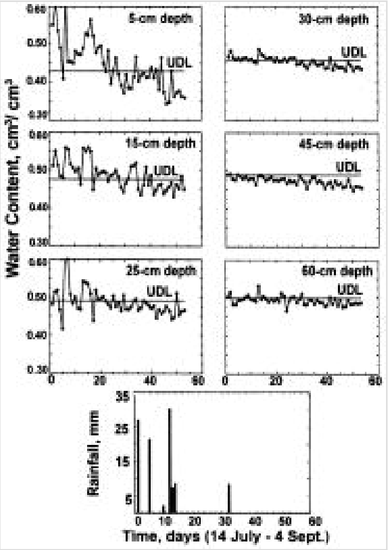
Month	Rainfall mm	Runoff mm	Intake	
			mm	% of rainfall
January	436	27	409	93.8
February	162	3	159	98.1
March	468	46	422	90.2
April	151	1	150	99.3
May	239	20	219	91.6
June	44	1	43	97.7
July	78	0	78	100.0
August	258	30	228	88.4
September	242	13	229	94.6
October	389	96	293	75.3
November	409	130	279	68.2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

[a]Data published in Arya et al. (1992).

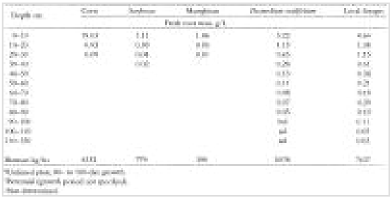
☐ Table 2



☐ Fig. 3



☐ Fig. 4



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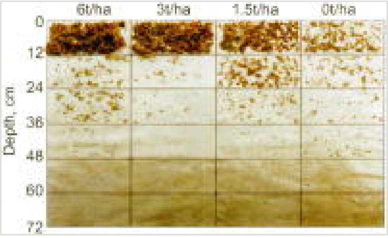

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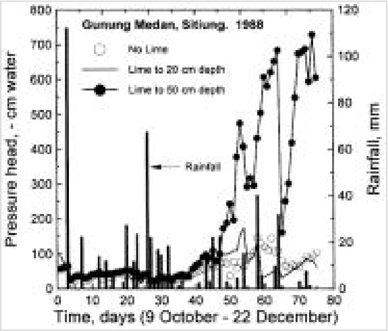

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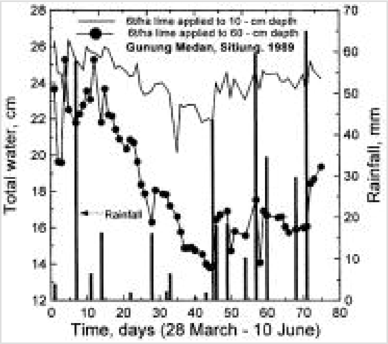
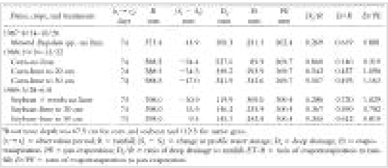


☐ Fig. 7



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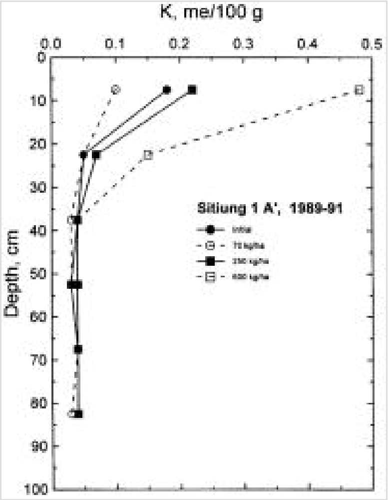

☐ Fig. 8

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