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PHYSICAL AND CHEMICAL PROPERTIES OF SOILS IN THE FIRE-AFFECTED FOREST OF EAST KALIMANTAN, INDONESIA

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SEKI K, SUZUKI K, NISHIMURA T, MIZOGUCHI M, IMOTO H & MIYAZAKI T. 2010. Physical and chemical properties of soils in the fire-affected forest of East Kalimantan, Indonesia. The ecological recovery of Dipterocarpaceae forest in East Kalimantan, Indonesia, after the forest fire in 1997–1998 was studied. Soil physical and chemical properties of the plots—heavily damaged by forest fire (HD), lightly damaged by fire (LD) and control site not burned by fire (K)—were investigated eight to nine years after the fire. Soil water content was monitored for one year in the HD and K plots. The white sand layer found in the HD plot had low water retention and high permeability. Therefore, soil was not saturated in the surface sandy layer during rainfall and water infiltrated quickly into the subsurface layer. Such sandy soil, often found in kerangas forest, generally has low pH and low nutrient availability. However, the sandy soil in the HD plot had higher pH and lower electrical conductivity (EC) than other pits at the upper boundary of the sandy soil. Total carbon, total nitrogen and water repellency were high at the lower boundary of the sandy layer. This may be because ash and charcoal produced by the fire have leached downwards.

Keywords: Ecosystem, water repellency, soil hydrophobicity, water content

SEKI K, SUZUKI K, NISHIMURA T, MIZOGUCHI M, IMOTO H & MIYAZAKI T. 2010. Ciri-ciri fizikal dan kimia tanah di hutan yang terbakar di Kalimantan Timur, Indonesia. Pemulihan ekologi hutan Dipterocarpaceae di Kalimantan Timur, Indonesia selepas kebakaran hutan pada tahun 1997–1998 dikaji. Ciri-ciri fizikal dan kimia plot yang rosak teruk akibat kebakaran hutan (HD), plot yang rosak sedikit akibat kebakaran hutan (LD) dan plot kawalan yang tidak terbakar dikaji lapan hingga sembilan tahun selepas kebakaran. Kandungan air tanah dipantau selama setahun di plot HD dan K. Lapisan pasir putih yang terdapat di plot HD mempunyai nilai pemegangan air yang rendah dan ketelapan yang tinggi. Semasa hujan, tanah pada lapisan pasir permukaan tidak menjadi tepu dengan air kerana air menyusup dengan cepat ke dalam lapisan subpermukaan. Tanah berpasir sedemikian yang biasa dijumpai di hutan kerangas pada amnya mempunyai nilai pH dan nutrien tersedia yang rendah. Namun, tanah berpasir di plot HD mempunyai pH yang lebih tinggi dan kekonduksian elektrik (EC) yang lebih rendah berbanding sempadan atas tanah berpasir. Jumlah karbon, jumlah nitrogen dan penolakan air juga tinggi pada sempadan bawah lapisan berpasir. Ini mungkin disebabkan abu dan arang yang terhasil akibat kebakaran telah larut resap ke bawah tanah.

INTRODUCTION

Forest fires are growing in size and frequency across the tropics (Cochrane 2003). In 1997–1998, a drought induced by the El Niño caused fire in many tropical regions in South-East Asia and Latin America. In East Kalimantan, Indonesia, the fire in 1997–1998 burned 5.2 million hectares including 2.6 million hectares of forest (Siegert *et al.* 2001). The forest fires exert influences not only on ecosystems of aboveground biomass but also on physical and chemical properties of the subsurface soil. Therefore, the recovery of the aboveground ecosystem from forest fire may depend on the belowground sustainability.

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The forest fire in East Kalimantan in 1997–1998 decreased the seed availability of litter layer by 85% and that of 1.5 cm soil surface by 60% (van Nieuwstadt *et al.* 2001). Fires can decrease or increase nutrients by different processes. Removal of nutrients by fire can be due to oxidation of compounds to a gaseous form, vapourisation of compounds that are solid at normal temperatures, convection of ash particles in fire-generated winds, leaching of ions in solution out of the soil following fire and accelerated erosion after fire (Fischer *et al.* 2000). In contrast, fires can also increase nutrients through the ash. Fires produce large amounts of ash, typically from 2 to 15 Mg ha^{-1} (Raison *et al.* 1985). The concentrations of nutrients in ash are usually high. Therefore, ash provides nutrient. Johnson and Curtis (2001) compared fire effects on soils of 48 observations from 13 publications. Significant increase in both soil C and N more than 10 years after fire was found.There was no effect at shorter time period after the fire. Low-temperature fires cause little initial loss in C and N but result in later gain because unburned residues are incorporated into the soil. High-temperature fires can cause increase of soil C in the subsurface horizon because of the transport of hydrophobic organic matter from surface horizons (Giovannini *et al.* 1987). Through the transport of hydrophobic organic material, a water repellent layer on the soil surface or just beneath the surface layer is created after a fire, which can enhance the erosion of the surface soil (DeBano 2000). Fernandez *et al.* (1997) measured the chemical composition of organic matter immediately after fire and compared it with unburned samples and samples heated at different temperatures in the laboratory. The fire decreased the amount of unhumified organic matter and humic acids, but the net amount of humin and pH increased.

The overall effects of fire on belowground ecosystem and the process of feedback to the aboveground system are complex and highly variable (Neary *et al.* 1999). As the temperature rises very high at the surface, effect of fire is usually found at the surface layer of soil. Most investigations on fire effects were immediate and short-term studies performed on surface horizons of soils. For example, Saharjo (1999) examined chemical and physical properties of surface soil of young *Acacia mangium* plantations and found that pH and available P increased immediately after fire but decreased one year after. Organic C and total N decreased immediately after fire and one year after. These values were significant compared with pre-burning levels. The effect of fire usually diminishes after one year at the surface horizon. However, as most studies examined only the surface horizons of soils, it was not clear if the effect of fire actually diminished or the fire-produced materials moved to the deeper soil horizon due to leaching and the effect of fire remained at the deeper horizon.

The purpose of this study was to see if the effect of fire on soil physical and chemical properties at the subsurface soil horizon remained eight to nine years after fire.

MATERIALS AND METHODS

Site description

The study was conducted at a natural Dipterocarpaceae forest in Bukit Bangkirai, 38 km north of Balikpapan, East Kalimantan, Borneo Island, Indonesia (Figure 1). The area has tropical rainforest climate with high temperature and heavy annual rainfall of 2500 mm. This site was affected by forest fire in East Kalimantan in 1997–1998. Three plots were set up as shown in Figure 2—heavily-damaged (HD), lightly-damaged (LD) and control (K). This study focused on the soil hydraulic behaviour of these sites. Forest fire did not reach the area surrounded by the rivers (Figure 2). According to the people living in Bukit Bangkirai, soil erosion occurred at some parts of the forest, but in our study site there seemed to be no severe soil erosion. In the unburned K plot, climax plants of Dipterocarpaceae such as *Shorea laevis*, *Cotylelobium melanoxylon* and *Dipterocarpus confertus* were the dominant species. In the HD plot, as the effect of fire was severest, most of the trees were burned. After the fire, pioneer species of plants such as *Macaranga gigantea* grew. *Macaranga gigantea* was the most dominant species in the HD plot when we started the research. In the LD plot, the effect of fire was not as severe as the HD plot and most of the trees were not burned, but some trees seemed to have died because of the drying effect. In the LD plot, climax plants such as *Madhuca kingiana* (Sapotaceae) and *Shorea parvifolia* (Dipterocarpaceae) were dominant, and the pioneer plant such as *M. gigantea* (Euphorbiaceae) was widely found.

The soils at K and LD plots were Ultisols, strongly weathered, unfertile acid forest soils, widely found in the lowland Dipterocarpaceae forest of East Kalimantan (Ohta & Effendi 1992). Layers of white quartz sand, kerangas, exist in some areas in K and HD plots. In Borneo Island, forest having white sand can be widely found. It is known as Sunderland heath forest, also known as kerangas forest. Kerangas forest is a type of tropical moist forest on Borneo Island (Wikramanayake 2001). The thickness of the quartz sand layer ranges from about 10 cm to more than 2 m.

Figure 1 Map of Indonesia

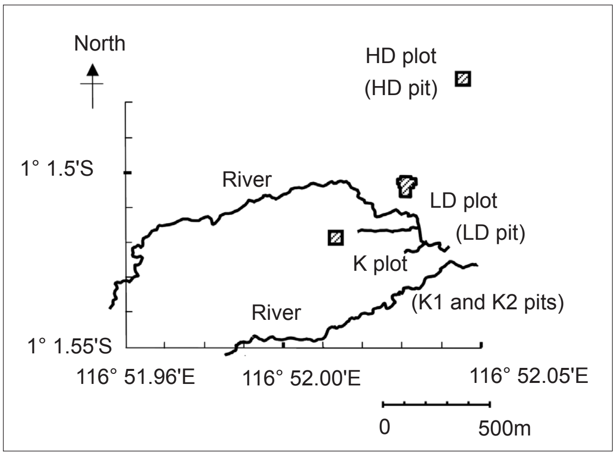

Figure 2 Locations of HD (heavily damaged by fire), LD (lightly damaged) and K (control) plots. Forest fire stopped at the rivers and areas surrounded by the rivers. K plot was not burned.

Soil properties

Soil sampling pits were dug at each plot—one pit each for HD and LD plots and two pits for K plots. The pits at HD and LD plots were denoted as HD pit and LD pit while the pits at K plot, K1 and K2 pits. As white quartz sand layers were found in some parts of K pits, K1 pit was selected from the place where quartz sand layer was not found and K2 pit was selected from the place where the thickness of the quartz sand layer was similar to that of HD pit. The distance between K1 and K2 pits was 54 m. The soil profile was recorded. Disturbed and undisturbed soil samples were obtained, and sealed carefully to prevent water loss before analysis of soil physical and chemical properties. The soils of HD, K1 and K2 pits were sampled at the end of August 2006, while the soils of LD pit were sampled in March 2006. Water content was measured gravimetrically by oven drying the disturbed sample in 105 °C for 24 hours (three replicates). Particle density was measured by a pycnometer method (three replicates). Soil texture was measured using the wet sieve method and bouyoucos hydrometer method based on air-dried disturbed samples. The samples were classified according to the system of the International Union of Soil Science (IUSS). Saturated hydraulic conductivities were determined by the falling-head and constant-head methods on undisturbed sample of a cylindrical core of 5 cm diameter and 5 cm height. The bulk densities were measured gravimetrically. From the values of water content, particle density and bulk density, volumetric fractions of solid, liquid and gas phases were calculated. Soil water retention was measured by the hanging water column and the pressure plate methods using undisturbed samples of cylindrical cores of 5 cm diameter and 2.5 cm in height (Dane & Topp 2002).

pH was measured 30 min after adding distilled water to each undisturbed soil sample to attain a 2:5 soil–water ratio. Electrical conductivity (EC) was measured after adding distilled water to attain 1:5 soil–water ratio. After homogenising the air-dry sample with mortar and pestle, total carbon (TC) and total nitrogen (TN) contents were measured. Water repellency was measured by the molarity of an ethanol droplet (MED) test (Doerr 1998). Disturbed soil sample at field water content was packed into a cylindrical core of 5 cm diameter, placed on a plate and a droplet of ethanol water mixture of a specified concentration (Table 1) was dropped on the soil surface. The extent of the hydrophobicity is classified according to the maximum concentration of ethanol when water drop penetrates into the soil in 3 s, as shown in Table 1. The classification criteria in Table 1 are according to Doerr (1998), except that the classification exceeds class 7, corresponding to 6.1 mol l^{-1} of ethanol (Table 1).

Continuous measurement of soil water content

Soil water content was measured continuously with ECH_2O sensors (EC-10; Decagon Devices Inc.) buried in the pits at a depth of 20 and 30 cm in the HD pit and at 10 and 20 cm in the K1 pit. The sensors were connected to a data logger and buried from the end of September 2005 until the end of August 2006. ECH_2O sensors measure dielectric permitivity of the soil and convert it to volumetric water content. Although a general calibration curve was given in the user's manual as the relationship between the dielectric permitivity and the volumetric water content, calibration curves for each soil was measured in the laboratory to improve precision of the measurement. The general and measured calibration curves were very close for the sandy clay loam soils in K1 pits and sandy soil in HD pits, but the calibration curve of sandy loam in HD pit was different from the manufacturer's calibration curve. Rainfall gauge was set near the pit in the HD pit and the rainfall intensity was measured every 10 min.

Table 1 Classification of the level of water repellency according to the molarity of an ethanol droplet (MED) test

Class	Description	Molarity of ethanol (mol l^{-1})
9	Extremely hydrophobic	7.5
8		7.0
7		6.1
6	Very strongly hydrophobic	4.1
5	Strongly hydrophobic	2.2
4	Moderately hydrophobic	1.5
3	Slightly hydrophobic	0.9
2	Hydrophilic	0.5
1	Very hydrophilic	0.0

RESULTS AND DISCUSSION

Soil properties

At the K1 pit, root mat was observed at the surface (Figure 3). At 3 cm and below, it was brown sandy clay loam layer. The clay content gradually increased with depth within the 30–60 cm depth. The colour also changed within the depth, from yellowish brown to reddish brown. This horizon of clay accumulation was formed by continuous downward movement of water. At the LD pit, 5 cm thick root mat was also found at the surface. Below it was a sandy clay layer of brown colour, underlain by a yellowish brown sandy clay loam layer. The profiles at the HD pit and K2 pit were different from those at K1 and LD. White quartz sand layers were found at a depth of 10 to 30 cm for HD pit (texture:sand) and 13 to 30 cm at K2 pit (texture:loamy sand). The colour of the sand layer was uniform at the HD pit. At the K2 pit, the colour gradually changed from white to grey in the 2 cm layer at the lower boundary. At the HD pit, below the sand layer was a brown sandy loam layer. At the K2 pit, below the sand layer was sandy loam layer. The sand of the kerangas forest is highly acidic and often lacking in nutrients, which restricts the growth of plant. While Ultisols was predominantly found in the study site, white sand of kerangas forest could also be found in some parts of the HD and K plots.

Volume fractions of the three phases (Figure 3b) showed that sandy clay and sandy clay loam layers in the LD and K1 pits had porosity of around 40%, sand layer in the HD pit and the loamy sand layer of K2 pit had porosity of around 50%, and the sandy loam layers in the HD and K2 pit had porosity of around 60%. Porosity of the root mat (60–80%) was higher than the mineral soil. However, these values were not as precise as other data because the particle density measurement of root mat layer was not available and we assumed a value of 1.5 g cm^{-3}. Volumetric water content was small at the HD, K1 and K2 pits, especially at the sandy layer at the HD pit and loamy sand layer at the K2 pit. These values were measured at the end of the dry season, while the volumetric water content at LD pits was rather high because it was measured during the rainy season. Saturated hydraulic conductivities

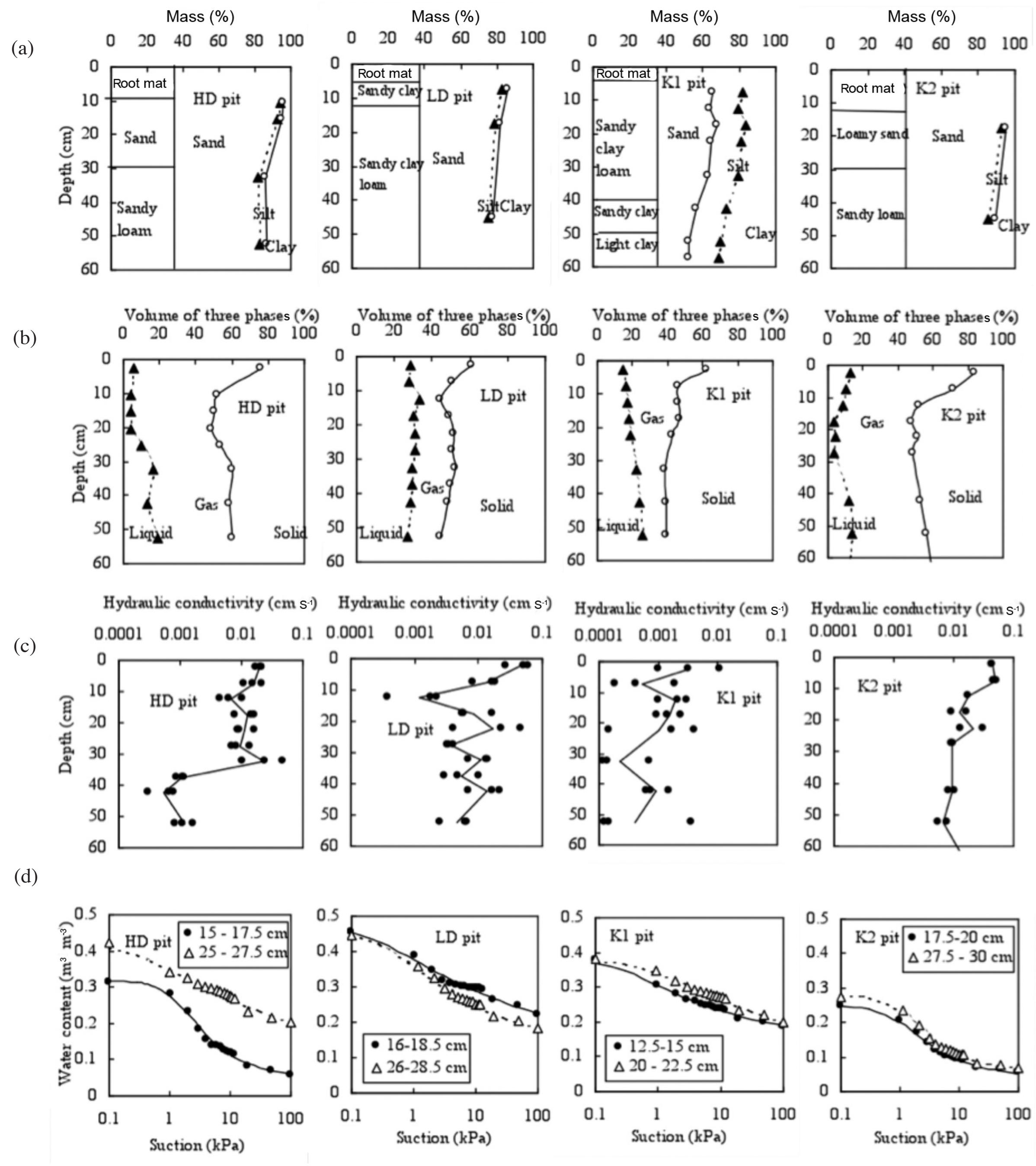

Figure 3 Soil physical properties at HD, LD, K1 and K2 pits: (a) soil texture (IUSS), (b) three phase distribution, (c) saturated hydraulic conductivity and (d) water retention curve

were small at K1 pit and large at the sand layer of HD and K2 pits (Figure 3c). It was also large in the LD pit. Variability of the saturated hydraulic conductivity was large at LD and K pits.

As for the soil water retention curves, sand in HD pit (25–27.5 cm) and K2 pit (27.5–30 cm) retained less water than the other soils (Figure 3d). Soil water retention curves were fitted with van Genuchten equation (van Genuchten 1980):

$$\theta = \theta_r + \left(\theta_s - \theta_r\right)\left[\frac{1}{1+\left(\alpha h\right)^n}\right]^m$$

where θ is the volumetric water content, θ_s is the saturated water content, θ_r is the residual water content, h is the suction head, and α, n and m are parameters where m = 1 – 1/n. As shown in Table 2, the values of θ_s, θ_r, α, n and m were determined by fitting the function to the measured data using SWRC fit software (Seki 2007). The equations fitted well with all the measured data sets as shown in Figure 3d. Therefore, the fitted functions were used to estimate the suction values from the measured water content values.

Figure 4 shows the profile of pH, EC, TC and TN at HD, LD, K1 and K2 pits. Some of the samples at the surface layer were root mat. The thickness of the root mat was 10 cm thick for the HD pit, 5 cm thick for the LD pit, 3 cm thick for the K1 pit and 13 cm thick for the K2 pit (Figure 3a). Soil pH (Figure 4a) was low, especially at the K1, K2 and LD pits. The increase in pH in the region affected by fire was also observed by Ulery *et al.* (1993) and Fernandez *et al.* (1997). They attributed the increase in pH to the ash produced by fire. The peaks of pH at the HD and LD pits were observed at a depth of 10–15 cm. At the K1 and K2 pits, pH increased slightly and gradually downwards. At the HD, LD and K2 pits, EC values in the root mat layers were higher than the mineral soil layers (Figure 4b). At the HD pit, EC was lower than other pits. This shows that water-soluble nutrient is not very rich

Table 2 Parameters of van Genuchten equation fitted to soil water retention curve

Pit	Depth (cm)	θ_s	θ_r	α	n
HD	15.0–17.5	0.319	0.052	0.0648	1.777
	25.0–27.5	0.421	0.000	0.340	1.125
LD	16.0–18.5	0.474	0.092	0.521	1.167
	26.0–28.5	0.456	0.131	0.211	1.330
K1	12.5–15.0	0.380	0.131	0.362	1.245
	20.0–22.5	0.381	0.033	0.147	1.147
K2	17.5–20.0	0.250	0.042	0.0941	1.654
	27.5–30.0	0.278	0.065	0.0759	1.815

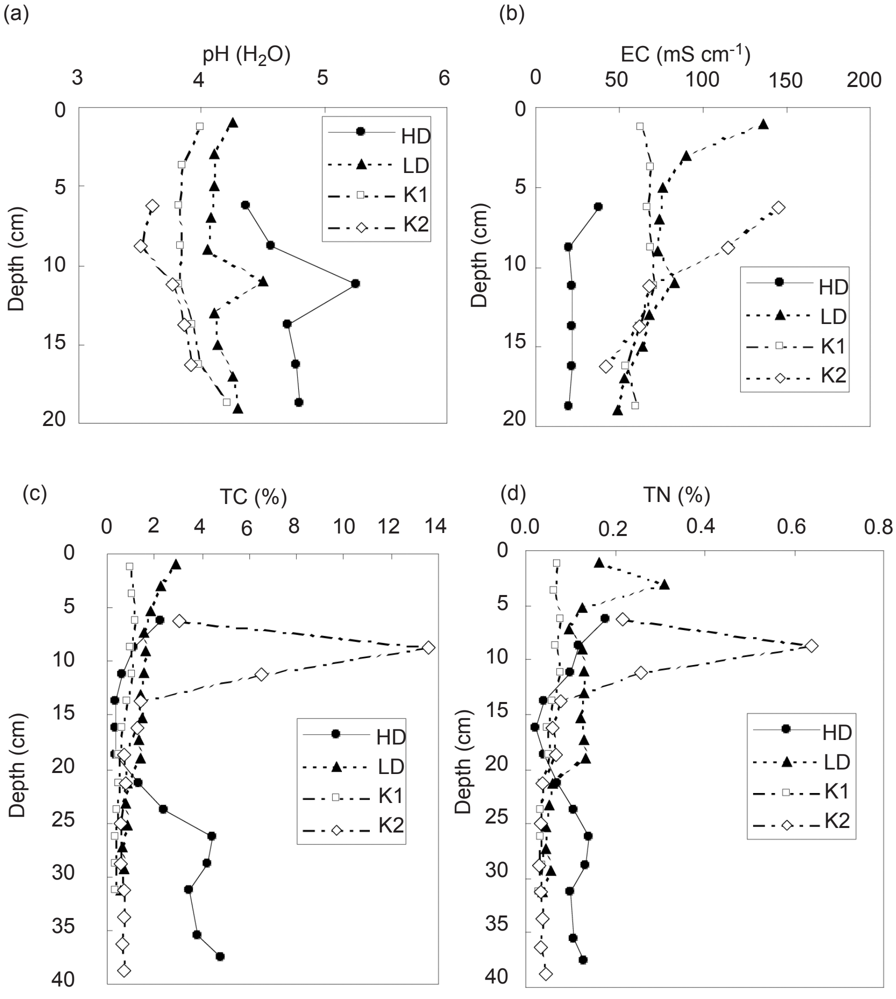

Figure 4 Soil chemical properties at HD, LD, K1 and K2 pits (a) pH, (b) EC (electrical conductivity) (soil:water = 1:5), (c) TC (total carbon) and (d) TN (total nitrogen)

at the sand layer of the HD pit. As sand had high hydraulic conductivity, low water retention and low ion holding capacity, water-soluble nutrient was leached downwards to the underlying layer.

Total carbon at HD pit showed an interesting profile (Figure 4c). In the sand layer of depth 10–30 cm, TC increased from 0.3% at depth of 15 cm to more than 4% at depth of 30 cm. The TC at the layer below 30 cm was very high compared with other pits. Profiles of TN in the HD pit also showed a similar trend. Higher TC and TN values in the LD pit compared with those of the K1 and K2 pits could be the result of incorporating the residue of burned organic matter into the soil (Giovannini *et al.* 1987). At the K2 pit, there was a sharp peak of TC and TN at depth of 10 cm within the root mat.

Water repellency

Soil water repellence (Figure 5) was studied only in samples of HD, K1 and K2 pits because they were collected after a dry period. Data for LD were collected after a rainy period. At the K2 pit, strong water repellency was found throughout the 40 cm soil profile. At the K1 pit, strong water repellency existed at the surface layer and with depth. At the HD pit, water repellency decreased suddenly with depth in the upper sand layer, from 10 to 15 cm and increased with depth in the lower sand layer, from 15 to 30 cm. The agreement of the pattern of the profile of water repellency of HD pit with the pattern of the profile of TC and TN suggests that water repellency comes from the soil organic matter in this site.

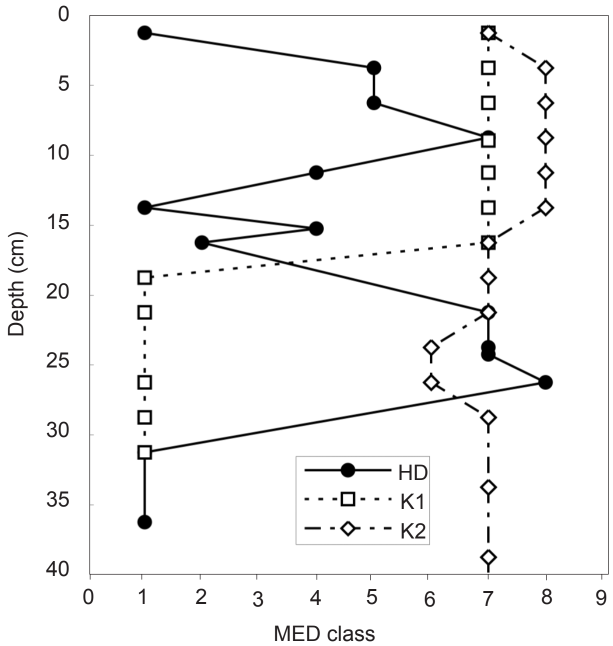

Figure 5 Water repellency at HD, K1 and K2 pits

Water repellency is related to organic carbon and soil texture (Rodriguez-Alleres *et al.* 2007). Therefore, relationship between total carbon and water repellency was drawn for different textures (Figure 6). A good relationship between TC and water repellency was found, except for two sandy loam samples at HD pit, whereby TC was very high and soil was very hydrophilic. For each soil layer, hydrophobicity increased with increase in TC. For most soils, it reached the level of 7 (extremely hydrophobic) at a TC value of 1.5%. For sandy clay loam at K1 pit, the threshold value was lower and hydrophobicity increased sharply at TC of 0.5%.

Change in soil water content

Figure 7 shows the changes in water content and rainfall intensity at K1 and HD pits. Rainfall data after 20 December 2005 were missing due to faulty rain gauge. The rainy season started at the end of September and ended at the end of April. There was no rain for six weeks before we started measurement from mid-August till the end of September 2005. Therefore, initially the soil was very dry at both HD and K1 pits. When rain started at the beginning of October, soil water content increased with rainfall and decreased after the stop of the rainfall. At the HD pit, sand layer at the depth of 20 cm was not fully saturated with rain and the water content was higher at the lower 30 cm sandy loam layer. Increase in the soil water content was observed at most of the recorded rainfall event.

Figure 8 shows the changes in soil water content and rainfall intensity on 10 October 2005. The first rainfall at 6.30 a.m. did not increase soil water content, but the second rainfall from 9 till 10 a.m. which had the maximum rainfall intensity of 12 mm/10 min increased soil water content of each layer at the both pits. At the HD pit, water content of the sand layer at 20 cm depth did not increase very much but increased substantially at the lower sandy loam layer of 30 cm depth. The water content in the sand layer remained unsaturated even at rainfall. Therefore, the unsaturated hydraulic conductivity corresponded to rainfall intensity and most of the time even during the rainy season water content was 10 to

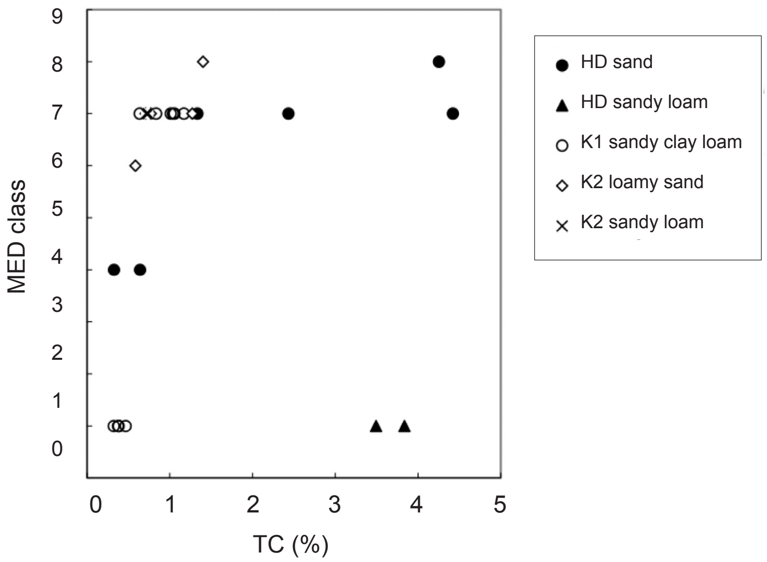

Figure 6 Relationship between total carbon and water repellency at HD, K1 and K2 pits

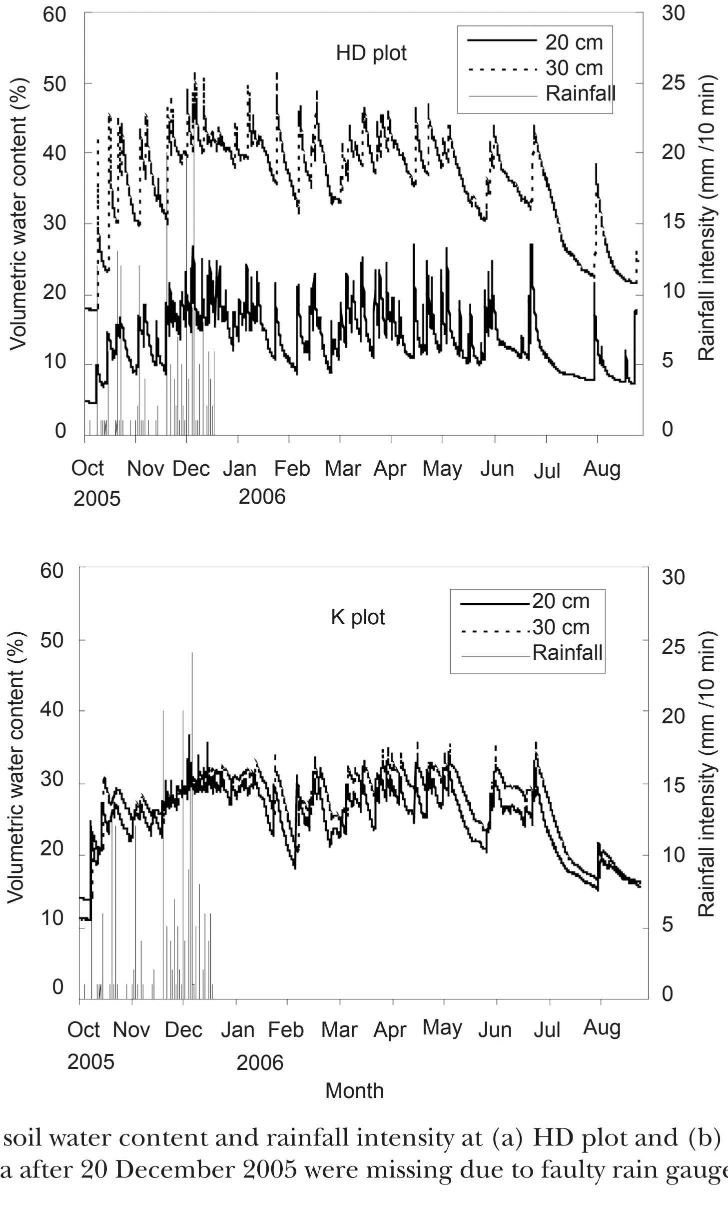

Figure 7 Changes in soil water content and rainfall intensity at (a) HD plot and (b) K plot (K1 pit). Rainfall data after 20 December 2005 were missing due to faulty rain gauge.

20%. It meant that the downward infiltration of water at the HD pit was very rapid, the infiltration rate being equal to the rainfall intensity. At the sandy loam layer, the hydraulic conductivity was in the order of 0.001 cm s^{-1} (Figure 3c), corresponding to 6 mm/10 min. Therefore, the soil was nearly saturated.

At a depth of 10 and 20 cm of the K1 pit, the soil water content behaved almost identically and the deeper layer tended to have higher water content (Figures 7 and 8). However, the difference in water content does not necessarily cause difference in soil water suction. By substituting the inverse function of soil water retention given in Figure 3d, change in the estimated suction was calculated as shown in Figure 9. In the dry season after April, the suctions of the two layers of K1 pit were almost identical. During this period, as there was no difference in the soil water suction between the two layers, water steadily moved downwards due to the difference of gravitational potential. In the rainy season, suction at 10 cm was smaller than that at 20 cm and this water moved downwards. From the measurement of soil water, it was evident that downward movement of water was dominant throughout the year.

Effect of fire

Downward movement of water was dominant. Infiltration of water to the underlying layer is rapid especially in the sand layer of the HD pit. The change in the chemical properties of the HD

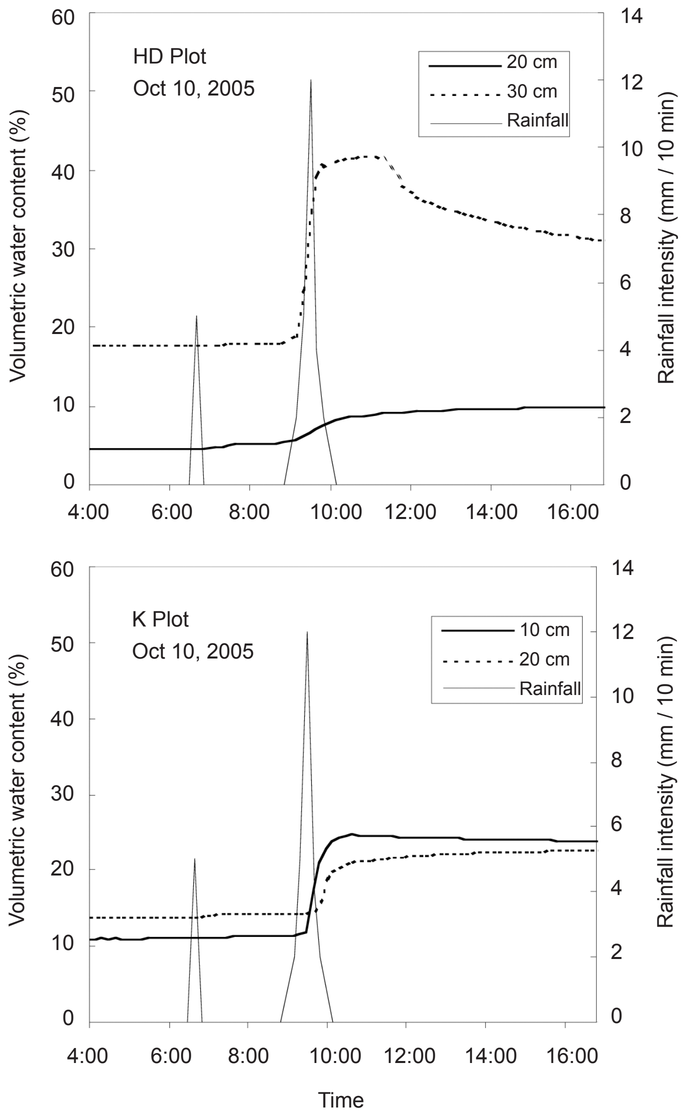

Figure 8 Changes in soil water content and rainfall intensity at (a) HD plot and (b) K plot (K1 pit) on 10 October 2005

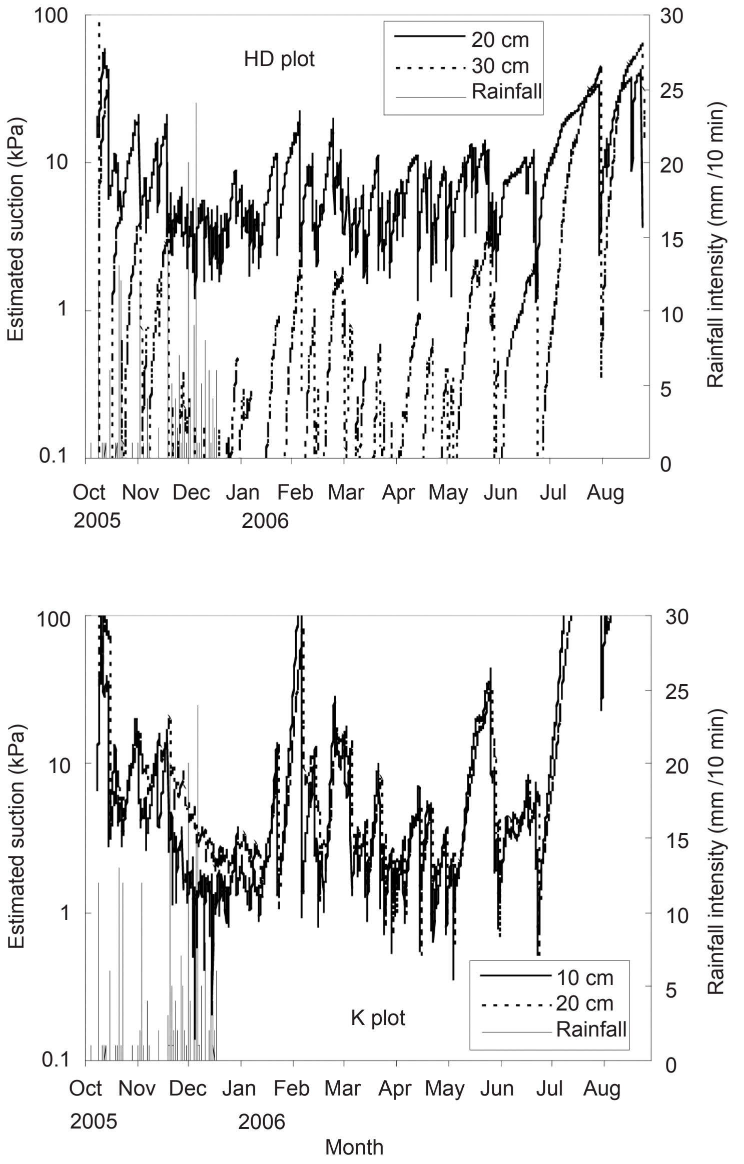

Figure 9 Changes in the estimated suction and rainfall intensity at (a) HD plot and (b) K plot (K1 pit). Rainfall data after 20 December 2005 were missing due faulty rain gauge.

pit, as shown in Figures 4 and 5, can be explained by two factors. Firstly is the change of soil properties caused by the fire and secondly is the change in the soil properties caused by leaching of solute eight to nine years after the fire. The increase of pH at the 10–15 cm layer of the HD pit (Figure 4a) was the effect of ash produced by fire which had been leached down to this layer. Although EC was low in this layer (Figure 4b), alkali and alkaline earth elements released from ash produced by fire contributed to the increase of pH. At the lower layer of sand at the HD pit (20–30 cm; 10–20 cm below the rootmat), increases of TC (Figure 4c), TN (Figure 4d) and water repellency (Figure 5) were observed. It was not likely that the organic material found in this layer was hydrophobic organic matter that had vapourised and condensed (DeBano 2000). This is because such hydrophobic organic matter is not easy to be leached by water and the amount of the organic matter (total carbon) is very large. As the C/N ratio (20–30) in this layer was higher than other pits, it is likely that ash and charcoal produced by fire were leached down to this layer.

Statistical validation is not possible in this study because we have only data of 4 pits and there are many independent variables to be studied such as severity of fire, depth, time and type of soil. Although most studies showed that the effect of fire could be restricted to short-term time scale, apart from soil erosion and surface horizon of soil, our findings indicated that the effect of fire could also be found at the deeper soil layer at longer-time scale as the fire-produced materials moved downwards to the deeper soil layers.

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