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Fire changes the larger aggregate size classes in slash-and-burn agricultural systems

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ABSTRACT

The slash-and-burn agricultural system is one of the oldest types of no-tillage soil management. However, farmers using fire may cause unintentional damage to soil structure in the slash-and-burn system. Herein, it is assumed that larger soil aggregates ($\geq$2.0 mm to $<$8.0 mm) are the most affected by fire, with direct impacts to their structural stability. An experimental fire was carried out, and the rainfall simulation approach for a period of 30 min with a rainfall intensity of 58 mm h^{-1} was used to assess the effects of fire on soil aggregate stability. The macro-aggregate stability was evaluated for the test plot as well as an undisturbed soil sample using two aggregate sizes: 2–4 mm and 4–8 mm. The fire temperature measured at the soil surface was very high (673 $\pm$ 93 °C). Consequently, the soil structural stability under the slash-and-burn agricultural system rose significantly. Larger aggregates of $\geq$2.0 mm or $\geq$4.0 mm size indicated a clear influence of fire on soil physical properties. The fire temperature dramatically changed the distribution of the aggregates of $\geq$4 mm, since aggregates of this size were more frequent (51%) and stronger compared to unburned soil. The methodology is critical to detect the changes in the physical properties of aggregates affected by fire. Aggregate stability methods using a single sieve of $\geq$0.25 mm over rainfall simulation, but without consideration of the completely fragmented particles remaining in the sieve, were not able to detect the aggregation changes.

1. Introduction

Fire is a key factor in the global ecosystem. Fire regulates the physical, chemical, and biological processes in the soil. Overall, fire affects the physical-chemical and mineralogical soil properties such as structural stability, particle-size distribution, mineralogical assemblage, organic matter, available nutrients, and others (Arocena and Opio, 2003; Bento-Gonçalves et al., 2012; Certini, 2005; Mataix-Solera et al., 2011; Yusiharni and Gilkes, 2012). In addition, fire can affect the biological soil properties belowground through the reduction in microbial biomass, micro and macro fauna, and alterations in the microbial population (Neary et al., 1999).

The slash-and-burn agricultural system is one of oldest types of no-tillage soil management. Farmers sow their crops post-fire over an ash-bed layer with minimal disturbance of the topsoil (Cerri et al., 2007; Thomaz, 2009). However, the fire's effects may be detrimental to the soil structure in the slash-and-burn system (Are et al., 2009; Thomaz et al., 2014).

Soil structural stability is the relative resistance of the soil aggregates against external disrupting forces (e.g., raindrop impact, soil wetting processes, and soil management). Declining aggregate stability might affect several soil processes such as soil water infiltration, crusting, sealing, soil water retention, runoff, and soil erosion (Amézketa, 1999; Dı'az-Zorita et al., 2002; Le Bissonnais, 1996; Yan et al., 2008).

Aggregate stabilization is a complex hierarchical process involving biological and physical-chemical agents. Overall, organic binding agents are classified as transient, temporary, or persistent (Tisdall and Oades, 1982). In macro-aggregates ($\geq$0.25 mm) transient and temporary material such as fine roots and fungi hyphae are the key cementing agents. Micro-aggregates ($<$0.25 mm), however, are stabilized by persistent organic matter, e.g., aromatic humic material associated with metal cations and iron and aluminum oxides (Tisdall and Oades, 1982).

Macro-aggregates are naturally prone to an intense dynamic as they are affected by building up processes and breaking down processes, i.e., they have a rapid turnover ratio (Amézketa, 1999;

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Dı'az-Zorita et al., 2002; Six et al., 2004; Tisdall and Oades, 1982). Moreover, larger aggregates are susceptible to soil management and fire effects as well. Organic matter is dramatically reduced around 300–400 °C, and abundance of fungi begins to reduce around 50 °C and is completely depleted at ~200 °C (Certini, 2005; DeBano et al., 1998; Neary et al., 1999). Because macro-aggregates are stabilized by transient and temporary material such as fine roots and fungal hyphae, these cementing agents could be destroyed due to fire applied in the slash-and-burn agricultural system.

The study's hypothesis is that larger aggregates (≥2.0 mm–<8.0 mm) are greatly affected by fire, leading to a decrease in their structural stability. In addition, it is assumed that post-fire raindrop impact causes higher aggregate breakdown, producing finer macro-aggregates and micro-aggregates. To test this hypothesis, I applied a rainfall simulation to detect the effects of fire on soil aggregate stability over an undisturbed soil sample and selected aggregate sizes. The rainfall approach was chosen because following the fire the topsoil becomes exposed due to the loss of vegetation and the protective cover of the litter layer. Therefore, raindrop impact seems to be a key factor in aggregate breakdown, especially in wet tropical environments. Furthermore, previous studies carried out to assess aggregate stability in slash-and-burn have employed the wet sieving approach using the whole soil, i.e., water stable aggregates (Are et al., 2009; Thomaz et al., 2014; Thomaz and Fachin, 2014), or the water drop method (Obale-Ebanga et al., 2003; Thomaz et al., 2014).

2. Methods

2.1. Soil characteristics

This study was conducted in the rural community of Tijuco Preto in the Prudentópolis municipality of southern Brazil (Fig. 1). The site is a typical plot where shifting cultivation is practiced, and it was chosen to assess the effects of fire on soil aggregate stability. The soil is classified as Haplic Cambisol with moderate depth of 1.0 m and clayey texture (Table 1). The climate is classified as a Cfb temperate climate having 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, 900–1000 mm for evapotranspiration, and 16–18 °C for temperature (Caviglione et al., 2000).

2.2. Measurement design

A plot of ~0.35 ha that had been fallow for 10 years was slashed, dried, and burned according to the local slash-and-burn system for cropping black beans and maize. The biomass above ground (5–10 t ha^{-1}) was scattered due to farmers harvesting the timber. However, there were tree canopies and shrubs that had not been harvested and remained on the plot.

Nine trenches 15 cm in depth and covered with biomass were monitored during the course of this study. A set of 3 thermocouples registering temperature every second was placed in each trench (i.e., 9 trenches × 3 depth = 27 thermocouples) at the following depths: 0 cm on top of the mineral horizon beneath the litter layer, 1 cm within the mineral horizon, and 2 cm within the mineral horizon.

After the fire, six samples in total composed by five disturbed soil subsamples (i.e., samples were joined) were collected with a metal ring (50 cm^3 in volume, 2.5 cm in height) at depths of 0–2.5 cm. The samples were collected approximately 12 h after the fire (Table 2). The samples were collected close to the trench to ensure that measurements accurately reflected the relationship between the registered temperatures and the associated temperature effects on the soil properties. The soil collected in the field was air-dried. Next, the disturbed soil samples were screened in fractions of 2–4 mm and 4–8 mm and submitted to rainfall simulation for 30 min for aggregate stability and fragmented particles determination. Six samples in total composed by five subsamples collected nearby the trenches before the fire were used as unburned soil controls (Table 2).

In addition, post-fire three undisturbed soil samples were taken close to each trench (9 × 3 = 27). The samples were collected through a metal ring 10 cm in diameter and 5 cm in height (393 cm^3). Six soil samples collected nearby the trenches before the fire were used as unburned soil controls. Next, the undisturbed soil samples were submitted to a rainfall simulation for 5 min for rainsplash determination and particle size distribution (Imeson and Vis, 1984) (Table 2).

2.3. Rainfall simulation

The multi-drop simulator consisted of a framework of pipes (20 mm diameter) and a 6 m tall SPRACO cone jet nozzle. An electric water pump with a pressure of 78 kPa supplied the water. The simulated rainfall was dripped from a height of 6 m from the central plot for a period of 30 min with a rainfall intensity of 58 mm h^{-1}. The drop diameter of the rainfall simulator varied from 0.35 to 6.35 mm, with a median drop size of 2.4 mm and a coefficient of uniformity of more than 90% on the splash pan area. The device produced rain with 90% of the kinetic energy of natural rainfall and with similar intensity (Luk et al., 1986).

The macro-aggregate stability was tested using two aggregates size: 2–4 mm and 4–8 mm. Five grams of aggregate were placed on the top of a 0.25-mm sieve with (Kemper and Rosenau, 1986). The sieve was set in a container to hold both soil splashed and soil passed through the sieve.

The material removed from the sieves was dried (105 °C for 24 h) and weighed. Next, aggregates remaining in the sieve were subjected to dry sieving for 30 s in an electromechanical agitator to separate the fragmented aggregate sizes (Dı'az-Zorita et al., 2002). The aggregates were fractionated according to the following sieve openings: 4, 2, 1, 0.5, 0.25, and <0.25 mm. The sand fraction was removed through a sieve with an opening of 0.053 mm.

The size distribution and quantity of aggregates (weight and percentage), were measured using the ratio between the aggregate amounts retained in the sieve to the total sample amount (Eq. (1)). Indices of the aggregate measurements, such as the aggregate stability index (Eq. (1)), and the mean weight diameter (MWD) (Eq. (2)), were obtained using the equations below (Table 2). Overall, the aggregate stability index can vary from 1% to 100% and indicates the aggretation ratio and MWD are affected by larger aggregates remaining in the soil sample (Castro Filho et al., 2002; Hillel, 1998).

The same procedures described above were applied to analyze the undisturbed soil samples. In short, the metal ring was set in a container and submitted to rainfall for 5 min. The splashed particles were oven dried and sieved (see description above) (Table 2). Soil organic matter was assessed using three replicates for each aggregate class before and postfire. Soil organic matter content was determined using the Walkley-Black method (Walkley and Black, 1934) (Table 2).

$$AS\% = \frac{W_i}{W} \times 100, \quad (1)$$

AS% = Aggregate stability in percentageW_i = Weight of the aggregate remaining in the sieve ≥0.250 mm or ≥2.0 mm and ≥4.0 mm