Effect of Heating and Rewetting on Properties of Ultisols from South Sumatra Province, Indonesia

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ABSTRACT   We investigated the effect of soil heating and rewetting on the characteristics of Ultisols from Pendopo, South Sumatra Province, Indonesia, in a laboratory experiment. Soil samples from the depth of 0–10 cm were subjected to different temperatures (100, 300, and 500℃) for different periods (4, 8, and 12 hr). The heated soils were then either rewetted or un-rewetted with deionized water. Heating significantly changed the color from dark brown to red, and significantly increased sand fraction and decreased clay fraction. The changes in soil fraction were observable during the first four hours of heating. Heating had drastic effect on soil mineralogy, even at lower temperature. Significant changes were also observed in soil chemical characteristics. Total C and N were almost totally eliminated at 500℃ regardless of the heating time but increased with watering as compared with those did not receive water treatment. Soil pH also increased with heating up to 300℃ in accordance with decreases in exchangeable Al and H of the soil. Watering further increased the pH, which was most likely due to decreases in soluble Al and H. Exchangeable bases and CEC significantly decreased with heating but increased again with watering. P also significantly decreased with increasing temperature. Heating time did not exert significant effect on available P, suggesting that the losses of P occurred mainly within the first 4 hr of heating. The results obtained partly explained immediate fertility degradation of heated soil unless proper management means are employed.

Key words: heating / ladang / Ultisols / watering

Vegetation fires during prolonged dry seasons in South Sumatra Province of Indonesia have been recorded for almost a hundred years. However, it is only in the last twenty years have they become a regular phenomenon and caused major economic and environmental damage not only within the country but also to its neighbors and to the global climate.

In addition, farmers have also been practicing shifting cultivations known as *ladang* since the ancient time. *Ladang* is the felling and burning of the forest followed by the planting of upland rice with other crops for one or two years. In such system, no chemical fertilizers are used. When the crop productivity declines, the fields are abandoned to forest re-growth. The long fallow (20 years) enables the fertility to regenerate that would be available for the next cycle. With increasing population, the fallow periods are shortened, and grasses, mainly *Imperata cylindrica*, which are more prone to fire, invade the areas. Thus, fire pressure has grown even more intense. However, the study on the effects of heating on soil characteristics is still limited (Kadir et al., 2001), although fire has assumed a prominent role in Indonesian forest.

During actual fire the resulting temperature and the duration of the thermal effects in the upper

soil might be variable. Severe or high intensity burning is typically found in areas of high fuel concentration, such as fallen logs and slash piles, and may have created surface temperature of 500℃ (Chandler et al., 1983; Wells et al., 1979). Giovannini and Lucchesi (1997) in an artificial burning experiment detected a temperature above 500℃, 57℃, and 18℃ at the depth of 0, 2.5, and 5 cm, respectively. In forest fires and chaparral fires, a temperature of 850℃ at the soil surface and slightly lower temperature at upper soil had also been reported (DeBano et al., 1979). Although Giovaninni et al. (1988) regarded duration of heating less important because the soil responded according to discrete model to heating, the actual fact in the field frequently showed that fire could persist for hours or days. Kang and Sajjapongse (1980) registered a temperature of 40 to 80℃, which could persist for several hours at the upper soil layer.

Heating caused by fire has been known to have important effects on soil chemical properties and could have beneficial and detrimental effects on soil fertility and plant growth. An increase of soil temperature above normal has been known to alter soil properties, kill roots, seeds, and soil microbes (Hungerfold et al., 1991). These effects depend on the amount of combustible fuel per unit area, the humidity of the fuel and the soil, the type of soil, the temperature level, and the length of heating. Heating has been reported to decrease organic matter content and CEC (Kitur and Frye, 1983; Giovannini et al., 1990; Giovannini and Lucchesi, 1997; Nishita and Haug, 1972; Sertsu and Sanchez, 1978). Nishita and Haug (1972), Sertsu and Sanchez (1978), and Kitur and Frye (1983) reported a decrease of Ca, Mg, and Na of heated soils. Potassium was reported to either increase (Nishita and Haug, 1972) or decrease (Sertsu and Sanchez, 1978; Kitur and Frye, 1983). Although there has been research regarding natural and prescribed fires in other vegetation types and in different regions as described above, we are unaware, however, of studies that have measured changes in properties of burnt tropical forest soils, which immediately receives water treatment.

Since 1998, we have monitored the changes and possible natural recovery of soils under different ecosystems with varied wildfire history in South Sumatra, Indonesia. However, at field scale it is difficult to distinct the possible causes of changes in soil properties because the effects of heat and input of ash are concomitant. To overcome these difficulties, we subjected the soil samples to artificial heating under controlled condition. To study possible changes in soil characteristics after rain in the field, we have conducted a laboratory experiment on the effect of watering on the characteristics of heated soils. In the current paper we reported the immediate modifications induced by heating on soil properties and those induced by watering on the heated soil.

MATERIALS AND METHODS

Soil material used in this study was from A horizon of an undisturbed forest soil in Pendopo, South Sumatra, Indonesia (103°30′ E, 1°23′ S), having elevation of 134 m and receiving 2,600 to 4,200 mm of precipitation annually with annual air temperature of 25℃. The area has mixed-tree species, i.e. *Agathis loranthifolia* Salibs, *Peronema canescens* Jack, *Shorea* spp., *Altingia excelsa* Noronhae, and *Durio zibethinus* Meur. Open spaces between trees are occupied by shrubs and grasses. A detailed description of the climate and vegetation in the study area was already given in Kadir et al. (2001). Soils of the study area are classified as Hapludult (Soil Survey Staff, 1999), equivalent to Yellowish-brown Podzolic (LPT, 1974). This soil can be considered as a representative undisturbed soil because

the area was under a conservation forest and the disturbances was minimized. Bulk samples of the soil were collected (0–10 cm) and air-dried, and passed through a 2-mm sieve. Selected soil properties are given in Table 1.

Table 1. Initial properties of the soil used in the experiment

Soil property	Indonesia Ultisols
pH-H_2O	4.36
pH-KCl	3.61
EC (mS m^{-1})	7.65
T-C (g kg soil^{-1})	31.21
T-N (g kg soil^{-1})	2.37
Exch. Ca (cmol(+) kg soil^{-1})	0.56
Exch. Mg (cmol(+) kg soil^{-1})	0.30
Exch. K (cmol(+) kg soil^{-1})	0.27
Exch. Na (cmol(+) kg soil^{-1})	0.02
CEC (cmol(+) kg soil^{-1})	27.56
Exch. Al (cmol(+) kg soil^{-1})	3.57
Exch. H (cmol(+) kg soil^{-1})	0.42
Available P (mg kg soil^{-1})	12.32
Sand (%)	22.1
Silt (%)	8.6
Clay (%)	69.3
Textural class	Clay (HC)*
Clay mineralogy	Kaolinitic

* "Clay" by USDA, "HC" by FAO/UNESCO

Soil samples weighing 200 g were placed in shallow porcelain crucibles and heated at 100, 300, and 500℃ in an oven or a muffle furnace for 4, 8, and 12 hours. The thickness of the soil in the porcelain crucibles was about 10 mm. Each treatment consisted of three replications arranged in a completely randomized design (CRD). After cooling, the samples were divided into two compartments. One was stored in plastic bags and tied closely until analyzed; while the other was watered with deionized water to field capacity and equilibrated in 250-mL plastic cups for one week.

Moist soil colors were determined with Munsell soil color chart. Particles size distribution was determined by the pipette method using 6 and 30%-H_2O_2 as a decomposing agent of organic matter. Clay minerals were identified by X-ray diffraction after saturation of the clay with K and Mg. Soil pH was measured in a soil to water or 1 M KCl ratio of 5 g to 25 mL after reciprocal shaking for 1 h (designated as pH-H_2O and pH-KCl, respectively). Electrical conductivity (EC) was measured before pH-H_2O measurement. The filtrate from pH-KCl measurement was then used for exchangeable Al and H analysis using the titration method. Exchangeable cations (Ca, Mg, K, and Na) were extracted three

times with 1M ammonium acetate (pH 7.0), followed by reciprocal shaking and centrifugation in a soil to solution ratio of 5 to 25 for 10 min at 200 g. The amount of exchangeable cations was then analyzed using atomic absorption spectrophotometer (Shimadzu, AA-610S). After extraction of the exchangeable bases, the residual fraction was then washed with 20 mL of deionized water once and twice with 20 mL of 99% EtOH to remove the excess salt. The ammonium was extracted with 30 mL of 10%-NaCl solution twice, followed by reciprocal shaking for 1 h. and centrifugation for 10 min at 800 g. The ammonium ion content was determined as cation exchange capacity (CEC) by Kjedahl distillation and titration method. Total Carbon (T-C) and Nitrogen (T-N) were determined by a dry combustion method with NC-Analyzer (Sumitomo, Sumigraph NC-80). Available phosphorus was extracted with an extracting solution containing 1N NH$_4$F and 0.5 N HCl, followed by reciprocal shaking for 1 min (Bray-1 method). The P content was measured using a spectrophotometer at 660 nm. Al, Fe, and Si oxides were extracted with 0.2M ammonium oxalate solution (pH 3.0), using reciprocal shaking in the dark for 1 h in a soil to solution ratio of 1 to 25 (Mckeague and Day, 1966), then designated as Alo, Feo, and Sio. Al, Fe, and Si oxides were also extracted with citrate-bicarbonate mixed solution (pH 7.3) with the addition of sodium dithionate at 75 to 80℃ for 15 min in a soil to solution ratio of 1 to 100 (Mehra and Jackson, 1960), then designated as Ald, Fed, and Si. Al, Fe, and Si were determined using a sequential plasma spectrometer (Shimadzu-ICPS-1000IV). All results are presented on an oven-dry basis (105℃).

All data collected were statistically analyzed with two objectives. The first objective was to compare the effect of the three different temperatures and the three different heating times on the characteristics of heated soils. The Costat V. 2.0 (Cohort) was used to perform a two-way analysis of variance and where significant differences were found at $P<0.05$, LSDs were calculated for mean separation. The second objective was to discriminate the effect of watering treatment on soil characteristics. The paired t-test was used to test whether differences between unwatering and watering treatments were statistically significant at $P<0.05$.

RESULTS AND DISCUSSION

Because the soil in the porcelain crucibles was about 10 mm thick, all results obtained were representatives of similar thickness of soils in the field. The summary of ANOVA is given in Table 2. Main effect of temperature was significant ($P<0.05$) on Fed and highly significant ($P<0.001$) on other parameters. The effect of heating time was significant on total C, exchangeable Mg, K, Na and Fed, and highly significant on total N. The interaction between temperature and heating time was significant on total C and exchangeable Ca and highly significant on total N and exchangeable K. The main effects of each treatment and the effects of watering on chemical characteristics of the soil are given in Table 4 to 6.

Soil Color
Although heating the soil at 100℃ did not significantly change the color of the dark brown Ultisols, it decreased the chroma of soil material by one unit (Table 3). Visually, the soils heated at 100℃ were slightly darker than the unheated soil. The darkening of the soil was due to the charring of organic matter (Boyer and Dell, 1980; Ulery and Graham, 1993). This mechanism seemed to operate in the current experiment. Heating the soil at 100℃ did not burn the organic C of the soil but it was enough to char the organic C. This is also confirmed by lack of changes in C content of soils heated at 100℃

relative to unheated soils (Table 5).

Table 2. **Statistical significance of the effect of heating temperature and time on the soil properties**

Parameter	Treatment		
	Temperature (T)	Time (D)	T x D
pH-H_2O	***	NS	NS
EC	***	NS	NS
Total C	***	*	*
Total N	***	***	***
Avail. P	***	NS	NS
Exchangeable cations :			
Al	***	NS	NS
H	***	NS	NS
Ca	***	NS	NS
Mg	***	*	*
K	***	*	**
Na	***	*	NS
CEC	***	NS	NS
Amorphous oxides :			
Alo	***	NS	NS
Feo	***	NS	NS
Sio	***	NS	NS
Crystalline oxides :			
Ald	***	NS	NS
Fed	*	*	NS
Sid	***	NS	NS

*, **, *** indicate significance at $P<0.05$, 0.01, 0.001, respectively.
NS indicates not significant at $P<0.05$.

Table 3. **Effects of heating on soil colors**

Temperature (℃)	Color
30	10YR3/4 (dark brown)
100	10YR3/3 (dark brown)
300	5YR3/2 (dark reddish brown)
500	10R4/6 (red)

The effect of heating was much more prominent at 300 and 500℃ at which, the color of soil material changed to reddish and red, respectively. The reddening can be attributed to the removal of organic C, the oxidation of Fe compounds, and the dehydroxylation of Fe compounds (Sertsu and Sanchez, 1978). The changes in Fe compounds, such as Fe oxides and significant removal of organic C

were also observed in current study, as will be given in the following section. In addition, the thermal conversion of goethite (yellow) to maghemite (reddish) and hematite (red), especially if organic matter is present, which contributes to an O_2-deficient environment has also been reported to be responsible for the reddening color (Schwertmann and Fechter, 1984; Ketterings and Bigham, 2000). Maghemite and hematite are highly effective pigmenting agents, imparting reddish brown and red colors, respectively, even when present in very small quantities (Schwertmann and Taylor, 1989). Scheffer et al. (1958) and Torrent et al. (1983) stated that only 1–1.7% of hematite could give a soil a red color.

Table 4. Effect of temperature and heating time on the amorphous and crystalline oxides

Treatment	Alo		Feo		Sio		Ald		Fed		Sid	
	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted
	(%)											
Heat												
None	0.68		0.95		0.03		0.88		5.21		0.24	
100℃	0.68 a x	1.33 x	0.97 a x	0.97 x	0.03 a x	0.01 y	0.89 a x	0.91 x	5.31 a x	5.26 x	0.24 a x	0.20 y
300℃	1.27 b x	1.33 x	1.19 b x	1.19 x	0.24 b x	0.23 x	1.04 b x	1.04 x	5.73 b x	5.56 x	0.28 a x	0.24 y
500℃	2.42 c x	2.95 y	1.37 b x	1.52 x	1.34 c x	1.96 y	2.20 c x	2.20 x	5.66 ab x	5.54 x	0.77 b x	0.75 x
Time												
4 hr	1.46 a x	1.62 x	1.21 a x	1.30 x	0.56 a x	0.72 x	1.41 a x	1.36 x	5.87 a x	5.55 x	0.45 a x	0.39 x
8 hr	1.43 a x	1.67 y	1.15 a x	1.11 x	0.53 a x	0.73 x	1.38 a x	1.39 x	5.46 ab x	5.27 y	0.43 a x	0.40 x
12 hr	1.49 a x	1.69 x	1.18 a x	1.26 x	0.51 a x	0.75 x	1.34 a x	1.39 x	5.37 b x	5.53 x	0.41 a x	0.40 x

Values are means for $n=9$; a, b, c indicate LSD comparison of means in the same column. The means followed by the same letter are not significantly different at $P<0.05$.

x, y indicate paired t-test comparison of means in the same row. The means followed by the same letter are not significantly different at $P<0.05$.

Table 5. Effect of temperature and heating time, and watering on T-C and T-N, pH, EC, and exchangeable Al and H of soils

Treatment	T-C		T-N		pH		EC		Al		H	
	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted
	g kg soil^{-1}						mS m^{-1}		cmol(+) kg^{-1} soil			
Heating												
No	31.21		2.37		4.36		7.65		3.57		0.42	
100℃	31.29 a x	31.08 x	2.51 a x	2.61 x	4.02 a x	4.57 y	16.87 a x	13.59 a y	3.47 a x	2.72 y	1.42 a x	0.56 y
300℃	6.74 b x	7.78 x	1.79 b x	1.82 x	5.15 b x	5.33 y	9.07 b x	10.60 b y	0.27 b x	0.25 x	0.29 b x	0.20 y
500℃	0.15 c x	0.83 y	0.04 c x	0.07 y	4.94 c x	5.28 y	7.51 b x	8.42 c x	1.00 c x	0.39 y	0.23 b x	0.13 y
Time												
4 hr	13.42 a x	13.52 x	1.54 a x	1.56 x	4.71 a x	5.07 y	11.44 a x	10.90 x	1.58 a x	1.13 y	0.66 a x	0.24 y
8 hr	12.48 a x	13.05 x	1.42 b x	1.45 x	4.70 a x	5.08 y	10.50 a x	10.52 x	1.55 a x	1.13 y	0.63 a x	0.34 y
12 hr	12.27 a x	13.12 y	1.39 b x	1.49 y	4.69 a x	5.03 y	11.51 a x	11.50 x	1.61 a x	1.11 y	0.66 a x	0.31 y

Values are means for $n=9$; a, b, c indicate LSD comparison of means in the same column. The means followed by the same letter are not significantly different at P<0.05.

x, y indicate t-test comparison of means in the same row. The means followed by the same letter are not significantly different at $P<0.05$.

Table 6. Effect of temperature and heating time, and watering on exchangeable bases, CEC and available P of soils

Treatment	Ca		Mg		K		Na		CEC		Avail. P	
	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted	Unwetted	Wetted
	---------- cmol(+) kg⁻¹ soil ----------										-- mg P_2O_5 kg⁻¹ --	
Heating												
No	0.56		0.30		0.27		0.02		27.56		12.32	
100℃	0.64 a x	0.63 x	0.28 a x	0.33 y	0.29 a x	0.36 y	0.03 a x	0.09 y	26.48 a x	26.58 x	11.83 a x	9.73 x
300℃	0.63 a x	0.68 y	0.23 b x	0.28 y	0.29 a x	0.34 y	0.08 b x	0.15 y	17.96 b x	19.95 y	4.74 b x	1.91 y
500℃	0.34 b x	0.37 x	0.19 b x	0.31 y	0.02 b x	0.09 y	0.01 c x	0.02 y	17.43 b x	15.31 y	1.69 b x	0.80 x
Time												
4 hr	0.57 a x	0.56 x	0.25 a x	0.30 y	0.21 a x	0.26 y	0.05 a x	0.08 y	21.32 a x	21.04 x	5.98 a x	3.66 y
8 hr	0.51 a x	0.56 x	0.23 a x	0.31 y	0.19 a x	0.24 y	0.04 a x	0.08 y	20.48 a x	20.22 x	5.95 a x	4.39 x
12 hr	0.54 a x	0.58 x	0.22 a x	0.30 y	0.19 a x	0.30 y	0.04 a x	0.10 y	20.07 a x	20.57 x	6.32 a x	4.38 y

a, b, c indicate LSD comparison of means in the same column. The means followed by the same letter are not significantly different at $P<0.05$.

x, y indicate paired t-test comparison of means in the same row. The means followed by the same letter are not significantly different at $P<0.05$.

Particle Size Distribution, Mineralogy and Oxide

The soil used in current study was initially high in clay (69%) but low in sand (22%) prior to heating. The changes in particle size distribution in relation to heating were averaged over different temperatures and different heating times, and the results are given in Figure 1. Exposing the soil to 100℃ had little effect on the particle-size distribution and did not change the textural class of the soil (Fig. 1a). At 300℃, the laterization process occurred, causing a significant increase in sand (from 22.1% to 27.2%) but a significant decrease in clay (from 69.3% to 51.5%), which then resulted in coarser textural class. These changes were caused by the fusion of clay particles into sand-sized particle as a result of thermal modification of the iron and aluminosilicate (Betremieux et al., 1960), and were in a good agreement with those obtained in laboratory study by Sertsu and Sanchez (1978), and field study by Kadir et al. (2001).

The length of heating at above-normal temperature appeared to be crucial to soils. Although exposing the soil to high temperature for 4 hr had little effect on silt fraction, this 4-hr period was seemingly a critical time for changes in clay and sand fractions. During the first 4 hr, clay fraction decreased by 35% (from 69.3% to 44.9%), while sand fraction increased by 115% (from 22.1% to 47.6%) (Fig. 1b). A further increase in heating time caused further decreases in clay fraction, increases in silt fraction, but did not alter the sand fraction. These results implied that the fusion of clay particles into sand-sized particles mostly occurred during the first 4 hr of continuous exposure to elevated temperatures. Therefore, in addition to heat pulse penetration produced by burning, the length of a fire persisting in the field is also a crucial factor determining the total effect of fire on physical properties of soils.

Mineralogically, kaolinite was a predominant (94%) found in clay fraction of the soil, while the others existed in much smaller proportion prior to heating treatment. The weakening of diagnostic
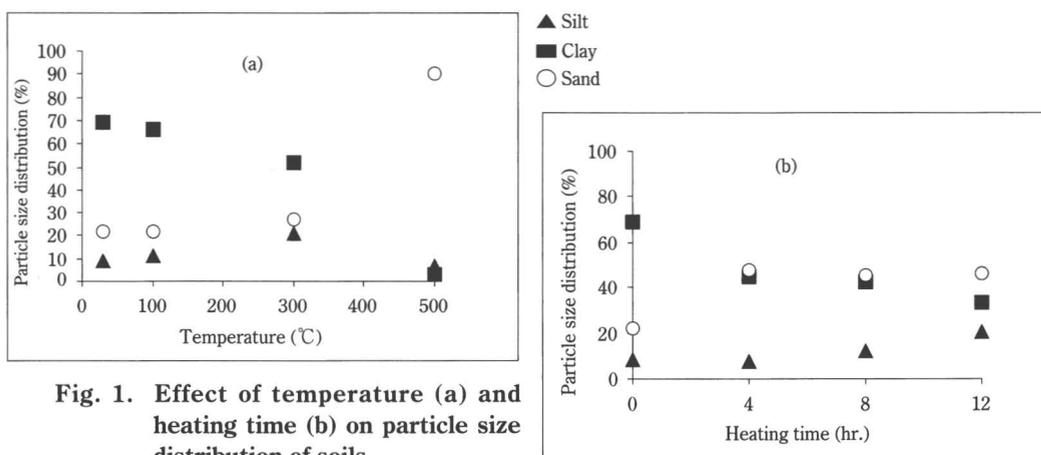
Fig. 1. Effect of temperature (a) and heating time (b) on particle size distribution of soils
(a) Averaged over 4, 8, and 12 hr
(b) Averaged over 100, 300, and 500°C

XRD peaks for kaolinite was observable at 100°C, gradually decreased at 300°C, and completely disappeared at 500°C. Unfortunately changes in other minerals, especially those exist in much lower proportion, could not be further detected with XRD technique. However, our results showed that soil heating at low temperature (100°C) was enough to cause significant changes in soil mineralogy, which then might have significant effect on other characteristics of soils.

Heating significantly affected Al, Fe and Si oxides of the soils but the effect of heating time was significant only on Fed (Table 4). Exposing the soils to 100°C did not cause marked changes in oxides status of the soils. Given the fact that the content of oxides has been known closely related with organic matter content (Sakurai et al., 1996), the release of Alo, Feo, and Sio did not occur at 100°C because at this temperature, the organic C was charring, instead of being combusted. It was confirmed by the lowering chroma, resulting in darker soils. In addition, total C of soils heated at 100°C was not different from the unheated soils, as will be shown in the following section. Similarly, no changes in the Ald, Fed, and Sid could be observed at 100°C because at this temperature, the oxidation of oxide compounds, the removal of total C, and the dehydroxylation of oxide compounds as described by Sertsu and Sanchez (1978) did not occur yet. However, increasing temperature to 300 and 500°C significantly increased the amount of oxides of Al, Fe, and Si of soils. Combustion of total C released the Alo, Feo, and Sio oxides into the soil. In addition, increasing temperature also caused thermal modification of the iron and aluminosilicate, releasing Ald, Fed, and Sid. The decomposition of poorly crystalline aluminosilicates and amorphous Si and Al from kaolin during burning has been found to contribute to the formation of sand-sized aggregates in severely burnt soils (Ulery and Graham, 1993).

In current experiment we did not detect consistent effect of watering on oxides of the heated soils (Table 4). Intense heating has been shown to induce water repellency in soils (DeBano et al., 1976; Giovannini and Lucchesi, 1983). The effect of watering on oxides was significant only on Alo of soils heated at 500°C, Sio of soils heated at 100°C and 500°C and on Sid of soils heated at 100°C and 300°C (Table 4). The losses of organic matter and thermal modification of the iron and aluminosilicate seemed

to be the main cause.

Exposing the soil to high temperatures for 4 hr increased levels of soil oxides compared to the unheated soils but no further changes in their content at longer periods of heating (Table 4). It confirmed that the changes in oxides had occurred during the first 4 hr of heating.

Soil Total Carbon and Nitrogen

Resulting temperature and heating time are two important factors, determining the effects of fire on soil characteristics (Kang and Sajjapongse, 1980). Artificial heating in current experiment showed that temperature and heating time significantly affected both total C and N contents. There was no change of total C at 100℃ as compared with unheated soil but at 300 and 500℃ a significant decrease occurred (Table 5). The lack of changes in total C content of the soil at 100℃ was likely related to the stage before burning. As mentioned by Sandberg et al. (1979) and Pyne et al. (1996), at the stage before burning, both dehydration and pyrolysis occurred at which moisture in the soil was driven out of the soil, and to some extent could cause decomposition of long-chain organic molecules (Shafizadeh, 1984). Pyrolysis causes formation of char, which is a carbonaceous residue left in the soil that is neither intact organic compound nor pure C. In the current study we found a shift in color toward darker color of soils exposed to 100℃ (Table 3), which is usually related with charring organic matter. Organic C in the soil is usually destructively distilled between 200 and 300℃ (Hungerfold et al., 1991) and almost totally combusted at 500℃ (Hosking, 1938). Our results showed that heating the soil at 300 and 500℃ resulted in loss of about 78% and 99% of the soil total C, respectively. These figures were in a good agreement with those reported by Hosking (1938) and DeBano et al. (1998).

The temperature and length of heating combination is a crucial factor. Although heating the soil at 100℃ did not change total C and N content of the soil, increasing heating temperature from 100℃ to 500℃ was followed by significant decrease in total C and N of soil (Fig. 2). The result of current experiment indicated that the temperature of 300℃ appeared to be crucial. At this temperature, a significant decrease of total C and N was already observable 4 hours after exposure. At 500℃, almost total elimination of total C and N occurred, regardless of the duration, because at this temperature, most if not all of organic matter, which was the main reserve of C and N, was already combusted.
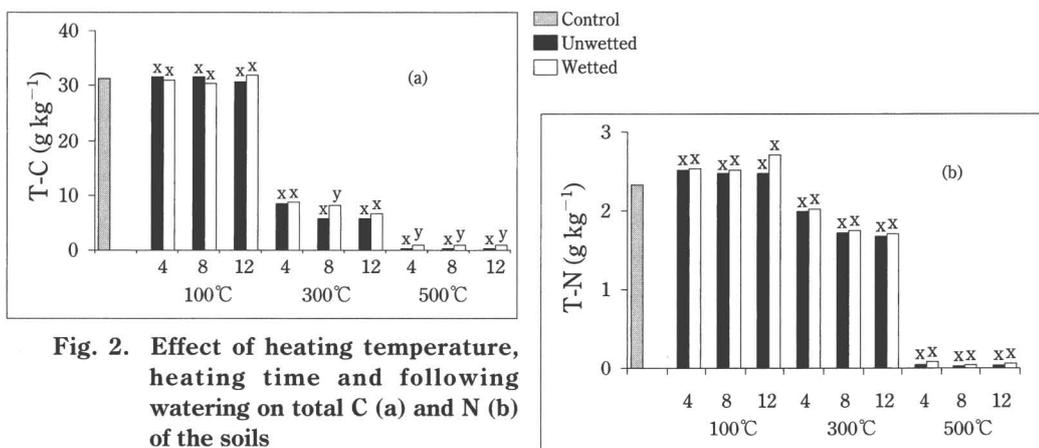

Fig. 2. **Effect of heating temperature, heating time and following watering on total C (a) and N (b) of the soils**

When treated with water, the total C of soil exposed to $100\,^\circ\text{C}$ within different times did not change (Fig. 2a). Although soils exposed to $300\,^\circ\text{C}$ and received water treatment tended to have higher total C content than those exposed to the same temperature but did not receive water treatment, significant difference was detected only on soils exposed to $300\,^\circ\text{C}$ for 8 hr. However, soils treated $500\,^\circ\text{C}$ and received water treatment had total C content of 5 to 7.5 times higher after receiving water treatment and statistically different from those did not receive water treatment (Fig. 2a). On the other hand, although watering increased total N of soil at all temperature levels, the difference was not enough to be statistically different from unwatered soils (Fig. 2b). The source of both C and N turnover in current experiment was not apparent. However, possible sources included dissolved C and N in water and microbial cells.

Soil pH, EC, Aluminum, and Hydrogen Levels

Heating significantly affected soil pH, EC, and solubility of exchangeable Al and H of the soil. When the soil was heated at $100\,^\circ\text{C}$, there was slight decrease of soil pH as compared with unheated soil, followed by a significant increase at $300\,^\circ\text{C}$ and significant decrease at $500\,^\circ\text{C}$ (Table 5). The cause of decrease in pH at $100\,^\circ\text{C}$ was most likely due the increasing solubility of H ions when the soil was heated at $100\,^\circ\text{C}$. Similar results had also been reported by Kitur and Frye (1983) who argued that the decreases in pH might be due to organic acids being released more rapidly than base elements at this temperature. In a field experiment Blank et al. (1994) also found elevated amount of organic acids immediately after wildfire in the surface 5 cm of under-shrub soils. As described earlier, during dehydration and pyrolysis at the preignition stage of a fire, decomposition of long-chain organic molecules also occurred (Shafizadeh, 1984). Pyrolisis of humic fraction in soils has been shown to produce organic acids (Blank et al., 1994). In addition, the lowering of buffer capacity due to combustion of organic C and the exposure of new surfaces were other possible mechanisms contributing to the lowering pH (Giovannini and Lucchesi, 1997; Nishita and Haug, 1972). Johnson (1916) suggested that the lowering pH could also be attributed to an increase in CO_2 with heating, but it seems unlikely that H_2CO_3 could persist to an appreciable extent at $100\,^\circ\text{C}$. On the other hand, the increasing pH at higher temperature might be attributed to significant losses or precipitation of Al and H ions due to liming effect of heating (Table 5), the formation of oxides of several elements (Nishita and Haug, 1972), and release of NH_3 (Kitur and Frye, 1983).

Watering increased pH of soils heated at each temperature (Table 5). This increase was in accordance with decreases in soluble Al and H in the heated soils receiving water treatment (Table 5). Watering had caused precipitation of Al and H in the heated soils, most likely mediated by carbonates. In contrast, the solubility of exchangeable bases increased as will be given in the following section.

Electrical conductivity, taken as a measure of soluble salts, was significantly affected (p<0.001) by the temperature but not by the heating time (Table 2). The EC of soil heated at $100\,^\circ\text{C}$ doubled as compared with the unheated soil, then decreased significantly above this temperature (Table 5). The large increase in the EC at $100\,^\circ\text{C}$ might have been due to the increase in Ca and Na of the soil at this temperature. When regressed on the exchangeable bases, the EC was significantly correlated ($p<0.001$) with the exchangeable Ca, Mg and Na but not with the exchangeable K. On the other hand the following decrease at higher temperature would be due to significant decreases of all exchangeable bases (Table 6).

When the heated soils were treated with water, the EC of soil heated at $100°C$ significantly decreased but the EC of soils heated at $100°C$ in contrast significantly increased (Table 5). The cause of decreased EC in soil heated at $100°C$ was not apparent because all exchangeable bases but Ca significantly increased after watering (Table 6). However, mechanisms as described by Kitur and Frye (1983) might have occurred in the heated soil. In their study Kitur and Frye (1983) found an increase in water-soluble SO_4^{2-} at 110 and $200°C$. On the other hand, significant increases in EC of heated soil and receiving water treatment were in accordance with the increasing all exchangeable bases observed in current study.

Exchangeable Bases and CEC

Heating significantly affected exchangeable bases of forest soil. Exchangeable Ca, K, and Na increased as the soil was heated up to $300°C$. Such increases had also been indicated in previous reports (Nishita and Haug, 1972; Kitur and Frye, 1983; Giovannini et al., 1990; Ketterings and Bigham, 2000) but none reported the possible mechanisms responsible for such increases. However Kim et al. (1999) also found an increase in Ca, Mg, and K and related the increase with the accretion of ash from burning of surface organic matter. Although soils used in current experiment were visually free from plant residue, the initial total C content was 31 g kg^{-1} (Table 5). The decomposition of this C source due to heating might have contributed to the increases in exchangeable bases.

Increasing temperature to $500°C$ caused decline of all exchangeable bases and significantly different from the lower temperatures (Table 6). Such a decrease may have been due to the formation of insoluble oxides and carbonate of these elements, as suggested by Sertsu and Sanchez (1978). In addition to losses of total C, the decrease was also related with decreases in clay fraction of the soils. The aggregation of fine particle into sand-sized particles caused a decrease in the surface area in contact with the NH_4-OAc. Therefore the exchangeable bases remained trapped inside the aggregates and not be extracted.

Exchangeable Mg behaved differently from the other bases. This cation significantly decreased with increasing temperature. It suggested that the formation on insoluble oxides and carbonates of this element as suggested by Sertzu and Sanchez (1978) occurred at lower temperature than that for Ca, K, and Na.

When the heated soils were watered, we found significant increase of exchangeable bases at all temperature levels, compared to the unwatered soils (Table 6). As the water was added, the oxides and mainly carbonate of the exchangeable bases (Sertsu and Sanchez, 1978) might have been dissolved and released into soil solution.

Although the exchangeable bases except Ca were significantly affected by the heating time of a soil to different temperatures (Table 2), the differences within the times were not statistically different. If the mechanisms suggested by Sertsu and Sanchez (1978) occurred, the results obtained in Table 2 implied that most of oxides and carbonates of the exchangeable bases formed in the first 4 hours of heating.

Cation exchange capacity (CEC) (Table 6) significantly decreased with increasing temperature but not with increasing time. The combustion of organic matter was contributing to the decreased CEC following heating in current experiment. The data showed that CEC was significantly correlated ($p < 0.001$) with total C content (CEC $= 16.34 + 0.336$ x Total carbon). Due to the combustion of organic

matter, most if not all of the exchange sites had been disrupted. Because most of total C was combusted at 300 and 500℃, the possible source of CEC was clay. However, the clay fraction of the soils also dropped significantly at these temperatures (Fig. 1). The aggregation of finer particles into sand-sized particles at higher temperature with the consequent decrease of the reactive surface area (Giovannini and Lucchesi, 1997), and dehydration of the mineral crystal lattice and the resulting breakdown of the lattice (Giovannini et al., 1990) had caused further reduction of the CEC at higher temperatures.

In current study we also found significant relationship between CEC and amorphous oxides represented as Alo ($p < 0.001$), Feo ($p < 0.005$), and Sio ($p < 0.005$) and crystalline oxides represented as Ald ($p < 0.005$) and Sid ($p < 0.005$). The increases in these oxides due to heating were followed by decreases in CEC of the soils. Heating has enhanced the release of these elements through the disruption of mineralogical properties of the soils. However, because the CEC of Al and Fe oxides is low, the increases in their content adversely decrease the CEC of the soil.

Available P

The available phosphorus significantly decreased with increasing temperature (Table 6). This result was in contradictory with previous studies (Giovannini and Lucchesi, 1997; Giovannini et al., 1990; Kitur and Frye, 1983; Sertsu and Sanchez, 1978), which reported an increase of available P with increasing temperature. They attributed this increase to the decomposition of organic matter present on the soil surface. It suggested that the increase in P they observed did not present the actual changes in available P in soil. In addition, they did not consider the losses of P through nonparticulate transfer, which could account for 60%, when organic matter is totally combusted (Raison et al., 1985). In current experiment, the soil used was free from plant residue. Therefore, the only possible source of P was expected from organic C pool in the soil. However, instead of gaining available P decreased as temperatures increased. Although the losses of P were negligible at 100℃ as compared with pre-heating level, about 62 and 86% of P lost at 300 and 500℃, consecutively (Table 6). These losses were corresponding with 78 and 99% loss of total C at the same temperatures as compared with the pre-heating level (Table 5). Statistically the reduction in available P was significantly correlated with the loss of total C from the heated soils (Available P=0.400+0.316 x Total carbon, $p < 0.001$).

Heating time did not significantly affect available P of the soils (Table 2). However, exposing the soils to high temperature continuously for 4 hr caused 52% reduction of available P but further increase in the heating time did not cause any changes in P status of the soil (Table 6). These results suggested that the losses of P from the soil in relation to heating occurred during the first 4 hr. It once again confirmed that significant changes in soil characteristics due to elevating temperatures occurred within 4 hr.

Water treatment decreased available P of heated soil (Table 6). Under acidic condition, as found in current study, P is immobilized in insoluble compounds. Williams et al. (1958) and Williams (1960) found that the P sorption capacity of acid Scottish soils was closely related to the Alo. In current experiment, we also found significant increases in oxides of Fe, Al, and Si as the soils were heated. Decreases in available P were significantly correlated with increases in Alo ($p < 0.001$), Feo ($p < 0.001$), and Sio ($p < 0.001$) and Ald ($p < 0.001$) and Sid ($p < 0.001$). With the addition of water, the chemical reactions involved in the formation of insoluble complex of Al- and Fe-P were insured, as shown by

lower available P in soils receiving water treatment than those not receiving water treatment (Table 6).

PRACTICAL IMPLICATIONS

Darkened soils that resulted from low- and medium-severity burns are preferred for agricultural productivity by farmers in Sumatra, Indonesia, because they were associated with higher crop yield and quicker crop establishment. On the other hand, areas of reddened topsoil were classified as undesirable due to their perceived low fertility status and poor water-holding capacity (Kettering, 1999). From the results of the current study, it is clear that heating the soils at 100°C for a short period, which could be regarded as *light* burning usually practiced by farmers in the field, did not cause significant changes in soil chemical characteristics. However, cautions must be given because increases in sand fraction but decreases in clay fraction started occurring at this temperature. At field scale such increase would have more important implication because it can increase soil erodibility. In contrast heating at 300 and 500°C, a representative of *intensive* burning for longer periods, for example during forest fires, adversely affected soil characteristics. In current experiment it was found that changes in all characteristics occurred during the first four hours.

Watering to some extent showed positive effects on chemical characteristics, except available P of soils. On the other hand nutrient losses through leaching and/or erosion could concomitantly occur due to direct expose of the soils to precipitation. In the field, burning and watering of the surface soils occur repeatedly. In other words, intensive oxidation and reduction occur alternatively, which cause more weathering and degradation of soils. To protect land and biological resources in the tropics, prevention of forest fire is one of the most important practices.

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