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Characteristics of Ultisols Differing in Wildfire History in South Sumatra, Indonesia

II. Dynamics of Chemical Properties

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In spite of the significant increase in the frequency and extent of fire occurrence in Indonesia recently, little information is available about the immediate, short-term, and long-term effects of fire on soils. To investigate the effects of wildfires on the dynamics of T-C, T-N, available P, pH, exchangeable bases, and cation exchange capacity (CEC) of Ultisols from South Sumatra Indonesia, surface soils of an unburnt 9-year old *Acacia mangium* plantation and of *A. mangium* plantations burnt in 1995, 1997, 1998, and 2000 were sampled in triplicate consecutively from December 1998 until December 2000. The values of T-C, T-N, available P, pH, and exchangeable bases significantly increased immediately after the fire while the levels of Al saturation and CEC significantly decreased. Soil nutrients were still accumulated 1 year after the fire but by the end of the second year, they were depleted and returned to the pre-fire levels. Although fallowing aggraded the burnt sites, the nutrient levels in the burnt sites were still lower than those in the unburnt sites. In addition, the residual effects of fire on the soil nutrient levels were still evident 5 years after the fire.

Key Words: **dynamics, immediate effect, leftover effect, Ultisols, wildfire.**

Forest fires during the prolonged dry season related to El Niño-Southern Oscillation (ENSO) in South Sumatra, Indonesia have been recorded for almost a hundred years. More frequent drought spells have markedly exacerbated the fire problems over the last 20 years (Bompard and Guizol 1999). In addition, widespread logging using flawed techniques, large-scale land clearance by agro-industrial companies, land clearance for major transmigration schemes, and land acquisition by companies and government with little consideration for the rights of the local people are contributing factors to the increase in the fire occurrence in South Sumatra Province, Indonesia (Gouyon 1999).

Removal of the forest cover by fire can result in immediate and drastic degradative changes in the soil properties. The risks of fire on forest soils include 1) nutrient losses in smoke, ash, runoff, and erosion (Ewel et al. 1981), 2) short-term increase in the availability of nutrients (Ghuman and Lal 1991), 3) increase in soil erosion due to the decrease in soil stability (Ghuman et al. 1991), and 4) changes in the soil physical and mineralogical properties (Ketterings et al. 2000). While the soil of a forest ecosystem is one of the major components in sustainable nutrient cycling, few studies have been carried out to assess the residual effects of fire on forest soils. Therefore, little information is available about the long-term effects of fire on forest soil properties. Kadir et al. (2001) reported significant changes in the characteristics of soils differing in fire history. The loss of nutrients from the forest sites by the removal of trees appears to be particularly important. Measuring the recovery of the ecosystem nutrient capital to pre-disturbance levels provides an assessment of biogeochemical resilience and may also facilitate cross-biome comparisons of ecosystem recovery rate (Zarin and Johnson 1995). The objective of this study was to investigate both the immediate and residual effects of forest fires on the levels of total carbon and nitrogen, available phosphorus, and exchangeable bases of Ultisols in South Sumatra Province, Indonesia.

MATERIALS AND METHODS

Study site. The study area was located in the Pendopo Sub-district, Muara Enim District, South Sumatra

Province, about 200 km Southwest to Palembang, Indonesia, stretching from 103°30′ E to 103°50′ E and 3°15′ N to 3°25′ N. The soil is classified as Yellowish-brown Podzolic, and association between Yellowish-red Podzolic and Yellowish-brown Podzolic (Lembaga Pemetaan Tanah (LPT) 1974), equivalent to Acrisols (FAO / UNESCO 1974) or Ultisols (Soil Survey Staff 1992).

The study sites consisted of unburnt and burnt sites. The unburnt site was an unburnt *Acacia mangium* plantation (AM); while the burnt sites were *A. mangium* plantations that burnt in 1995 (B95), 1997 (B97), 1998 (B98), and 2000 (B00), respectively. The trees in the AM were about 7 years old at the start of this study (in 1998) with average girth at breast height (GBH) of 44 cm (21 to 116 cm). The understory species included *Astonia* sp., *Caesalpinia pulchriina, Zingiber aromaticum* vail, and *Mimosa* spp. Pre-wildfire vegetation of the burnt *A. mangium* plantations consisted of 5-year old (B95), 6-year old (B97 and B00), and <1-year old (B98) *A. mangium* trees, respectively. The burnt area showed a sparse regrowth of *A. mangium* mixed with shrubs and grasses, mainly *Imperata cylindrica* as understory species except for the B00 site, which did not have any vegetation left after the fire.

Soil samples and analytical methods. Soil samples were collected at a 0- to 10-cm depth at approximately adjacent points in three replicates. Four subsamples were collected and combined to get one composite sample for each replicate. Schedule of sampling in order to evaluate the immediate, short-term, and long-term effects of the fire was as follows: 1) Immediate effect: the B00 site was sampled immediately (about 5 h) after the fire and an unburnt area adjacent to this site was also sampled as a control. 2) Short-term effect: the first sampling at the B98 site was carried out 1 month after the fire occurrence, followed by a 3-month interval until December 2000. 3) Long-term effect: the first sampling at the AM, B95, and B97 sites was carried out in December 1998, followed by May, September, December 1999, March, June, September, and December 2000 (8 times). The values of the soil pH(H_2O), exchangeable bases (Ca, Mg, K, and Na), the contents of exchangeable Al, total carbon (T-C) and nitrogen (T-N), available P, and the cation exchange capacity (CEC) levels of the soils were determined. The analytical methods employed here were described previously in the report of Kadir et al. (2001).

All the data collected were statistically analyzed to discriminate the effect of fire on the soil characteristics. Analysis of variance (ANOVA) was carried out to compare the effect of years of fire on the soil characteristics. The Costat V. 2.0 (Cohort) was used to perform a one-way ANOVA and where significant differences were found at $p < 0.05$, LSDs were calculated for mean separation. The paired *t*-test was used to determine whether differences in the nutrient contents before and after the fire were statistically significant at $p < 0.05$.

RESULTS AND DISCUSSION

Dynamics of soil properties immediately after fire

Because the current study was carried out under wildfire conditions, temperatures during the fire could not be measured. To evaluate the immediate effects of wildfire on the soil properties, a comparison was made between the results from the most recently burnt site (B00) and those from the adjacent unburnt site. Fire consumed most of the 9-year old *Acacia* trees and litter layer. As a result, ash accumulation ranging from 1 to 2 cm in thickness and soil cracks could be found on the soil surface immediately after the wildfire. Chemical analysis of the fire-exposed mineral horizon (0- to 10-cm depth) immediately after the fire revealed significant increases ($p < 0.05$) in the T-C, T-N, available P contents, values of pH, and exchangeable bases, while the Al saturation and CEC levels significantly ($p < 0.05$) decreased after the fire (Table 1).

Both the T-C and T-N contents increased by 6 and 10% after the fire (from 21.3 to 22.6 g kg^{-1} for T-C and from 2.0 to 2.2 g kg^{-1} for T-N). Similar results had been previously reported by Gimeno-García et al. (2000) who found a 24 and 5% increase in the T-C and T-N contents of the surface soils (0 to 5 cm), respectively, immediately after the fire and recorded a temperature of 200 to 400°C during the fire. On the other hand, a small decrease (2%) in the contents of organic matter and T-N was found in the soils from the plots that experienced a high intensity fire (400 and 600°C). Therefore the current results implied that the temperatures during the fire

Table 1. Pools and changes in chemical properties of surface soils (0–10 cm depth) immediately after the fire.

Variable	Before fire	After fire
T-C (g kg^{-1})	21.3 a	22.6 b
T-N (g kg^{-1})	2.0 a	2.2 b
Available P (mg P kg^{-1})	14.3 a	19.8 b
pH	4.9 a	5.4 b
Exchangeable Al	4.7 a	2.1 b
Ex. bases ($cmol_c$ kg^{-1})		
Ca	1.9 a	9.0 b
Mg	1.8 a	3.4 b
K	0.3 a	0.3 a
CEC ($cmol_c$ kg^{-1})	16.9 a	12.0 b

Means within the same row followed by the same letters are not significantly different at $p < 0.05$ (based on paired *t*-test). Values are means for $n = 3$.

were still likely to be lower than the temperatures at which T-C and T-N combustion could occur. Fire intensity and temperatures are related to the amount and condition of fuel. Severe or high-intensity burns are typically found in areas with a high fuel concentration, such as fallen logs and slash piles, and may have created surface temperatures of 500°C or more (Wells et al. 1979; Chandler et al. 1983). The concentrated fuel may burn slowly, over several days or weeks, baking the underlying soil at high temperatures and resulting in a reddened surface soil (Ulery and Graham 1993). In the current study, the conditions described by Wells et al. (1979) and Chandler et al. (1983) were not observed because the 9-year old *A. mangium* stands with sparse floor growth underneath had covered the field. Although there were organic debris (about 2-cm thick), they burnt quickly during the fire due to the dry climatic conditions prevailing when the fire occurred. In addition, reddening of the surface soil, as described by Ulery and Graham (1993), was not observed in the current study. Therefore, we concluded that the increase in the T-C and T-N contents immediately after the fire found in the current study were related mainly to the increase in the amounts of charred materials produced during the pyrolytic stage of burning. Charcoal produced during burning might have been also included in the sampling and estimated as soil material at the time of the analysis.

The soil moisture content is also important for determining the effect of fire on the soil properties as water can increase both the heat capacity and conductivity of soil (DeBano and Klopatek 1988). Soil moisture content at a 0- to 10-cm depth at the study site, which was about 28% prior to the fire, decreased to about 20% after the fire. The moist conditions of the soils prior to the fire allowed the soils to absorb large amounts of heat without a subsequent increase in temperature until water was vaporized and to conduct heat more rapidly due to the increase in the thermal conductivity. However, severe effects of fire on soil drying, hence on other chemical properties, might have occurred at the first 1- to 2-cm depth from the soil surface where soil cracking was observed, which indicated that at this depth the soil had undergone complete dehydration and that the temperature during the fire might have reached 220°C (Raison 1979; Giovannini and Lucchesi 1993). Therefore, it was most likely that the depletion in the T-C and T-N contents occurred at the first 1 to 2 cm depth form the soil surface but that the 10-cm sampling carried out in the current study did not allow the detection of these potential changes.

Significant increases in the soil pH and in the levels of exchangeable bases were attributed to the accumulation of ash from burning of plant biomass, plant litter on the soil surface, and to some extent to the charring of the organic C pools in the soil, as reported in the previous studies (Tanaka et al. 1997; Ketterings et al. 2000; Kadir et al. 2001). Since the increase in the pH was accompanied by a considerable decrease in the amount of exchangeable Al and concomitant increase in the amounts of exchangeable bases, it is suggested that the alkalinity properties induced by ash accretion precipitated soluble Al to $Al(OH)_3$, followed by the liberation of exchange sites and absorption of inorganic bases from the ash.

Similarly, the amount of plant-available P increased by about 39% after the fire (from 14.3 $mg\,P\,kg^{-1}$ soil before the fire to 19.8 $mg\,P\,kg^{-1}$ soil after the fire) (Table 1). Thermal decomposition of organic materials on the soil surface had led to the decomposition of organic P into available P. Several studies have reported increases in the levels of plant-available P and reductions in the organic pools of soil P following fire (Giardina et al. 2000). At our site, the fire-related increase in the amount of available P might have been caused by an input of P from the consumed litter layer, *Acacia* trees, and organic matter at the first 1- to 2-cm depth from the soil surface. In addition, this increase could also occur through ash included at the time of sampling. Although a chemical analysis of ash was not carried out in the current study, in a study on Pinyon-Juniper soils in Arizona, DeBano and Klopatek (1988) reported that litter ash of pinyon and juniper contained 378 and 422 $mg\,P\,kg^{-1}$, or approximately 26 and 29% of the total P remaining, respectively. Furthermore, the increase in the soil pH due to the alkalinity of ash may have released P from the Al-P complex. Alternatively, the increase in the amount of available P could also be attributed to the heat-induced death of the soil microbial population and the release of microbial P (DeBano and Klopatek 1988: Serrasolsa and Khanna 1995). Nevertheless, thermal decomposition must be involved, because the Bray method can measure only the level of inorganic P of soils. Since the soil microbes are concentrated in the surface soil and that this part was severely affected by the fire (as evidenced by soil cracking), thermal decomposition of microbial pools also occurred because microbial pools have been shown to have a threshold temperature of less than 100°C (Dunn et al. 1985; Klopatek et al. 1988).

In spite of the significant increases in the levels of exchangeable bases, in contrast, CEC significantly ($p < 0.05$) decreased after the fire (Table 1). Organic matter and clay are two important sources of CEC. However, in the current study, the decrease in CEC could not be attributed to the decrease in the T-C content because, instead of decreasing, the T-C content significantly increased immediately after the fire. Because the increase in the T-C content in the current study was caused by the increase in the amount of charred materials, which consisted of neither intact organic compounds nor pure C, chemically they did not contribute significantly to the CEC of soil. Alternatively, the possible source of CEC was clay. However, fire might have caused a fusion of clay into sand-sized particles as a result of the thermal modification of the iron and aluminosilicates (Betremieux et al. 1960; Sertsu and Sanchez 1978).

Residual effects of fire on soil properties

The residual effects of fire included the effects of fire on the short-term and long-term dynamics of soil properties. The short-term dynamics involved the nutrient budget at the B98 site during the first two years after the fire, which is expressed by the difference between the nutrient contents at the B98 site before the fire and those obtained 1 month, 1 year, and 2 years after the fire (Table 2). The T-C and T-N contents one month after the fire were significantly ($p < 0.05$) higher than those before the fire (Table 2). In addition to the charred materials, the increase in the temperature during the fire might have killed most if not all of the fine roots in soil at the first 10-cm depth. Because the site had received a sufficient amount of precipitation and experienced a wet- and dry-cycle, accumulation of organic matter derived from these two sources might have been responsible for the significant increase in the T-C and T-N contents observed 1 month after the fire. As the roots in the upper part of the soil (10 cm) were mainly those of *A. mangium*, which were nodulated, the accumulation of organic matter 1 month after the fire resulted in T-N values nearly two times higher than the amount of T-N before the fire, further resulting in an exceptionally low C / N ratio (7.8) (Table 2).

Similarly, the pH, and CEC values also still significantly ($p < 0.05$) increased (Table 2), indicating the residual effect of ash accretion on these two parameters. However, the increase in the pH values was not followed by a decrease in the content of exchangeable Al, suggesting that the liming effect of ash acted only on the active acidity of the soil (Table 2). The significant increase in the organic matter content may account for the significant increase in the CEC levels until 1 year after the fire (Table 2).

The amount of available P significantly ($p < 0.05$) decreased one month after the fire, resulting in a level of available P only about 50% of the pre-fire level (Table 2). This finding confirmed that the increase in the amount of available P immediately after the fire (Table 1) was in fact short-lived. Although the soil pH plays a major role in the availability of P in acid soils, the significant decrease observed in the current study could not be attributed to soil acidity because the soil pH also significantly increased from 4.9 before the fire to 5.2 1 month after the fire, and no changes were observed in the amount of exchangeable Al 1 month after the fire (Table 2). Therefore, we assumed that the vegetation, as pointed out by Vitousek and Matson (1984), had absorbed most of P from the soils during the period of regrowth. Furthermore, because the site had experienced wet and dry cycles during the period between the fire occurrence and sampling, a proportion of available P might have become equilibrated with the lesser available P fraction in soil, as indicated by Giardina and Rhoades (2001). This mechanism could be considered since the level of Al saturation 1 month after the fire was not different from the prefire level (Table 2).

The significant increase in the T-C, T-N contents, and pH still continued up to 1 year after the fire compared with the data for 1 month after the fire (Table 2). The increase in the T-C and T-N contents occurred through the accumulation of organic matter. On the other hand, the amount of available P once decreased (after 1 month) and recovered gradually at the end of the second year after the fire, probably due to the solubilization of inorganic P by P-solubilizing bacteria and / or arbuscular mycorrhizal fungi. Similarly, the pH also increased, indicating that the residual effect of ash accumulation on

Table 2. Short-term dynamics of nutrients in surface soil (0–10 cm depth) based on the results from the B98 site.

Variable	Before fire	After 1 month	After 1 year	After 2 years
T-C (g kg^{-1})	19.7 a	24.9 b	28.3 c	20.2 d
T-N (g kg^{-1})	1.7 a	3.2 b	2.3 c	1.8 a
C / N ratio	11.6	7.8	12.3	11.2
Available P (mg P kg^{-1})	6.9 a	3.4 b	5.4 c	12.6 d
pH	4.9 a	5.2 b	5.5 c	5.3 b
Exchangeable Al	3.0 ab	3.1 ab	2.9 a	3.5 b
Ex. bases (cmol$_c$ kg^{-1})				
Ca	2.6 a	3.9 b	3.6 c	3.8 bc
Mg	1.1 a	1.3 a	1.9 b	1.9 b
K	0.3 a	0.3 a	0.3 a	0.3 a
CEC (cmol$_c$ kg^{-1})	10.2 a	10.9 b	20.3 c	11.6 d

Means within the same row followed by the same letters are not significantly different at $p < 0.05$ (based on Tukey's t-test). Values are means for $n = 3$.

the soil acidity was still evident one year after the fire. In contrast, the amount of exchangeable Al was not affected, suggesting that the potential acidity was not affected by the ash, as confirmed by the decrease in the soil pH at the end of the second year after the fire (Table 2). However a significant depletion of T-N was observed 2 years after the fire, indicating that the consumption of organic N by the soil microbial population was faster than the accumulation due to active mineralization.

The values of exchangeable Ca fluctuated significantly over time. They significantly increased ($p < 0.05$) 1 month after the fire, due to accumulation through the ash but they showed a small yet significant decrease after 12 months, presumably due to plant uptake and leaching while no changes were observed afterwards (Table 2). In contrast, the amount of exchangeable Mg significantly ($p < 0.05$) increased and no changes were observed in the amount of exchangeable K (Table 2).

At 2 years after the fire, mineralization of the organic matter pools resulted in a significant decrease in the T-C and T-N contents ($p < 0.05$) but the pools were still comparable to their original levels. Concomitantly, P and exchangeable Ca availability significantly increased compared to their levels 1 year after the fire (Table 2). Although a deterioration of the soil organic matter-related properties in fields under shifting cultivation in Thailand had been reported by Funakawa et al. (1997), the current results showed that the amount of available P was still high and the values of other parameters, such as T-C, T-N, exchangeable bases, and CEC, were still comparable to their original levels, most likely because the site remained fallow after the fire.

As reported by Kadir et al. (2001), there might not be any definite differences in the climate and geological period for long-term weathering because all the study sites were located in one compound area. In addition, the type of soil in the study sites was the same, Yellowish-red Podzolic, which developed from the same material, tertiary fine sedimentary rocks. Table 3 presents a comparison of the soil characteristics of unburnt and burnt *A. mangium* plantations (B95 and B97, 5 and 3 years after the fire, respectively), where a 2-year average value is shown ($n = 8$). The accumulation of nutrients under AM in fact occurred for all the nutrients investigated. The *A. mangium* stands have been found to experience a considerable mortality as early as 2 years after planting (Fisher 1995). Because *A. mangium* stands in the current study were already 7 years old at the start of the study, a large amount of organic matter, particularly fine- and medium-sized roots, may have been returned to the soil. A significant difference was detected only in the levels of available P, exchangeable Mg, and CEC, which were significantly lower in B95 (5 years after the fire) than those in the control AM but not significantly different from those in B97 (3 years after the fire), in spite of the similarity in the other characteristics (Table 3). Since some other inherent soil properties among the sites such as texture (clay) (Kadir et al. 2001) were similar, these results suggested that the differences could be attributed to the fire occurrence, rather than to the inherent soil properties among the study sites.

The tree plantations, particularly those with closed canopies, obviously altered the microclimate within the stand. Measurement of the soil temperatures at a 10-cm depth at the AM and B97 sites did not show significant variations among the sites and within the sites. They ranged from 25.0 to 26.1°C at the AM site and from 25.2 to 26.1°C at the B97 site during the wet season and from 25.9 to 26.3°C at the AM site and from 25.6 to 25.9°C at the B97 site during the dry season. Due to their similarity, the soil temperature did not appear to play a major seasonal role in the variability of the soil nutrients through their effect on decomposition. On the other hand, the soil moisture was significantly higher in the wet season than in the dry season (Table 4). The

Table 4. Moisture content of surface soils (0–10 cm depth) from the unburnt and burnt *Acacia mangium* sites.

Site	Wet season (%)	Dry season (%)
AM	40.2 a	27.5 b
B97	35.2 a	27.6 b
B95	34.6 a	23.9 b

Means within season followed by the same letters are not significantly different at $p < 0.05$ (based on paired t-test). $n = 3$.

Table 3. Long-term dynamics of nutrients in surface soil (0–10 cm depth) based on the results from the AM, B95, and B97 sites.

Site	T-C ($g\ kg^{-1}$)	T-N ($g\ kg^{-1}$)	Available P ($mg\ P\ kg^{-1}$)	pH	Exchangeable bases ($cmol_c\ kg^{-1}$)				CEC
					Al	Ca	Mg	K	
AM	22.6 a	2.0 a	11.9 a	4.9 a	3.9 a	1.4 a	1.7 a	0.2 a	17.7 a
B97	22.9 a	1.7 a	5.5 b	5.0 a	3.3 a	1.6 a	1.1 b	0.3 a	13.3 b
B95	23.8 a	1.9 a	7.5 ab	5.0 a	4.2 a	1.0 a	1.3 b	0.2 a	14.9 ab

Means within the same row followed by the same letters are not significantly different at $p < 0.05$ (based on Tukey's t-test). Values are means for $n = 8$.

increase in the soil moisture level near the soil surface may favor biotic activity in that zone. These results emphasize the importance of extensive temporal replications of sampling and the importance of reference sites that normalize the factors affecting the nutrient cycles.

Summary and conclusion

Fire exerts significant direct and indirect effects on the nutrient dynamics in soils. The significant increase in the nutrient levels immediately after the fire indicates the positive effects of fire on available nutrients. However, these beneficial effects were short-lived. Although the accumulation of nutrients at the burnt sites was still evident 1 year after the fire, the nutrient levels started to decrease and return to the pre-fire levels after 2 years. The combination of plant uptake and leaching is considered to be responsible for the decrease, which also indicates that the rate of plant uptake and leaching was faster than that of deposition.

Leaving the burnt sites fallow contributed to the aggrading of the burnt sites. However, our findings provide evidence that the residual effects of fire on the soil nutrient levels were still evident 5 years after the fire (B95). Therefore, prevention of forest fire is essential in order to maintain the sustainability of ecosystems in the tropics.

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