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Notes

Soils in the Toposequence of the Gunung Gadut Tropical Rain Forest, West Sumatra

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Abstract

Chemical, physical, morphological and mineralogical properties of soils in the toposequence of Gunung Gadut tropical rain forest, West Sumatra, were determined. The study area has an annual rainfall of more than 5,000 mm, among the highest in the world, and no real dry season. No water deficit in the soil was found throughout the year. A reconnaissance soil survey revealed a close relation between the distribution of soil types and the topography as well as geologic conditions.

Soils in four permanent plots for study of forest ecology and flora were examined in detail. The Pinang Pinang plot is in a foothill Dipterocarp forest on a gentle hill top with a partly narrow and partly broad ridge at 550 m altitude. Soils were relatively young Typic Dystropepts developed from Quaternary andesite. Although the soils show a prominent red color and strong acidity, adequate nitrogen and base status make them relatively fertile. Clay minerals were kaolin and 2: 1 type vermiculite. The Gajabuih plot is also in a foothill Dipterocarp forest on a northwestern slope near a ridge with moderately steep to undulating relief at 550 m altitude. Soils were Oxic Dystropepts or Orthoxic Tropudults developed from Permian shale and phyllite, which had yellowish brown color and a well-developed structure. Although levels of nitrogen and available calcium seemed to be adequate, Mg was relatively poor in comparison with Ca. Clay minerals were predominantly kaolin and gibbsite. The Airsirah plot is in a hill oak forest on a broad and undulating ridge at 1,100 m altitude. Soils were highly leached and strongly acid Tropudults developed from Quaternary volcanic ash. Soil fertility was low. Clay minerals were spheroidal halloysites. The G. Gadut plot is in a mossy mountain oak forest on a wide plateau at 1,600 m altitude. Soils were extremely infertile Tropaquods developed from Quaternary volcanic ashes. A thick organic horizon was underlain by bleached and extremely leached subhorizons. The C/N ratios were very high. Clay minerals were allophane and imogolite.

Chemical fertility, especially available calcium, correlated well with tree heights. The upper limits of tree height were estimated at 119 m for the Pinang Pinang plot, 109 m for the Gajabuih plot, 51 m for the Airsirah plot, and 38 m for the G. Gadut plot, whereas the measured maximum heights were respectively 59 m, 61 m, 34 m, and 20 m.

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Introduction

Hotta and Ogino, in close cooperation with staff and students of Andalas University, Padang, Indonesia, have been studying the forest ecology and plant taxonomy of the tropical rain forest in the G. Gadut region, West Sumatra [Hotta and Ogino 1984; Ogino 1985]. They have established four plots for field observation at various altitudes from 550 to 1,600 m: Pinang Pinang and Gajabuih plots at 550 m, which have species characteristic of foothill Dipterocarp forest; Airsirah plot at 1,100 m, which has a hill oak forest; and G. Gadut plot at 1,600 m, which has a mossy mountain oak forest.

The authors also conducted soil survey as members of this field survey team. Soil supplies nutrients and water to plants, and thus forest ecosystems are strongly controlled by soil conditions. But little information is available on soil conditions or soil fertility in tropical rain forest [Baillie and Ashton 1983; Burnham 1975].

The G. Gadut region has one of the highest rainfalls in the world, i. e., 5,000-6,000 mm or more a year. Here the soils of the wettest tropical forest can be studied.

This report describes soils of the four permanent plots in the G. Gadut region as well as soils in the surrounding area and in Sumatra, principally from the viewpoint of natural soil fertility. To evaluate fertility, soil morphological, physical, chemical and mineralogical characteristics were investigated. These properties vary with the local topography which, in turn, is related to geologic conditions, and therefore soils are described according to their toposequences on three different scales: soils in Sumatra, soils in the G. Gadut region, and soils in the Pinang Pinang and Gajabuih plots.

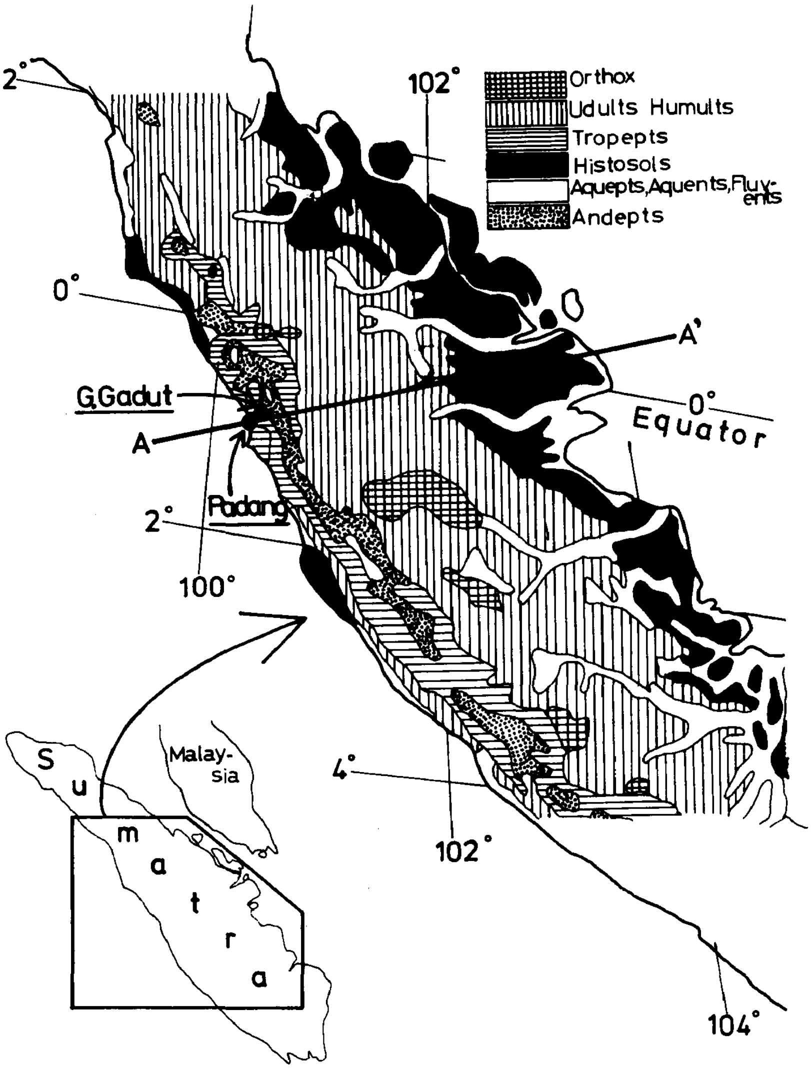


Fig. 1 Generalized soil map of Sumatra. Compiled from FAO-Unesco [1974] and modified according to Soil Taxonomy [USDA Soil Management Support Service 1983].

Soils in Sumatra: General Features of Soil Fertility

Sumatra stretches 1,650 km from Banda Aceh in the northwest to Tanjungkarang in the southeast, is about 400 km wide in the central part and has an area of about 435,000 km^2. Its backbone is formed by the Barisan range which runs along the western side [Nishimura 1980].

Fig. 1 shows a generalized soil map of the central part of Sumatra, which was adopted from an FAO-Unesco soil map of the world [FAO-Unesco 1974] with some generalization and modification by the authors according to Soil Taxonomy [USDA Soil Management Support Service 1983]. Fig. 2 shows the topography of the cross section from Padang along the line A-A' in Fig. 1. Major soil types are distributed in accordance with the three main geomorphic elements of Sumatra: the Barisan range, the central peneplain, and the coastal plain.

The Barisan range has relatively young and fertile soils such as Tropepts and Andepts. Volcanic activity and adequate erosion, which supply fresh, nutrient-rich parent materials, appear to be in a dynamic balance with intensive weathering and leaching, as a result of which relatively fertile soils form.

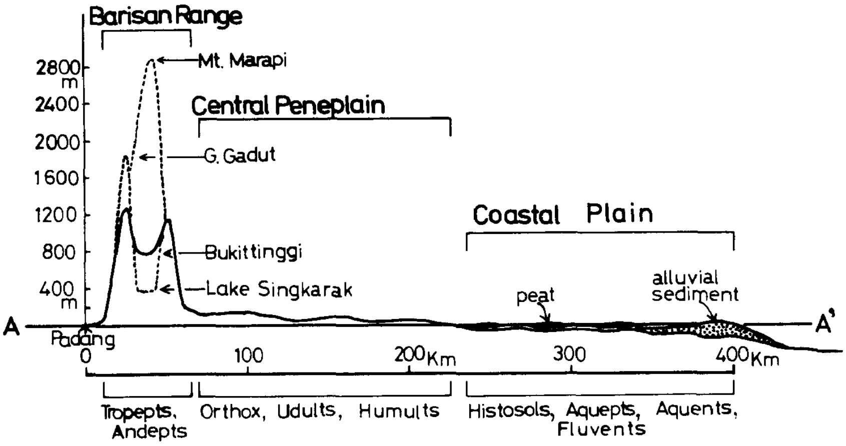


Fig. 2 Topography of the Cross Section from Padang along the Line A-A' in Fig. 1

In the coastal plain the accumulated sediments produce some young and fertile soils such as Aquepts, Aquents and Fluvents, but the stagnation of water results in reduced conditions and the widespread formation of poisonous and infertile Histosols. In addition, soils in this area often have pyritic minerals which produce very acidic conditions upon cultivation.

The central peneplain has old and very infertile soils such as Orthox, Udults and Humults. Soils formed on the stable topography have undergone intensive weathering and prolonged leaching. Furthermore, there is no addition of new parent materials, for this area has neither recent volcanic activity nor adequate erosion and sedimentation processes.

Soils in the Gunung Gadut Toposequence

Fig. 3 is a map of the Gunung Gadut area showing the four plots by double circles and some important places. G. Gadut is located in the Barisan range some 17 km northeast from the center of Padang (Fig. 1). The four plots lie at various altitudes along the Ulu Gadut valley, B-B' in Fig. 3.

1. *Climate*

Temperature: Detailed

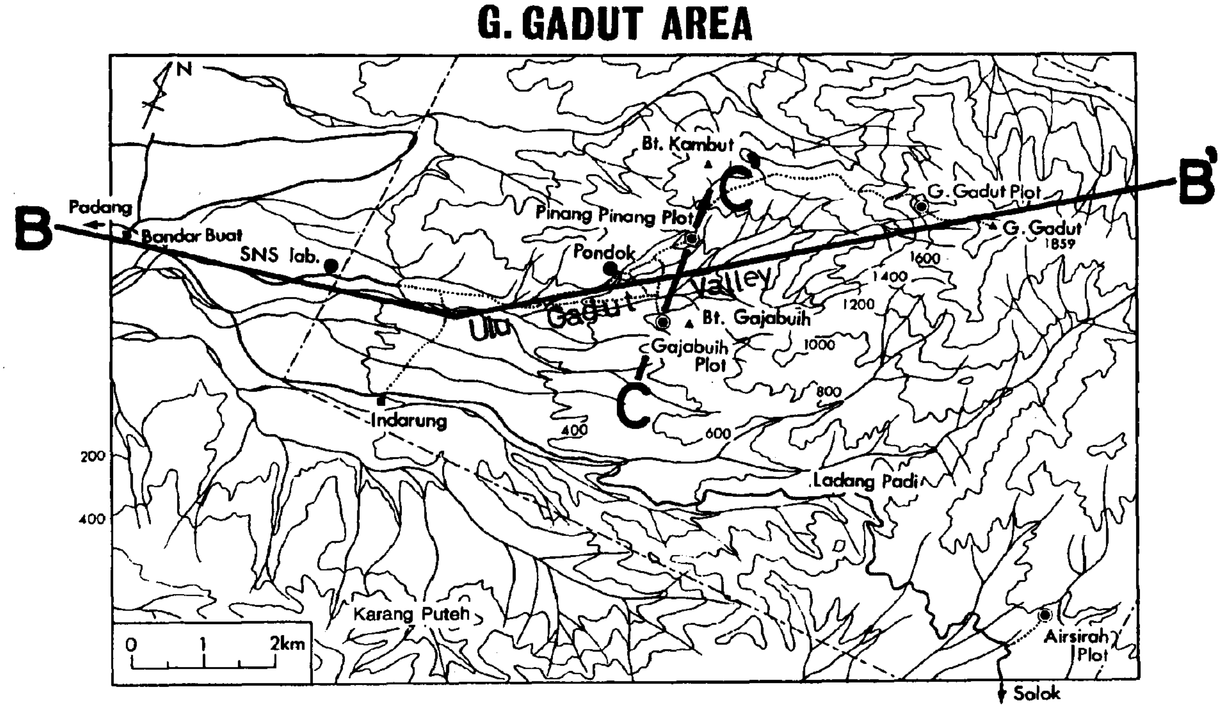


Fig. 3 Topographic map of the Gunung Gadut area showing the four permanent plots (double circles) and some important places. The four plots are Pinang Pinang, Gajabuih, Airsirah and G. Gadut.

climatic data have not been measured at the four plots. However, the major variation in temperature is related to the elevation above sea level. For example, the mean annual (monthly maximum-minimum) temperatures for some important places at various altitudes in Sumatra are reported as follows [Oldeman *et al.* 1979]: Padang at 7 m altitude, 26.9°C (30.4-23.4°C); Pematang Siantar at 400 m, 23.6°C (26.3-20.9°C); Bukittinggi at 920 m, 21.6°C (25.6-17.6°C); Seribu Dolok at 1,400 m, 18.2°C (21.7-14.6°C).

From these relationships, the temperature characteristics of the four plots are estimated roughly as follows: the Gajabuih and the Pinang Pinang plots at 550 m, 23°C (27-19°C); Airsirah plot at 1,100 m, 19°C (22-15°C); G. Gadut plot at 1,600 m, 16°C (19-13°C). The annual difference of monthly mean temperature rarely exceeds 2°C.

Rainfall: Table 1 gives the monthly rainfall data for Padang and Indarung in comparison with those of Singapore. The precipitation at Padang, located on the west coast, is very high. The town of Indarung, 11 km east of Padang at 200 m altitude at the south foot of G. Gadut, has still more rainfall, nearly 6,000 mm. Indarung is situated at the mouth of the Ulu

Table 1 Monthly Rainfall in mm for Padang, Indarung and Singapore

Location	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Indarung	499	368	480	521	450	349	293	425	536	656	715	622	5,914
Padang	361	252	355	409	340	289	250	350	459	573	581	545	4,764
Singapore	285	164	154	160	131	177	163	200	122	184	236	306	2,282

Gadut valley (Fig. 3), the main survey place in this study, where annual precipitation may exceed 7,000 mm [Hotta and Ogino 1984].

2. *Topography*

Fig. 4 shows the topography of the cross sections B-B' and C-C' in Fig. 3. Fig. 5 shows a geomorphological land classification map of the G. Gadut area. Heavy and extremely intense rainfall of more than 60 mm/h is not rare in this area, which has formed very steep mountains (Ml) and well-developed but deeply dissected fans. These are bordered by alluvial plains. As a result, areas occupied by hills, piedmonts and valley plains are small. The Gajabuih plot is located at the lowest end of an Ml unit. The Pinang Pinang plot is in a hill unit (H). The G. Gadut and Airsirah plots are on mountains with moderate relief.

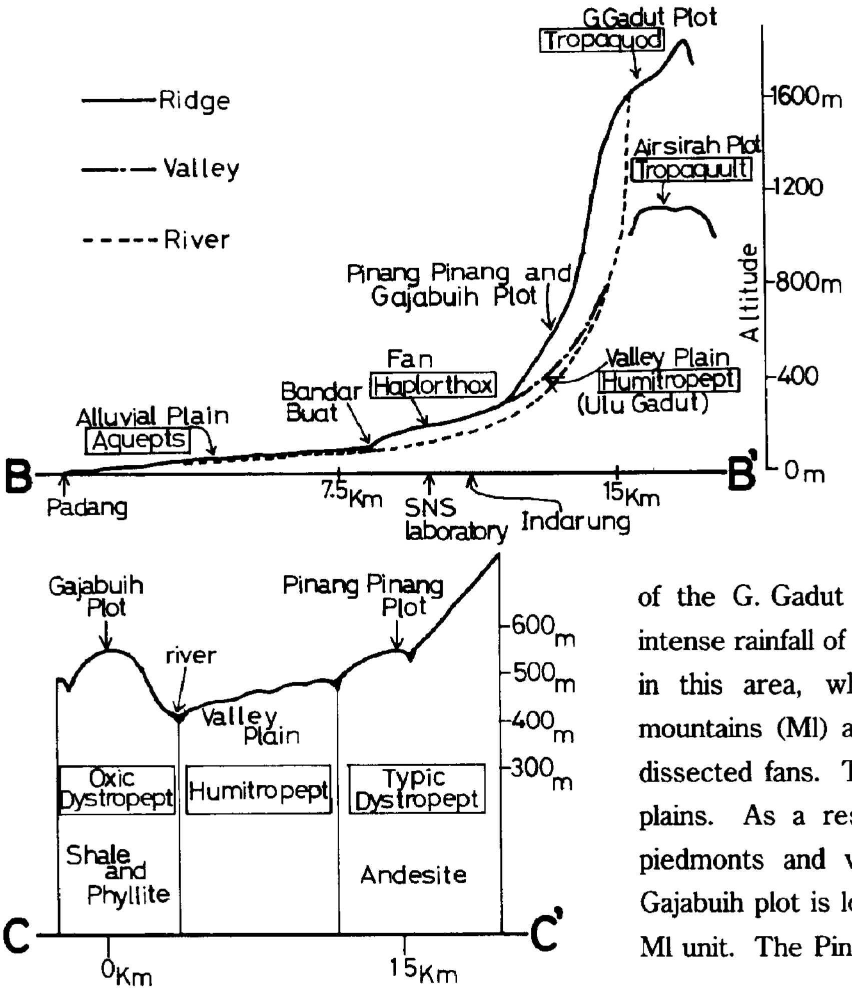


Fig. 4 Toposequences of the Cross Sections B-B' and C-C' in Fig. 3

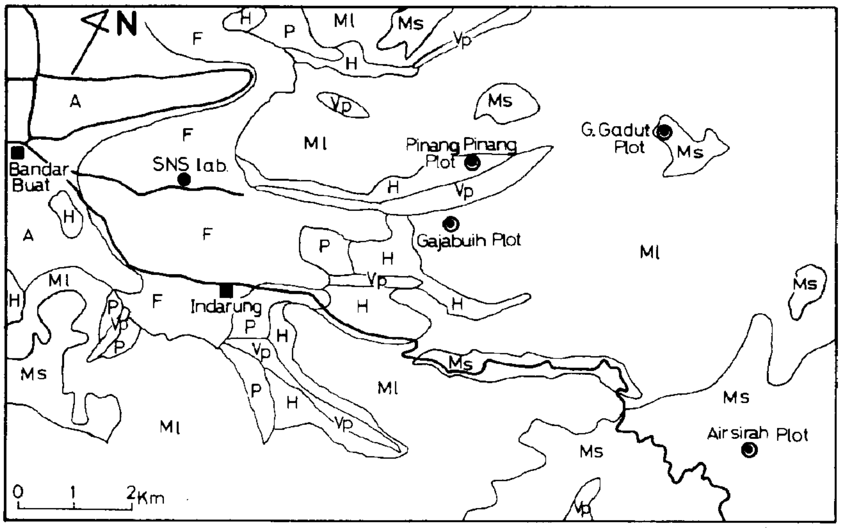


Fig. 5 Geomorphological land classification map of the G. Gadut area. Ml, mountains with relief more than 300 m/km^2; Ms, mountains with relief less than 300 m/km^2; P, piedmonts ; H, hills ; Vp, valley plain ; F, fans ; A, alluvial plain.

Land use is correlated with the geomorphology: alluvial plains for paddy cultivation exclusively; fans for grassland or bare land; valley plains for orchards of durian (*Durio zibethinus*) and mangosteen (*Garcinia mangostana*); hills and piedmonts for shifting cultivation; natural forest remains only in the Ml and Ms mapping units.

3. *Geology*

A geologic map of the G. Gadut area is shown in Fig. 6, which was compiled from the data of Kastowo and Leo [1973], Roshidi *et al.* [1976] and Silitonga and Kastowo [1975]. Since the major parent materials of soils in this area are andesitic or limestone, relatively rich nutrient levels can be expected. However, soil fertility is strongly influenced by not only geology but also topographic conditions.

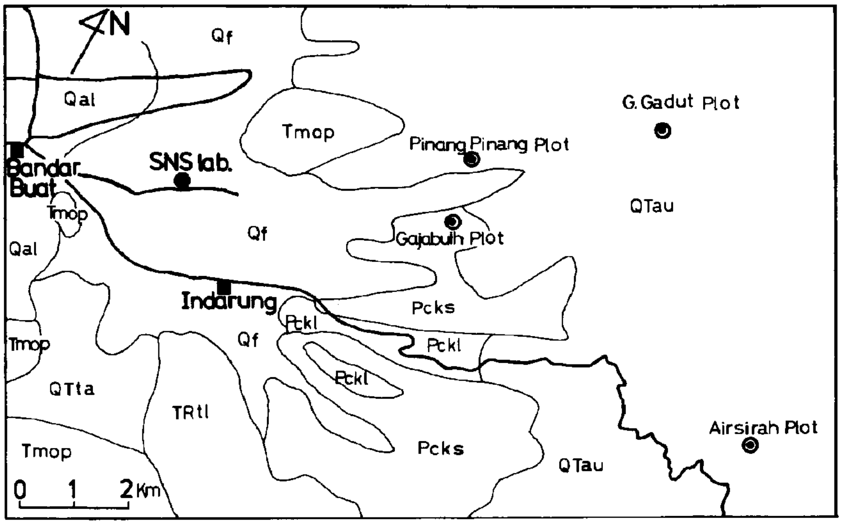


Fig. 6 Geologic map of the G. Gadut area compiled from Kastowo and Leo [1973], Roshidi *et al.* [1976] and Silitonga and Kastowo [1975]. Qal, river alluvium; Qf, alluvial fans; Tmop, Painan formation consisting of volcanic rocks of Oligo-Miocene age; QTta, Quaternary andesite and tuff interbedded; Pckl, phyllite and shale member of the Kuantan formation of the late Middle Permian age; Pcks, limestone member of the Kuantan formation of the late Middle Permian age; TRtl, limestone member of the Thurhur formation of the Triassic age; QTau, undifferentiated volcanic breccia consisting of tuff, lahar and lava flows mostly of andesitic composition, of which the eruption centers have not been located but the eruption time is inferred to be early Quaternary.

4. *Distribution of Soils*

A reconnaissance soil survey map of the G. Gadut area is shown in Fig. 7, which was compiled from the geologic map, geomorphological map and field observations. Soils were classified according to Soil Taxonomy [USDA Soil Management Support Service 1983]. In Fig. 7, solid circles show the sites of soil sampling and double circles show the four plots which were studied in more detail.

The alluvial plain has Tropaquepts and some Plinthaquepts (ITa mapping unit), which are relatively fertile and good soils for paddy cultivation. Sediments and nutrient-rich riverwater make the soils fertile.

Alluvial fans, on the other hand, have developed highly leached soils, Haplorthox and Umbriorthox (OHo unit). Although the surface is rather flat and slightly undulating, the fans are highly dissected as shown in Fig. 3. The contour lines show extreme tonguing at the fans. This means that soils on the fans were subjected to strong weathering and leaching for relatively long periods. Once the fans must have been covered with forests. However, after long use for shifting cultivation, the old and infertile soils have come to support only *alang-alang (Imperata cylindrica)* vegetation.

Piedmonts and hills with moderate relief have relatively leached soils, Tropudults (UTu unit), which are younger than the OHo soils. These soils are used for banana, coconut or irrigated paddy. Shifting cultivation is still observed on these soils.

Valley plains are very important for agriculture, having relatively fertile soils, Humitropepts

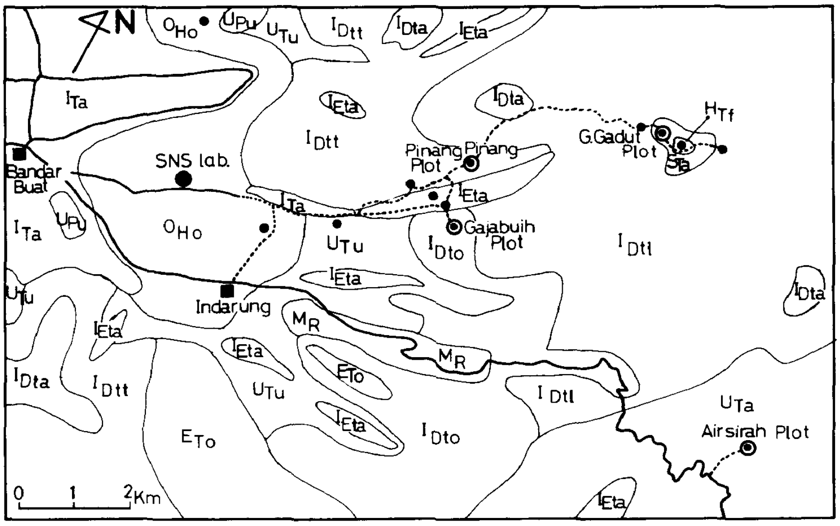


Fig. 7 Soil map of the G. Gadut area according to Soil Taxonomy [USDA Soil Management Support Service 1983]. ITa, Tropaquepts and Plinthaquepts; OHo, Haplorthox and Umbriorthox; UTu, Tropudults; UPu, Paleudults; IEta, Humitropepts; IDtt, Typic and Rhodic Dystropepts; IDto, Oxic and Typic Dystropepts; IDta, Aquic and Oxic Dystropepts; MR, Rendolls (?); ETo, Troporthents and Lithic Rendolls (?); UTa, Aquic Tropudults and Tropaquepts; IDtl, Lithic and Typic Dystropepts; STa, Tropaquods; HTf, Tropofibrists.

(IEta unit), which support durian and mangosteen orchards as well as paddy cultivation.

Andesitic steep mountains (QTta in Fig. 6 and Ml in Fig. 5) have young soils: Typic and Rhodic Dystropepts (IDtt unit), the main types of the Pinang Pinang plot, are present at altitudes lower than 800 m, while Lithic and Typic Dystropepts (IDtl unit) occupy altitudes higher than 800–1,000 m.

The old phyllite and shale (Pcks unit in Fig. 6) mountains with precipitous relief (Ml unit in Fig. 5) have Oxic Dystropepts, which may be the same as the soils of the Gajabuih plot.

Andesitic mountains with moderate relief have more developed soils such as Tropaquults and Aquic Tropudults, which are the soils of the Airsirah plot.

A wide, gently sloping relief at the top of G. Gadut has led to local development of extremely infertile Tropaquods (STa unit) and Tropofibrists (HTf unit) because of the perhumid moisture regime and the relatively low temperature.

Limestone distributed around Indarung may form specific soils including Rendolls (MR unit) or Troporthents and Lithic Rendolls (ETo unit). However, further fieldwork is needed to confirm the identity of these soils.

5. *Soils in the G. Gadut Toposequence*

G. Gadut Plot: Table 2 summarizes the morphological, physical and chemical properties of the typical soils in each of the four plots along the Ulu Gadut valley as shown in Figs. 3 and 4.

The G. Gadut plot is in a mossy mountain oak forest on a relatively wide plateau near the top of G. Gadut, at about 1,600 m above sea level. The soil type is extremely infertile Tropaquod. A thick organic horizon (O) is underlain by a bleached A2 horizon of olive-brown color (0.25Y4/2.6) which has mottling features like B2 and 2B2 horizons. Liquid volume percentages are extremely high, more than 70% throughout the profile. The pH values (H_2O and KCl) of the O and A2 horizons are low with high exchange acidity (1N KCl extractable) as shown in Table 2. However, the horizons under these show only weak acidity.

One of the most prominent characters of this soil is its extremely low content of nutrients such as Ca, Mg and K. As a result, the effec-

Table 2 Properties of Typical Soils in the G. Gadut, Airsirah, Gajabuih and Pinang Pinang Plots

Soil	Depth	Horizon	Color	Structure	Remarks	BD[1] g/cc	Liq.[2] Vol%	Sol.[3] Vol%	Tex-ture	pH H_2O	pH KCl	N %	C/N	Al[4]	Exchangeable Cations				CEC[5]	BS[6] %
															Ca	Mg	K	Na		
															(me/100 g soil)					
G. Gadut Plot	0-8 cm	O	1.6Y3.3/1.9	——	Sapric	0.39	73.5	19.4	SiC	3.8	3.4	0.43	21.6	8.7	1.6	0.66	0.37	0.10	12	23.9
	25-50	A2	0.25Y4/2.6	W M Cr	Mottle	0.49	73.3	24.5	SiC	4.5	4.1	0.12	43.0	8.0	0.1	0.01	0.06	0.03	8.1	1.8
	50-60	B2	2.5Y3.9/2.3	Massive	Mottle	0.55	78.1	21.9	CL	5.5	5.2	0.11	35.0	0.3	0.1	0.01	0.04	0.02	0.4	32.0
	70-80	2B2	0.4Y5.0/4.2	Massive	Mottle	0.67	75.0	24.8	CL	5.3	5.3	0.11	36.6	0.3	0.1	0.01	0.05	0.02	0.4	36.0
	90-100	3C2	4.6Y5.2/2.8	Massive	——	0.64	76.2	23.8	C	5.2	4.5	——	——	1.9	0.1	0.01	0.16	0.11	2.3	16.7
Airsirah Plot	0-4 cm	A11	2.9Y2.9/1.9	M M Cr	——	0.28	77.7	12.7	CL	3.9	3.7	0.52	14.2	9.0	8.5	0.78	0.40	0.14	19	52.3
	20-35	B21t	1.3Y4.4/4.7	M F Abl	Cutan	0.78	62.0	30.0	C	4.7	3.9	0.07	18.0	7.3	0.1	0.01	0.02	0.10	7.5	2.4
	50-65	B22t	9.5YR4.5/5.3	M F Abl	Cutan	0.88	66.9	32.6	C	4.8	3.8	0.03	7.2	9.7	0.1	0.01	0.02	0.07	9.9	1.5
	80-100	C1	8.9YR4.6/4.7	Massive	Mottle	0.76	71.8	27.6	CL	4.6	3.8	0.03	12.9	12	0.1	0.01	0.01	0.06	12	1.1
Gajabuih Plot	0-5 cm	A	9.0YR3.6/2.8	M C Gr	——	0.51	61.3	22.4	C	4.8	4.6	0.70	14.4	1.7	12	0.53	0.34	0.06	15	88.5
	15-25	B1	8.9YR4.2/4.2	M M Sabl	——	0.78	58.9	28.8	C	4.4	4.2	0.23	12.7	3.7	1.2	0.08	0.08	0.05	5.2	27.6
	45-55	B21	8.9YR4.2/4.7	W M Sabl	——	0.91	57.0	33.4	C	4.6	4.0	0.11	12.9	3.4	0.4	0.03	0.03	0.04	3.9	12.1
	95-105	B22	1.6Y4.5/4.5	W M Sabl	——	1.03	55.6	37.2	C	4.7	3.9	0.07	11.8	4.1	0.3	0.06	0.03	0.05	4.5	9.3
Pinang Pinang Plot	0-5 cm	A	8.3YR4.3/4.6	M F Sabl	——	0.53	60.4	22.1	C	4.4	4.3	0.72	13.5	4.4	9.6	1.5	0.42	0.09	16	72.6
	15-25	B1	7.3YR4.9/5.7	M M Sabl	——	0.97	53.5	35.4	CL	4.3	3.9	0.14	13.5	7.0	1.2	0.59	0.07	0.05	8.9	21.4
	45-55	B2	5.0YR5.2/6.8	Massive	——	1.11	52.2	39.7	CL	4.8	4.0	0.06	13.7	6.6	0.8	0.57	0.04	0.08	8.1	18.4
	95-105	C	5.1YR4.5/5.9	Single Gr	——	1.23	49.6	44.4	SCL	4.8	4.0	0.04	10.0	7.2	0.2	0.07	0.04	0.03	7.6	4.5
Valley Plain	0-5 cm	A11	9.5YR2.8/1.9	M M Gr	——	0.40	65.5	18.1	C	6.0	6.0	——	——	0.3	40	3.35	1.21	0.03	45	99.3
	15-25	AB	1.5Y3.9/3.3	W M Sabl	Mottle	0.92	59.3	33.4	C	5.5	4.7	——	——	0.3	5.8	0.74	0.52	0.04	7.3	96.6
	45-55	B11	9.8YR3.9/3.2	Massive	Mottle	1.15	53.6	41.4	C	5.5	4.0	——	——	4.6	1.9	0.45	0.60	0.04	7.5	39.4
	85-95	B12	0.68Y4.0/3.7	Massive	Mottle	1.10	58.8	39.5	C	5.0	4.0	——	——	4.1	1.6	0.61	0.63	0.04	7.1	41.4

1) bulk density (g/cc); 2) liquid volume %; 3) solid volume %; 4) 1N KCl extractable acidity (me/100 g soil); 5) effective cation exchange capacity = sum of exchangeable cations (Al + Ca + Mg + K + Na); 6) percentage of base saturation.

tive CEC (cation exchange capacity calculated as the sum of exchangeable cations) is low, especially in the horizons lower than 50 cm. In addition, the C/N ratios are very high. This shows the retarded decomposition of organic matter, which is a common feature of the organic horizons of Spodosols and Histosols.

The X-ray diffractogram (XRD) in Fig. 8 and transmission electron micrograph (TEM) in Plate 1 indicate that hydrated halloysite (10Å), gibbsite (4.88Å) and cristobalite (4.15Å) are the major clay minerals in the A2 horizon, whereas allophane and/or imogolite are dominant in the lower horizons. Field observations suggest the presence of at least three layers of different parent materials which formed the B2, 2B2 and 3C2 horizons. These indicate that volcanic ashes were the parent materials of soils in the G. Gadut plot.

However, the formation of halloysite in the surface horizon and allophane/imogolite in the lower horizons is not a common profile sequence in volcanic ash soils [Wada 1977]. In addition, the sharp peak at 13.8Å of 25-33 cm depth and the two broad peaks between 14-10Å at 70-80 cm depth are not charac-

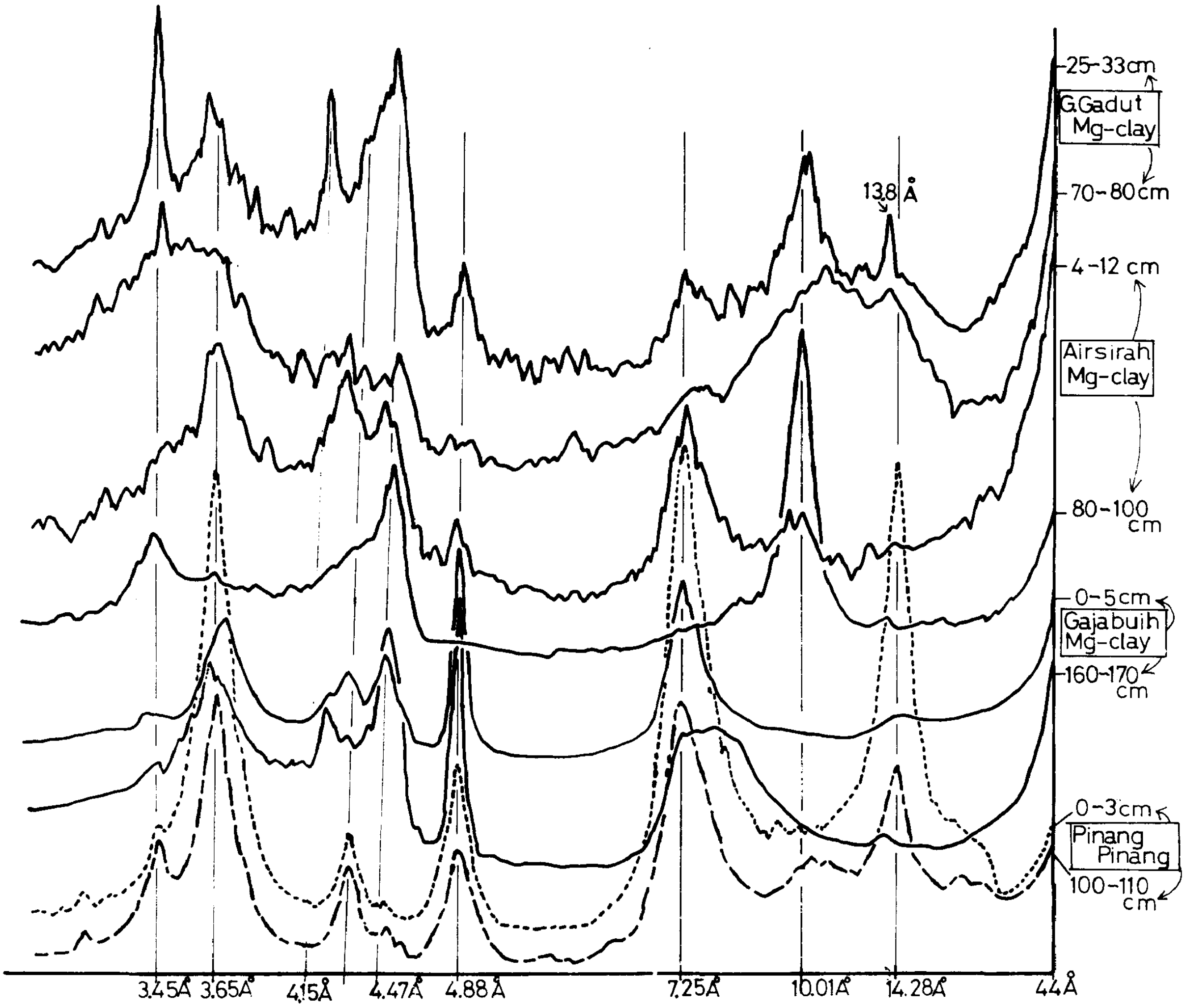
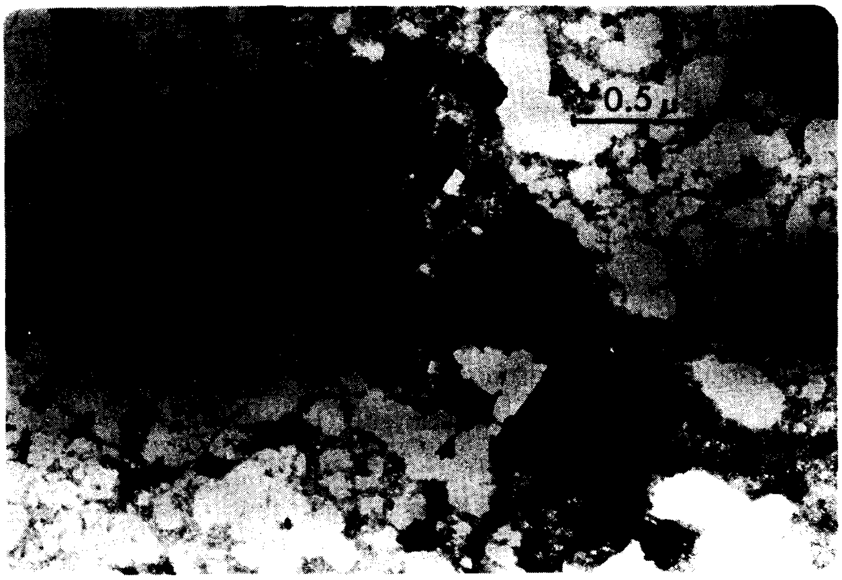


Fig. 8 X-ray Diffractogram of Mg-clay of Upper and Lower Horizons of Soils from the G. Gadut, Airsirah, Gajabuih and Pinang Pinang Plots terized, and need further study.

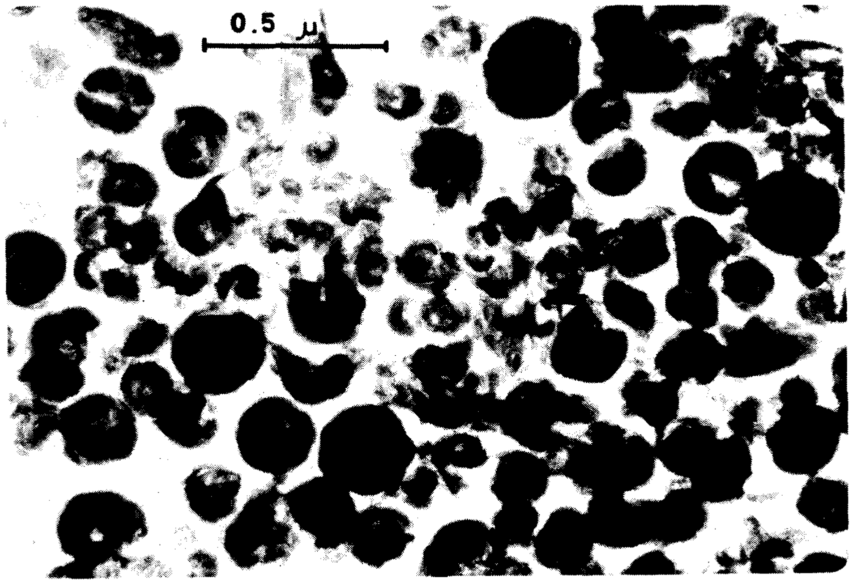
Airsirah Plot: The Airsirah plot is in a hill oak forest on a broad and undulating ridge of the Barisan range near the Airsirah pass. The altitude is about 1,100 m. Typical soil is highly leached and acid Tropudult of low fertility. A brown (9.5YR4.5/5.3) argillic horizon exists at 20-80 cm in the B21t and B22t horizons. Liquid percentages are 60-80%. Acidity is the strongest among the four plots. Levels of nitrogen and exchangeable bases were extremely low below the top 0-4 cm. The XRD and TEM observations in Fig. 8 and Plate 2 indicate the predominant formation of spheroidal halloysites and metahalloysite in the upper horizons and hydrated halloysite in the lower horizons. This suggests that volcanic ashes were the major parent materials of the soil, because there is substantial evidence that halloysite forms as unique spherules with diameters of 0.1-0.5 μm from volcanic ashes of various compositions [*ibid.*; Dixon 1977].

Gajabuih Plot: The Gajabuih plot is in a multi-stratal typical tropical rain forest, abundant in species of foothill Dipterocarp forest, on a northwestern slope near the ridge with moderately steep to undulating relief at about 550 m above sea level. Typical soil is Oxic Dystropept formed from shale and phyllite member in the Permian or older sedimentary rocks. However, if an argillic horizon is proved to be present in this soil, it will be reclassified



G. Gadut. 2B2　　× 50,000

Plate 1 Transmission Electron Micrograph of Clay Fraction of G. Gadut 2B2 Horizon at 70-80 cm Depth



Airsirah. B22t. DBC　　× 75,000

Plate 2 Transmission Electron Micrograph of Clay Fraction of Airsirah B22t Horizon at 50-65 cm Depth as Typic Paleudults or Orthoxic Tropudults.

The effective CEC per 100 g of clay was lower than 24 me (milliequivalent). The XRD shows kaolin and gibbsite in the clay fractions, which are thought to have originated partly from the parent materials.

Katagiri surveyed tropical rain forests and analysed some Oxisols distributed in Jambi, Sumatra, and Sampit, Kalimantan.[1] The effective CEC, base saturation and exchangeable Ca in his samples were only 1.5 (50-110 cm depth) - 3.5 (0-5 cm depth) me/100 g, 10% or so, and 0.05 (50-100 cm depth) - 0.07 (0-5 cm depth) me/100 g respectively. Other reports on Oxisols in Brazil and Africa [Sakuma 1984; Van Wambeke *et al.* 1983] show similar chemical properties to those found by Katagiri.

Compared with the foregoing data, the Gajabuih soils have a far better chemical nature than Oxisols. Their chemical properties are comparable to those of B_A, B_B or B_C types of brown and reddish or yellowish brown forest soils (Dystrochrepts and Oxic Dystrochrepts) in Japan [Arimitsu 1983]; but their moisture status is comparable to or wetter than those of B_E or B_F types of the brown forest soils [*ibid.*].

Pinang Pinang Plot: The Pinang Pinang plot is also in a foothill Dipterocarp forest on a gentle hill top with a partly narrow and partly broad ridge called Bukit Pinang Pinang at about 550 m above sea level. Typical soil is relatively young Typic Dystropept developed from andesitic parent materials. A prominent red color (5.0YR5.2/6.8), strong acidity, and adequate carbon, nitrogen and exchangeable base contents characterize this soil. The CEC per 100 g of clay was more than two times that of Gajabuih. The XRD in Fig. 8 shows Al-vermiculite and kaolin as major clay minerals. These results suggest that soils in the Pinang Pinang plot are younger and more fertile than those of Gajabuih.

Valley Plain: Table 2 lists some data of a soil in the valley plain. The soil was sampled at the foot of the Gajabuih plot near the river along the C-C' line in Figs. 3 and 4. The altitude is ca. 420 m. Although the soil has an aquic character (mottling), its chemical fertility is very high; the sum of exchangeable bases is higher than 3 me/100 g of soil throughout the profile.

6. *Soil Fertility and Forest Profile in the Four Plots*

Hotta and Ogino [1984] have described forest profiles in the four plots. The Pinang Pinang plot has three strata of high trees, excluding trees smaller than 9 cm in diameter at breast height (DBH): the emergent tree stratum has a height of 52-59 m, the subprominent tree stratum is 20 m in average height. Emergent trees of Dipterocarpaceae have disappeared. But huge cut stumps scattered over the forest floor suggest that the vegetation was once dominated by species of Shorea (Dipterocarpaceae). The Gajabuih plot has a similar basic structure to the Pinang Pinang plot. The emergent tree stratum is 50-61 m in height. In the Airsirah plot, two strata were recognized. The upper stratum is 25-34 m in height. The stand structure of the G. Gadut plot is basically the same as that of the Airsirah plot, but the first stratum is only 20 m in height.

Kira and Yamakura have induced an equation for the upper limit of tree height in tropical rain forest [Kira 1983]:

$$H^* = 5.0\,P + 2.2\,T + 8.4\,C - 62.$$

---

[1] Personal communication from S. Katagiri, 1983.

Where H* is the upper limit of tree height (m),

P is the number of months per year with rainfall higher than 100 mm,

T is the mean annual temperature and

C is the total calcium content (ton per hectare).

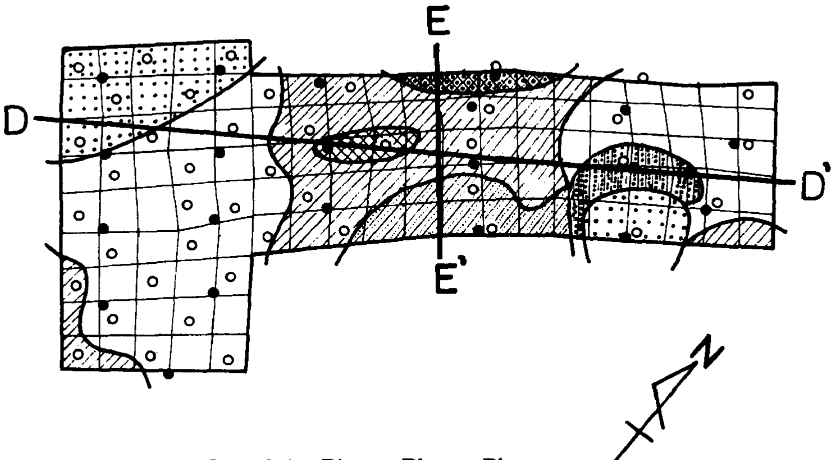


Fig. 9-A　Soil Map of the Pinang Pinang Plot

The exchangeable calcium in the four plots can be calculated based on the data in Table 2;

1.72 ton/ha for Pinang Pinang plot,
1.46 ton/ha for Gajabuih plot,
0.26 ton/ha for Airsirah plot and
0.12 ton/ha for G. Gadut plot.

The ratio of the total calcium to exchangeable calcium varies depending on the type of soil. However, the range is normally 2-14 and the mean is 4.9 [Kawaguchi and Kyuma 1977; Tsutsumi 1973]. We can roughly estimate the total calcium contents in the four plots using the conversion factor of 4.9; i. e.,

8.4 ton/ha for Pinang Pinang plot,
7.2 ton/ha for Gajabuih plot,
1.3 ton/ha for Airsirah plot and
0.6 ton/ha for G. Gadut plot.

The upper limit of tree height in each plot can then be calculated as follows:

H*(m) of Pinang Pinang
$=60+50.6+70.6-62=119,$

H*(m) of Gajabuih
$=60+50.6+60.5-62=109,$

H*(m) of Airsirah
$=60+41.8+10.9-62=51$ and

H*(m) of G. Gadut
$=60+35.2+5.0-62=38.$

The upper limit of height in each plot is compared well with the height of the forest profile; actual maximum height of 59 m or higher compared to the H* of 119 m for the Pinang Pinang plot; 61 m vs. 109 m for the Gajabuih plot; 34 m vs. 51 m for the Airsirah plot; and 20 m vs. 38 m for the G. Gadut plot.

The value of H*, and maybe the growth of forest, seems to be mainly determined by the soil chemical fertility, which could be described simply by the total calcium contents.

Soils in the Pinang Pinang and Gajabuih Plots

1. *Soils in the Pinang Pinang Plot*

A detailed soil map and toposequences along the cross sections D-D' and E-E' are shown in Figs. 9-A and 9-B. Fig. 10 shows topographical maps of the four plots. Although the total area of the Pinang Pinang plot is only 1.0 ha, three different soil subgroups were recognized, which were further subdivided into seven families, or series, according to their specific properties. The major subgroup was a Typic Dystropept, which was subdivided based on the differences of parent materials, texture, soil depth, degree

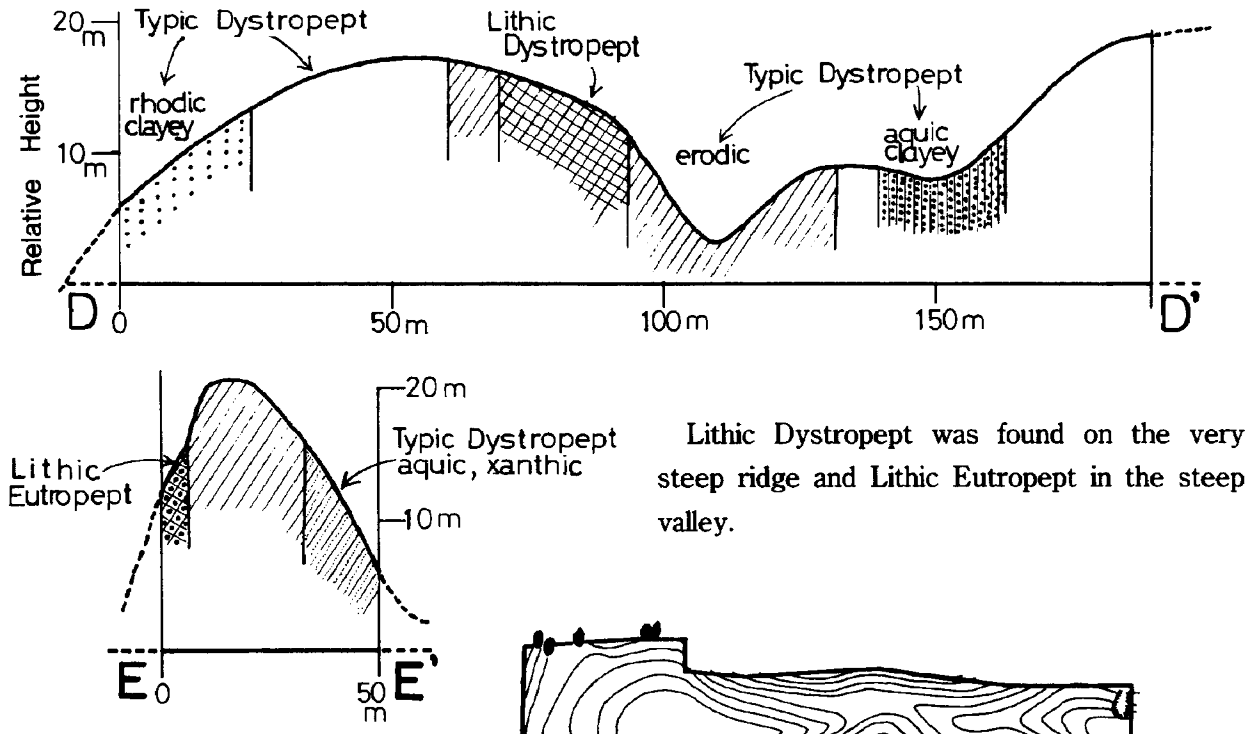


Fig. 9-B Toposequences along the Cross Sections D-D' and E-E'

of erosion and/or color.

On the broad ridge, andesite formed Typic Dystropept, fine loamy-clay, with relatively deep soil profile. On the concave slope, water and nutrients accumulate forming a Typic Dystropept of aquic and xanthic nature. On the ridge, erosion affects soil formation, and a Typic Dystropept with relatively shallow soil depth was formed.

At the western corner of the plot are limestone pinnacles, shown by black spots in Fig. 10, which formed heavy clay and deep red soil; Typic Dystropept, rhodic and clayey. On the broad concave valley, Typic Dystropept formed which was aquic and clayey with mottling features.

Lithic Dystropept was found on the very steep ridge and Lithic Eutropept in the steep valley.

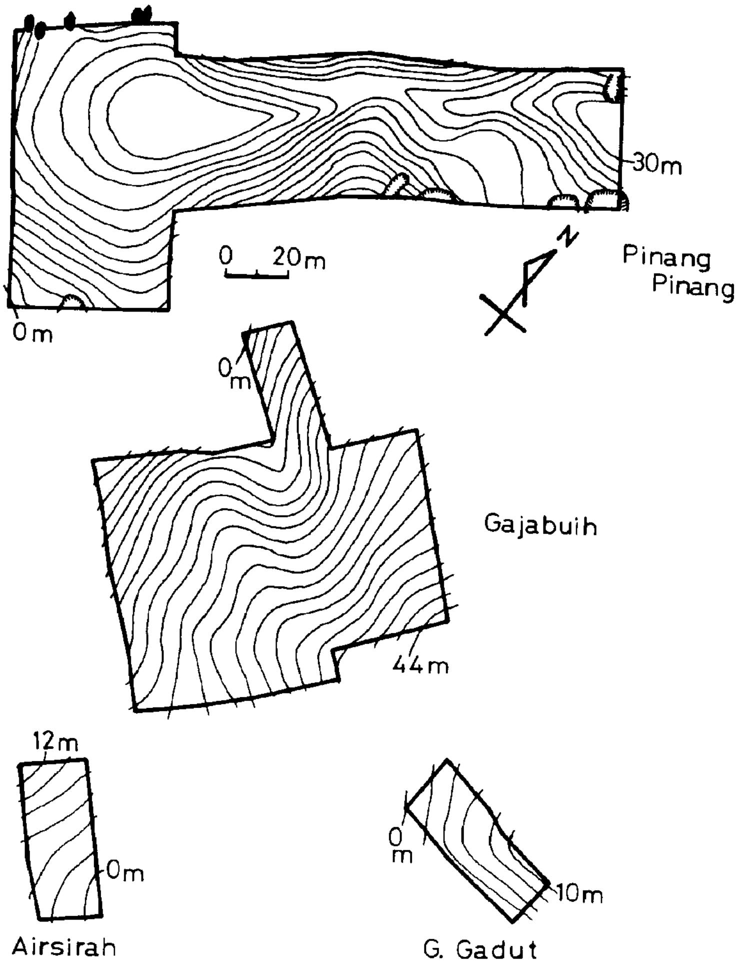


Fig. 10 Topographical maps of the Pinang Pinang, Gajabuih, Airsirah and G. Gadut plots. Contour lines represent intervals of 2 m of relative height.

Table 3 Summary of Soil Properties in the Gajabuih and Pinang Pinang Toposequences

	Soil	Depth	Color	BD[1]	Liq.[2]	Sol.[3]	Tex-	pH	pH	Al[4]	Ca	Mg	K	Na	CEC[5]	BS[6]
				g/cc	Vol%	Vol%	ture	H_2O	KCl			(me/100 g soil)				%
Gajabuih Plot	Oxic-Typic Dystropept (ridge)	0-5 cm	1.5Y3.9/3.1	0.54	60.8	25.5	C	4.4	4.3	1.5	10.8	0.31	0.44	0.05	13	88.6
		15-25	8.9YR4.2/4.7	0.72	60.8	27.0	C	4.1	4.0	5.7	0.79	0.06	0.12	0.04	6.7	15.0
		45-55	8.0YR4.1/5.5	0.96	54.7	34.9	C	4.4	3.9	5.3	0.09	0.01	0.02	0.05	5.5	3.1
		95-105	8.0YR4.3/5.5	1.05	53.7	37.7	C	4.5	3.8	5.6	0.08	0.01	0.02	0.07	5.7	3.1
	Oxic Dystropept (slope)	0-5 cm	9.0YR3.6/2.8	0.52	60.1	22.2	C	4.8	4.6	2.1	11.3	0.42	0.28	0.07	14	85.3
		15-25	8.9YR4.2/4.2	0.81	56.8	29.8	C	4.5	4.1	3.1	0.81	0.04	0.06	0.06	4.0	24.0
		45-55	8.9YR4.2/4.7	0.91	56.6	33.3	C	4.6	4.0	2.7	0.30	0.02	0.03	0.05	3.1	12.7
		95-105	1.6Y4.5/4.5	1.03	54.9	37.4	C	4.8	3.9	3.3	0.22	0.07	0.04	0.06	3.7	10.5
	Oxic Dystropept aquic, eutric (valley)	0-5 cm	0.38Y3.4/2.6	0.38	68.0	18.0	C	5.6	5.5	0.3	16.7	1.00	0.55	0.04	19	98.4
		15-25	1.1Y4.3/4.2	0.75	65.7	27.7	C	4.8	4.2	1.6	4.05	0.35	0.12	0.03	6.1	73.8
		45-55	1.6Y4.2/4.5	0.83	64.0	30.8	C	4.7	4.0	3.0	1.28	0.10	0.05	0.02	4.5	32.3
		95-105	1.3Y4.6/4.7	0.96	62.6	34.9	C	5.0	4.0	4.9	0.96	0.11	0.03	0.02	6.1	18.5
Pinang Pinang Plot	Lithic Dystropept (narrow ridge)	0-5 cm	9.6YR4.0/3.9	0.70	49.5	29.2	SCL	4.1	4.0	3.1	6.37	1.13	0.31	0.02	11	71.9
		15-25	8.0YR4.9/5.5	1.10	42.8	40.8	SCL	4.1	4.0	4.8	0.16	0.03	0.04	0.01	5.0	4.8
		40-50	7.6YR5.1/7.0	1.35	33.0	42.0	SCL	4.4	4.0	6.9	0.05	0.02	0.03	0.01	7.0	1.6
		50-60	8.0YR4.8/5.5	1.25	47.8	43.8	SL	4.4	4.0	6.3	0.17	0.06	0.03	0.01	6.6	4.1
	Lithic Eutropept (steep slope)	0-5 cm	2.1Y3.7/2.3	0.50	65.7	20.8	L	5.5	5.3	0.3	14.8	3.32	0.58	0.02	19	98.4
		15-25	1.1Y4.4/4.2	1.55	34.0	54.0	SCL	4.8	3.7	6.8	4.04	5.15	0.14	0.05	16	58.0
		30-40	2.8Y4.5/3.7	1.50	36.3	53.6	SL	5.7	3.8	3.0	7.48	6.79	0.06	0.06	14	82.6
	Typic Dystropept (broad ridge)	0-5 cm	9.2YR4.5/4.6	0.52	56.9	21.6	C	4.4	4.2	5.9	8.50	0.94	0.34	0.10	16	62.8
		15-25	8.0YR4.9/6.0	0.96	52.6	33.9	CL	4.1	3.9	8.4	0.66	0.14	0.08	0.06	9.3	10.1
		45-55	6.8YR5.0/6.5	1.15	50.9	41.8	CL	4.7	4.0	7.8	0.20	0.02	0.05	0.15	8.2	5.1
		95-105	6.6YR4.7/5.8	1.31	45.9	46.7	SCL	4.8	4.0	7.9	0.17	0.06	0.06	0.04	8.2	4.0
	Typic Dystropept rhodic, clayey	0-5 cm	7.8YR3.8/3.3	0.58	59.0	24.0	C	4.8	4.7	0.7	13.6	1.46	0.35	0.05	16	95.5
		15-25	5.1YR4.7/5.9	1.00	54.2	36.2	C	4.6	4.0	5.4	2.43	0.36	0.04	0.04	8.3	34.5
		45-55	4.6YR4.6/6.2	1.10	53.9	39.2	C	4.8	4.0	5.7	0.50	0.09	0.02	0.02	6.3	10.0
		95-105	3.0YR4.4/6.8	1.18	50.4	42.7	C	4.9	3.9	7.3	0.16	0.02	0.02	0.02	7.5	2.9

Pinang Pinang Plot	Typic Dystropept aquic, clayey	0-5cm	9.4YR4.1/3.9	0.40	70.7	17.4	C	3.8	4.0	7.9	7.54	1.34	0.55	0.18	18	54.9
		15-25	7.9YR4.9/5.5	0.74	62.0	28.4	C	4.2	3.9	8.2	0.05	0.01	0.06	0.08	8.4	2.4
		45-55	6.6YR5.1/6.6	0.89	62.8	32.9	C	4.7	4.0	7.9	0.05	0.01	0.04	0.12	8.2	2.7
		95-105	4.6YR4.6/6.2	1.15	57.5	41.1	C	5.0	3.9	9.6	0.35	0.09	0.02	0.05	10	5.0
	Typic Dystropept aquic, xanthic	0-5cm	1.3Y5/6	0.56	59.6	23.4	C	4.9	4.5	2.6	12.9	2.60	0.52	0.18	19	86.4
		15-25	10YR5/6	0.87	59.1	32.3	C	4.7	4.2	4.3	3.69	0.69	0.11	0.09	8.9	51.3
		45-55	8.8YR5.0/5.4	1.02	58.0	36.6	C	4.9	4.2	5.6	0.70	0.15	0.04	0.08	6.6	14.7
		95-105	8.1YR5.0/5.5	1.12	55.2	40.8	C	5.1	4.2	6.0	0.36	0.15	0.03	0.05	6.6	8.9
	Typic Dystropept erodic	0-5cm	0.9Y4.1/3.8	0.48	64.7	26.1	C	3.9	3.8	7.7	5.08	1.08	0.47	0.05	14	46.7
		15-25	8.7YR5.1/6.5	0.83	60.0	40.4	CL	4.2	4.0	7.6	0.16	0.09	0.07	0.02	7.9	4.3
		45-55	8.1YR5.1/6.0	0.98	59.0	42.2	SL	4.7	4.0	6.8	0.13	0.07	0.02	0.02	7.0	3.4
		95-105	8.1YR4.9/5.6	1.23	51.4	45.4	SL	4.8	4.0	6.1	0.20	0.07	0.03	0.02	6.4	5.0

1) bulk density (g/cc); 2) liquid volume %; 3) solid volume %; 4) 1N KCl extractable acidity (me/100 g soil); 5) effective cation exchange capacity=sum of exchangeable cations; 6) percentage of base saturation.

2. *Soils in the Gajabuih Plot*

A detailed soil map and the toposequence along the cross section F-F' are shown in Figs. 11-A and 11-B. Since the parent materials are shale and phyllite of the Permian age, the red coloration is weaker and the texture is heavier than in the soils of the Pinang Pinang plot.

Three different soil families were recognized according to the topographical positions: Oxic-Typic Dystropept, xanthic but slightly redder than the other soils, on the ridge; Oxic Dystropept, xanthic, eutric and aquic nature, on the broad concave valley; Oxic Dystropept, intermediate in character, at intermediate positions.

3. *Soil Properties in the Pinang Pinang and Gajabuih Toposequences*

Table 3 summarizes soil properties in the Gajabuih and Pinang Pinang toposequences.

Although red coloration is prominent in the ridge position in each toposequence, the effect

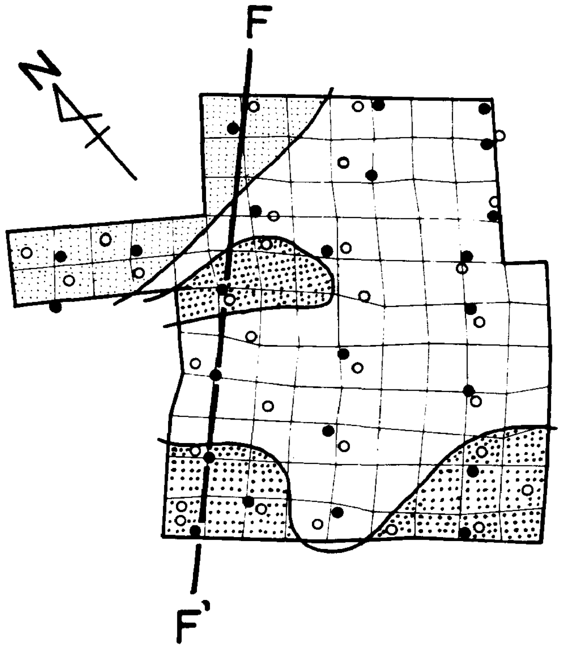


Fig. 11-A Soil Map of the Gajabuih Plot

of parent materials is also strong, with redder color of the B horizons developing as follows: limestone > andesite > shale.

Bulk density (BD) shows a reverse correlation with liquid volume percentages. The BDs were generally lower than 1.0 g/cc, which indicates good physical structure. However, the Lithic Dystropept and Eutropept in the Pinang Pinang plot have BD higher than 1.3-1.5 g/cc, which indicates physical conditions so poor as to prevent root growth.

There is a clear tendency for nutrients to be distributed deeper in the soil profiles in the valleys than on the ridges. As a result, pH values and base saturation increase.

One prominent feature of the soil profiles in both plots is nutrient accumulation in the surface horizons. This suggests intense and effective nutrient cycling through the forest ecosystems.

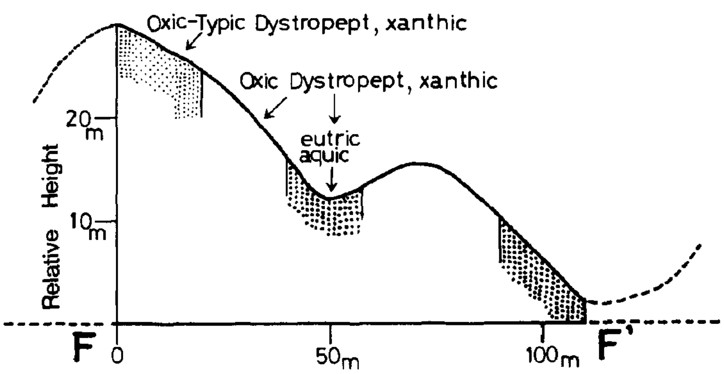


Fig. 11-B Toposequence along F-F' in the Gajabuih Plot

Table 4 Chemical Composition of Leaves, Bark and Earthworm Feces Collected from the Pinang Pinang and Gajabuih Plots

	Ca	Mg	K	Na	Ca/Mg	N
	(me/100 g	dry	matter)		Ratio	%
Pinang Pinang						
Leaf (n=13)	123	29	33	0.039	4.2	—
Bark (n=14)	134	7.5	15.6	0.026	18	—
Earthworm						
Feces (n=3)	46	7.9	0.83	0.14	5.8	1.6
Gajabuih						
Leaf (n=18)	133	16.7	22	0.41	8.0	—
Bark (n=18)	183	6.7	9	0.26	27.3	—
Earthworm						
Feces (n=3)	39	2.5	0.78	0.04	15.6	1.2

Table 4 shows the chemical composition of leaves, bark and earthworm feces collected from the Pinang Pinang and Gajabuih plots. The contents of calcium, magnesium and potassium in leaves and bark were more than 10 times those in the 0-5 cm horizons. Earthworms and other soil animals consume this plant litter and excrete very fertile fecal materials, as shown in Table 4, which can be termed natural ball fertilizers. The morphology and size of feces collected at the plots are shown in Fig. 12. Numbers 14 and 15 in Fig. 12 are the earthworm feces analysed in Table 4. The origins of the others were not identified.

The exchangeable Ca/Mg ratios of the surface horizons in the Gajabuih plot were more than three times higher than those in the Pinang Pinang plot. That in the Gajabuih plot was 17-35, mean 23, whereas that in the Pinang Pinang plot was 3-9.6, mean 6.0. The same difference appears in leaves, bark and earthworm feces as shown in Table 4. That in the Gajabuih plot was 8-27, whereas that in the Pinang Pinang plot was 4-18.

Bowen [1966; 1979] reported a total Ca/Mg ratio of 2-9, mean 5.5, in terrestrial plants. Kawaguchi and Kyuma [1977] reported the mean ratio of exchangeable Ca/Mg of paddy

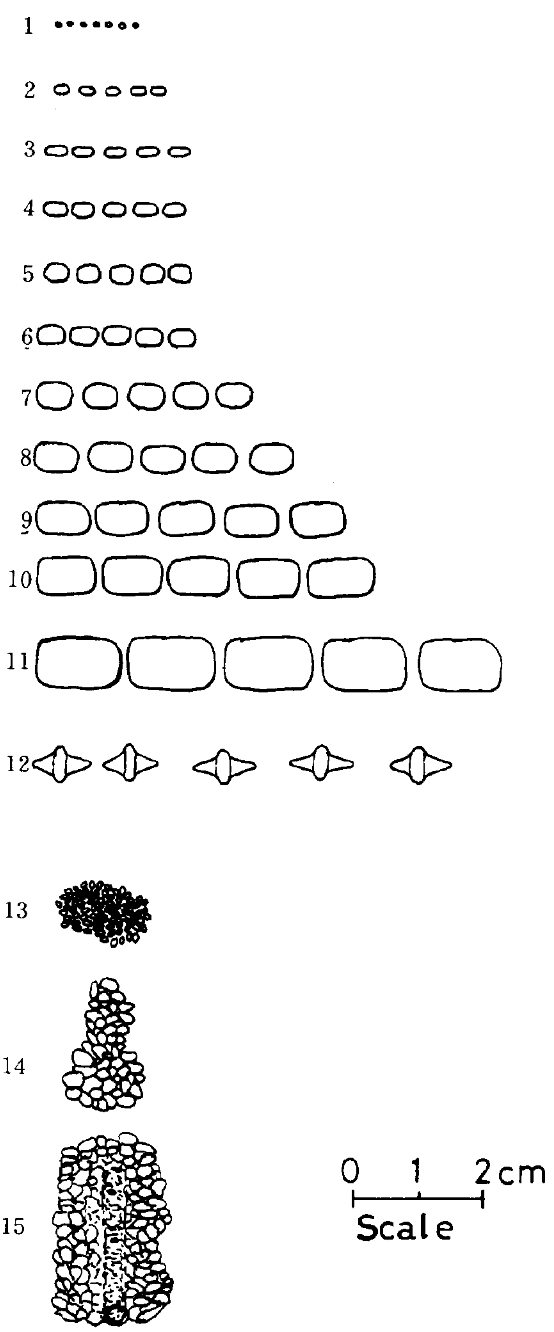


Fig. 12 Morphology and Size of Fecal Materials Collected from the Forest Floor at the Gajabuih and Pinang Pinang Plots

soils in tropical Asia to be 1.9, while Arimitsu [1983] reported a value of 4.1 for brown forest soils in Japan. These data suggest that soils in the Gajabuih plot have an abnormally high Ca/Mg ratio, probably as the result of a low level of Mg.

This Ca/Mg imbalance has, however, produced no observable effect on the forest ecosystem. The reason for the imbalance is not clear. One possibility is an influx of calcium-rich dust from a concrete factory in the town of Indarung. As shown in Fig. 3, the Gajabuih plot is nearer to Indarung than the Pinang Pinang plot.

Soil Moisture Dynamics in the Pinang Pinang and Gajabuih Plots

Rainfall data shown in Table 1 demonstrate the extremely wet condition of the G. Gadut area throughout the year. Even in the driest month, rainfall in the plots should be higher than in the month of highest rainfall in Singapore. Nieuwolt [1965] concluded that there was no water deficit in Singapore. But by calculating the water balance from monthly measurements over three years, Nieuwolt found that short periods of deficit occurred when the monthly rainfall was less than 150 mm [*ibid.* (cited from Whitmore [1975: 48])]. However, as shown in Table 1, even the lowest monthly rainfall should be higher than 300 mm in all the four plots. This suggests that there is also no water deficit in soils. This conclusion was confirmed by the direct measurement of seasonal changes of soil moisture status.

More than 50 gypsum block soil moisture sensors were buried at depths of 15 and 45 cm in the Gajabuih plot and another 50 were buried in the Pinang Pinang plot. Their locations are shown by white circles in Figs. 9-A and 11-A. Soil moisture measurements were carried out at intervals of 2-3 weeks.

The results are summarized in Fig. 13. The

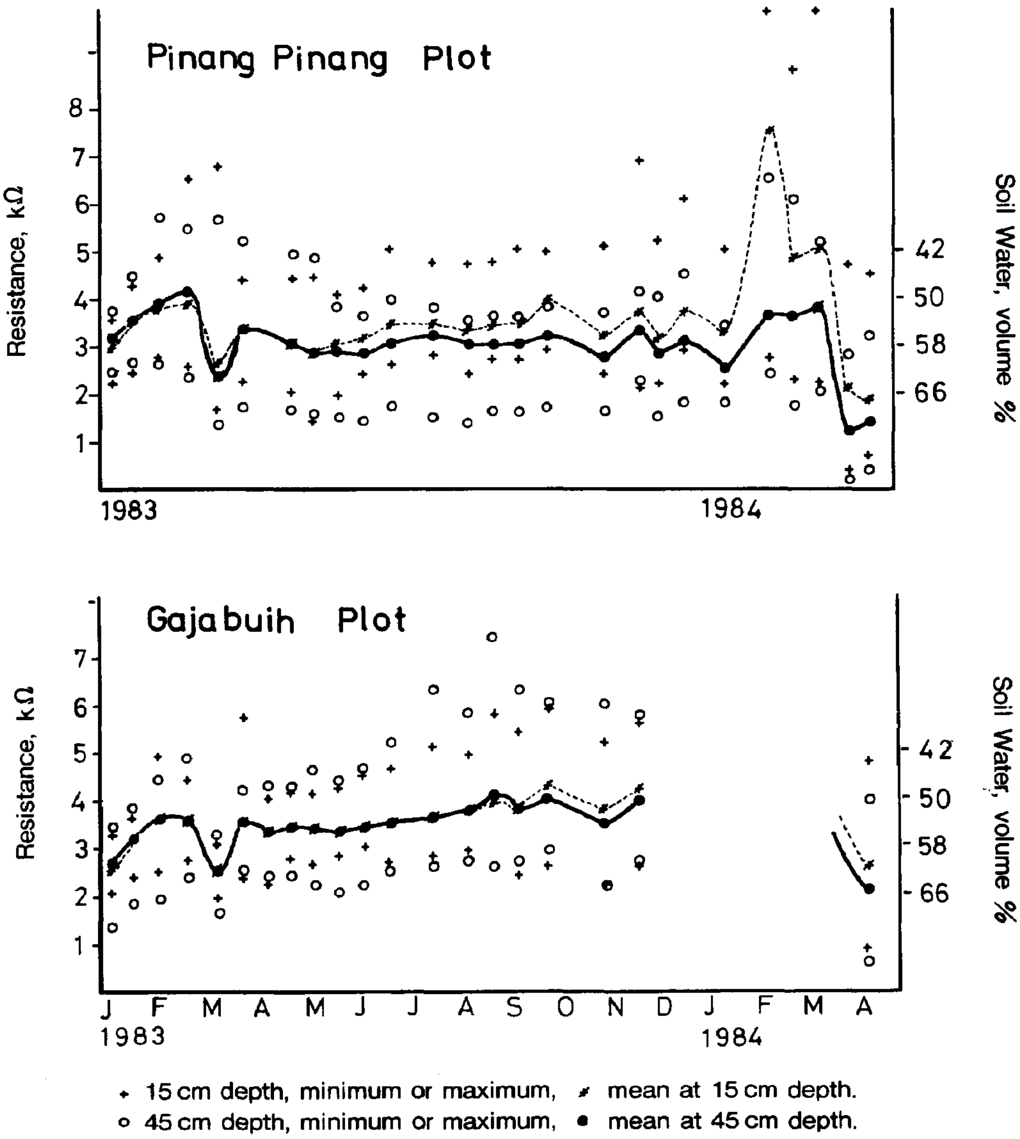


Fig. 13 Soil moisture dynamics in the Pinang Pinang and Gajabuih plots. Gypsum soil moisture sensors were buried at depths of 15 and 45 cm at the locations shown by white circles in Figs. 9-A and 11-A. The solid and broken lines are mean values at 45 and 15 cm depth respectively. Resistances in kΩ are also converted to volume percentages.

solid and broken lines are mean values at 45 cm and 15 cm depth respectively, and the wettest and driest readings at 15 cm (+) and 45 cm (○) are also shown. The resistance readings are roughly converted to soil water volume percentages on the vertical axis.

The seasonal variations were small in both plots. Mean soil water percentages were higher than 50% by volume, which means that there was no water deficit throughout the year. February was the driest month, while the following months, March and April, were the wettest. From July to September, readings at Gajabuih showed relatively dry conditions. These trends were in accord with the general monthly rainfall pattern, but absolute differences were so small that no water deficit would be expected in either plot.

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