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Note

High fire temperature changes soil aggregate stability in slash-and-burn agricultural systems

Edivaldo Lopes Thomaz

Midwest State University – Dept. of Geography – Soil Erosion Lab., R. Simeão Camargo Varela de Sá, 03, C.P. 3010 – 85040-080 – Guarapuava, PR – Brazil.
e-mail <thomaz@unicentro.br>

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ABSTRACT: Fire is a key controlling factor in ecosystem dynamics worldwide, especially, in tropical areas under slash-and-burn agricultural systems. Farmers use fire as a tool to clean the land, and benefit from nutrient enrichment from ash-soil heating. However, fire can cause some detrimental effects on soil systems, such as organic carbon depletion, increased soil erodibility, and changes to aggregate stability. In this study, an experimental fire was applied to a plot of land following the local traditional practice of slash-and-burn. The fire temperature was monitored in the field, and its effect on soil aggregate stability was assessed. The fire temperature on soil surface was measured in four trenches, and it ranged from 355 to 660 °C (average 484 ± 142 °C). The fire temperature did not affect soil organic matter content. However, aggregate stability increased by 10 % in comparison to unburned soil. Moreover, the geometric mean diameter of burned soil was 20 % higher than that of unburned soil. In conclusion, high fire temperature changes soil aggregate stability in slash-and-burn agricultural systems.

Keywords: burn severity, prescribed fire, soil erodibility, marginal land, subsistence agriculture

Introduction

The soil is a key component of the Earth system that control the biological, hydrological, geomorphological and geochemical cycles. In addition, the soil is a source of resources, goods and services for humankind (Keesstra et al., 2012; Brevik et al., 2015; Hedo et al., 2015; Smith et al., 2015; Wang et al., 2015). Fires have proven to significantly change the hydrological and geomorphological processes in hillslope (Lasanta and Cerdà, 2005; Shakesby and Doerr, 2006; Keesstra et al., 2014). Post-fire topsoil dramatically alters soil system functionality (Bodí et al., 2014; Doerr and Cerdà, 2005; Cerdà and Doerr, 2008; Pereira et al., 2015).

Most studies that investigate fire effects on soil properties have assessed mostly wildfire conditions (Bento-Gonçalves et al., 2012; Certini, 2005; DeBano, 2000; Shakesby and Doerr, 2006). Furthermore, in a recent review of fire effects on soil aggregation, most studies were conducted in Spain, that is, a Mediterranean ecosystem (Mataix-Solera et al., 2011). Only one study discussed in that review focused on the effects of slash-and-burn agricultural systems on soil quality in tropical environments (Are et al., 2009). In addition, no-tillage is practiced in the slash-and-burn agriculture as one of oldest system of soil management (Cerri et al., 2007).

Despite agricultural modernization, the slash-and-burn system is prevalent in tropical regions, such as Latin America (Grau and Brown, 2000; Silva-Forsberg and Fearnside 1997; Thomaz, 2013), Africa (Are et al., 2009; Ngo-Mbogba et al., 2015; Obale-Ebanga et al., 2003), and Asia (Bruun et al., 2009; Liao et al., 2015; Tanaka et al., 2005).

In spite of recent worldwide changes in slash-and-burn systems (e.g., economic and demographic changes, environmental impact, fallow length, etc.) (van Vliet et al., 2012), this agricultural system will persist as an important land-use and subsistence strategy in tropical countries for many years (Mukul and Herbohn, 2016). Overall, studies on soil physics and soil hydrology, that is, soil erosion, soil infiltration capacity, soil structural stability, are still limited (Mukul and Herbohn, 2016). Here, different fire intensities measured at field conditions were evaluated in relation to their effect on the structural stability of tropical soil under slash-and-burn systems.

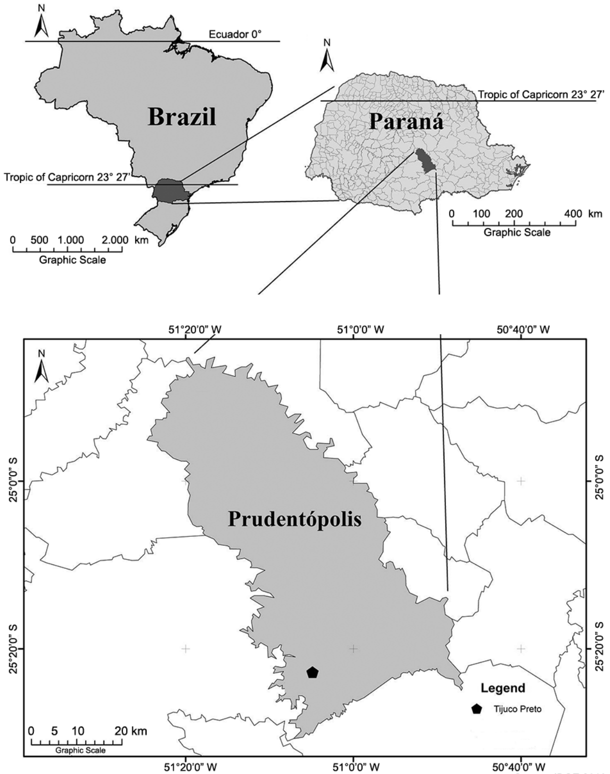
Materials and Methods

Site characteristics

This study was carried out at the Faxinal System, located in the rural community of Tijuco Preto in the Prudentópolis municipality of southern Brazil (25°23′46.6″ S, 51°6′21.7″ W) (Figure 1). The altitude of the site averages 800 m (above sea level). The study site, typical for the region, covers 17 ha in size and under shifting cultivation. It was chosen to assess the effects of fire on the physical and chemical properties of soil (Table 1). The climate is classified as a Cfb (humid temperate climate with temperate summer) temperate climate with average temperatures during the coldest month below 18 °C (mesothermal), cool summers with average temperatures during the warmest month below 22 °C, and no dry season. Annual averages range from 1600 to 1800 mm for rainfall, 900 to 1000 mm for evapotranspiration, and 16 to 18 °C for temperatures (Caviglione et al., 2000).

Table 1 – Soil Characteristics.

Soil type: Cambisol (IUSS Working Group WRB, 2006)	Sand	Silt	Clay
	——	kg kg^{-1}	——
Soil depth (0 -20 cm)	323	331	345
Chemical content		0-20 cm	
pH (CaCl$_2$ 0.01M)		3.4	
Soil organic matter (g kg^{-1}) (Walkley-Black, 1934)		28.0	
P (Mehlich) (mg kg^{-1})		1.9	
CEC (cmol kg^{-1})		21.7	
Base saturation (%)		16.9	



Source: IBGE 2016

Figure 1 – Location of the study site.

Measurement design

A ~1.5-ha plot with 44 ± 15 Mg ha^{-1} (n = 12) of biomass was slashed, dried, and burned, according to the local slash-and-burn system for cropping maize and black beans. Four trenches covered with biomass were monitored during the course of this study. A set of three thermocouples was placed in each trench at the following depths: 0 cm on top of the mineral horizon beneath the litter layer, 1.0 cm within the mineral horizon, and 2 cm within the mineral horizon.

Three soil samples were collected with a metal ring (50 cm^3 in volume, 2.5 cm in height) at depths 0-2.5 cm. The samples were collected approximately 12 h after the fire. The samples were collected at distances no greater than 50 cm from the trench center. This procedure ensured that the measurements accurately reflected the relationship between the registered temperatures and the associated temperature effects on soil properties. Unburned soil samples collected before the fire were used as control.

Measurement of soil physical properties

Three soil samples closer to the thermocouples were collected and split into six samples. Through wet sieving (WS), the samples were then fractionated according to the following sieve sizes: 4.0, 2.0, 1.0, 0.5, 0.25, and 0.125 mm. The soil samples (25 g) were subjected to immersion for capillary wetting, and the material remained in this condition for 5 min. The material was then shaken gently with upward and downward movements for 20 min at 40 rpm. The material removed from the sieves was dried (105 °C for 24 h) and weighed. The sand fraction was collected through a sieve with 0.053 mm mesh.

The distribution and quantity of aggregates (weight and percentage) were measured using the percentage of aggregate amounts retained in each sieve in relation to the total sample amount. The sand fraction contained in the aggregates was discarded in the analysis. Indices of the aggregates – the aggregate stability index (AS %) (Equation 1) and the geometric mean diameter (GMD) (Equation 2) – were obtained using the equations below. Each treatment (unburned and four measured temperatures) had six replicates for comparison in order to detect temperature effects on soil aggregate stability.

Results of the indices described above can have different interpretations. The percentage of AS can vary from 1 to 100 % and indicate the aggregation, whereas the GMD is used to indicate the class of aggregates found most frequently in the soil (Castro Filho et al., 2002; Hillel, 1998).

$$AS\% = \frac{WA - WI - S}{W - S} \times 100 \qquad \text{(Equation 1)}$$

where: AS% = aggregate stability as a percentage, WA = weight of aggregates > 0.25 mm, WI = weight of aggregates < 0.25 mm, W = sample weight, and S = sand.

$$GMD = \exp\left(\frac{\sum w_i \log x_i}{\sum ws_i}\right) \qquad \text{(Equation 2)}$$

where: GMD = geometric mean diameter, w_i = weight of the aggregates of each size class (g), log x_i = logarithm of the mean diameter of the size classes, ws_i = sample weight.

Soil organic matter was analyzed using three soil samples collected with a metal ring (50 cm^3 in volume, 2.5 cm in height) at depths 0-2.5 cm. The samples were collected approximately 12 h after the fire. The samples were collected at distances no greater than 50 cm from the center of the trench. Soil organic matter content was determined by the Walkley-Black method (Walkley and Black, 1934).

Data analysis

The analysis of variance (ANOVA) of the soil parameters was performed to compare soil properties in each treatment before and after soil heating. Differences between individual averages were tested using the post-hoc Dunnett test at $p < 0.05$, since the objective was to compare fire effects on soil properties in relation to unburned soil (control samples). The samples were checked for homoscedasticity and normality (Shapiro-Wilk). Additionally, a simple correlation analysis was performed to evaluate the response of the geometric mean diameter changes following the temperature gradient.

Results and Discussion

Fire temperature dynamics

Surface soil fire temperatures measured in the four trenches ranged from 355 to 660 °C (average 484 ± 142 °C) (Figure 2A). The temperature dropped abruptly between depths 1 cm and 2 cm, and was slightly above 56 °C at both depths. In addition, the higher the temperature, the shorter was its residence time (Figure 2B). The temperatures registered were similar to those found in the literature, since high surface temperatures persist for only a few seconds (Bento-Gonçalves et al., 2012) and temperature decreases at depth (DeBano et al., 1998).

Fire severity or burn severity is related to fire intensity (peak temperatures and energy release) and temperature residence time (Keeley, 2009). In the study site, the temperature recorded ranged from moderate (355 °C) to high (660 °C). Therefore, ecosystem responses such as soil erodibility and changes in soil aggregation are expected. Critical changes in physical, chemical, and mineralogical soil properties can be expected in soil systems influenced by severe fire (Certini, 2005; DeBano et al., 1998; Ulery and Graham, 1993). In this study, a noticeable change in soil aggregate stability due to fire temperature was detected and it will be explained further.

Fire temperature effects on organic matter and aggregate stability

In this study, the fire temperature did not affect soil organic matter content (Figure 3A). Despite the high temperatures prevalent in the burned soil, no significant loss of organic matter (OM) was observed. One possible explanation for this may be the peak temperature that did not last long enough to reduce OM (Figure 2B). Additionally, the topsoil was rich in large aggregates (4-8 mm), which may have had a protective effect on OM because much of it was located inside of aggregates isolated from the high surface temperatures. In a previous study, we observed no effect of fire on soil organic depletion at topsoil, that is, 2.5 cm at depth (Thomaz et al., 2014). In contrast, we observed, in a laboratory experiment, that a temperature of 250 °C lasting 15 min was enough to reduce OM (Thomaz and Fachin, 2014). However, field experiments are complex, and many variables cannot be controlled properly (e.g., fire intensity, soil moisture, soil texture, etc.). Conversely, results obtained in the laboratory are not translated directly into the field-scale effects of fire (Úbeda and Outeiro, 2009).

Aggregate stability increased only at the highest temperature, in comparison to unburned soil and other lower temperatures (Figure 3B). Aggregate stability was 10 % higher in comparison to unburned soil. Overall, the slash-and-burn agricultural system displayed stable

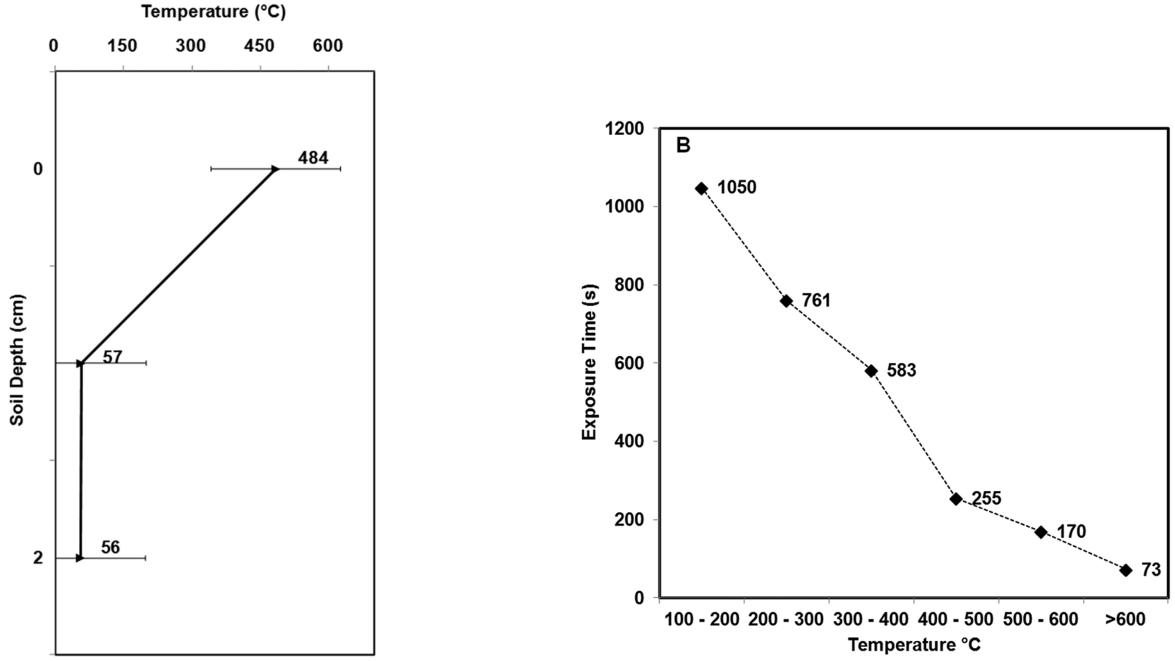


Figure 2 – Fire temperature dynamic: A) temperature in soil profile; B) residence time according to temperature class.

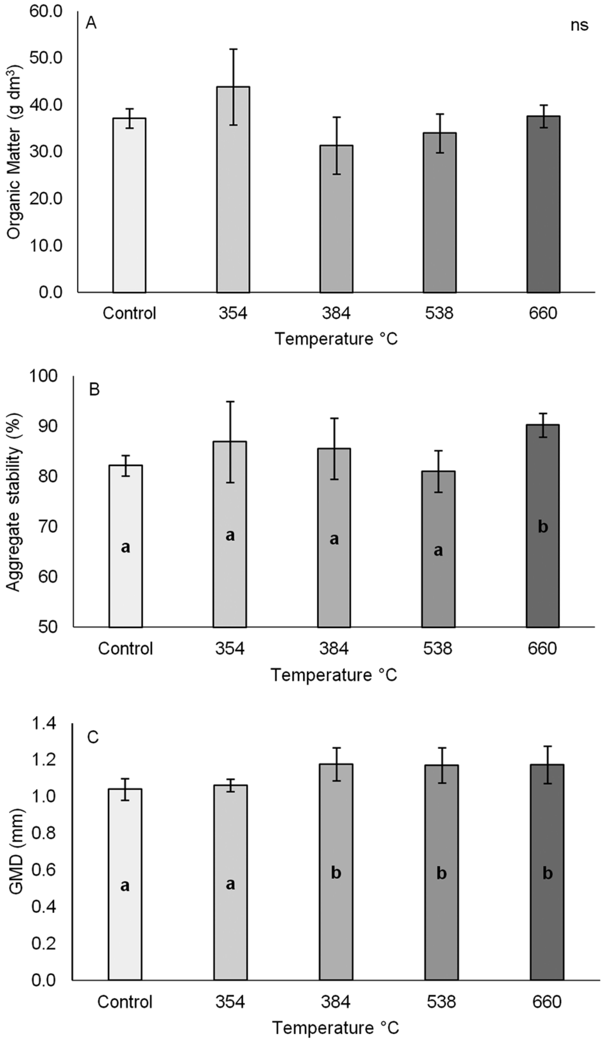


Figure 3 – Effects of fire on soil properties according to temperature gradient: A) Organic matter content; B) Aggregate stability increases at very high temperature; C) Geometric mean diameter increases at moderate to very high temperature. The same lowercase letters in the bars indicate no significant difference at 0.05 % level according to Dunnett test.

aggregates in the topsoil (82 ± 6%; average), in relation to the unburned soil. However, the increase in aggregate stability at the highest temperature could be ascribed to the effect of fire on the topsoil.

Furthermore, the geometric mean diameter (GMD) of burned soil increased by 20 % in comparison to the unburned soil (Figure 3C). In other words, larger aggregates became more frequent in burned soil than in unburned soil, and GMD increased from ≥ 1.0 ± 0.1 mm in the unburned soil to ≥ 1.2 ± 0.1 mm at the highest temperature (660 °C). Moderate temperature (354 °C) was not sufficient to change aggregate stability. Overall, GMD increased linearly from unburned soil to the highest temperature (r = 0.813, p = 0.09).

In this study, soil physical properties were affected by fire: in particular, aggregate stability at the highest temperature, and geometric mean diameter at moderate-to-high temperatures. In tropical soil, aggregate stability is associated with the presence of Fe and Al oxides. These oxides act as the main cementing agents along with organic matter in the soil (Amézketa, 1999; Tisdall and Oades, 1982).

Aggregate stability tends to be high in tropical soils, even under fire activity. Aggregate stability increases in tropical soils when subjected to fires of medium-to-high severity (Mataix-Solera et al., 2011). Temperatures higher than 400 °C transform mineral components of the soil, such as Fe and Al oxyhydroxides, through the process of recrystallization, and even higher temperatures (600-700 °C) can cause thermal fusion of clay minerals (Certini, 2005; Ulery and Graham, 1993).

In addition, findings of the previous laboratory tests support the increase in aggregate stability reported in the present study. An increase in aggregate stability was observed when the temperature increased from high (550 °C) to very high (650 °C), in spite of soil carbon reduction (Thomaz and Fachin, 2014). Overall, the slash-and-burn system displayed immediate effects on some soil physical properties (Are et al., 2009; Thomaz et al., 2014).

Stable aggregates are desirable in order to reduce sealing, crusting, and erodibility (Le Bissonnais, 1996). However, little is known about the potential effects of increased stability on the functionality of aggregates in soil systems over medium to long-term periods (Mataix-Solera et al., 2011). In addition, it is necessary to know in agriculture fields if the aggregates affected by fire are less rich in nutrients, because the temperature may damage the chemistry, biology and fertility of the soil.

Conclusions

Fire temperature at soil surface in slash-and-burn agricultural systems is moderate to very high; however, the residence time of such temperatures is short. The temperature decreases abruptly at soil depth. Despite moderate-to-high temperatures, no carbon content depletion occurs at topsoil. However, significant changes in aggregate stability occur in this agricultural system.

Aggregate stability is naturally high in slash-and-burn agricultural systems (> 80 %). However, aggregate stability increases even more (by 10 %) at the highest temperature, 660 °C, an enhancement attributed to fire effects on topsoil. Conversely, the geometric mean diameter, that is, the most frequent aggregate class increases by 20 % at moderate to high temperatures. Moreover, a temperature of 354 °C does not affect the geometric mean diameter.

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