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Fire severity in slash-and-burn agriculture in southern Brazil: an overview

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ABSTRACT: Slash-and-burn is a traditional agricultural system still widely used in Brazil. The variation in temperature during fires results in different levels of physical, chemical, and biological changes in the soil, which makes it necessarily better to understand the dynamics of fire severity in this system. The aim of this study was to make an analytical comparison of the variation in the temperature reached in the soil during fires in slash-and-burn agriculture. Temperature data were measured in burnt areas with similar fallow times at the following soil depths 0; 2.5 and 5 cm and compared with secondary data from other studies in the same slash-and-burn system in southern Brazil. The peak temperature showed more significant variations in the surface (0 cm) of different soils and different types of regeneration vegetation in each area. Overall, the peak temperatures ranged from 32 to 673 °C across the three depths. The peak temperature reduction in the 5 cm layer was 88 % compared to the surface and 30 % compared to the 2.5 cm layer. The sandier soils showed greater thermal conductivity at depth. The surface litter seems to exert a more significant influence on the burning severity than the biomass load cut for burning, suggesting that the characteristics of the litter layer on the surface should be better characterized in future studies on fire severity.

Keywords: soil heating, temperature, litter

Introduction

Subsistence farmers have used the traditional slash-and-burn agricultural system for decades, a practice that will continue since a significant portion of the food produced on the planet is currently subjected to this process. Several studies have shown that the price of increasing demographic pressure and agricultural modernization is a reduction in fallow times in the slash-and-burn system around the world (Lintemani et al., 2020). Over the last 30 years, fallow times have fallen from 15 to 5 to 7 years and, in some places, to 2 to 4 years, reducing the intervals between fires and making soil resilience difficult (Hattori et al., 2019; Mukul and Herbohn, 2016). In this regard, it is necessary to investigate the particularities of this system in different contexts to guarantee its sustainability.

The use of fire is a procedure aimed at the rapid fertilization of soil through the ash produced, which ensures good germination of the planting seeds (Fachin et al., 2021; Giardina et al., 2000). However, fire temperature affects several physical, chemical, mineralogical and biological attributes of the soil (Zavala et al., 2010; Certini, 2005; González-Pérez et al., 2004; Neary et al., 1999). The magnitude of changes in soil properties depends on the soil type and is directly related to burning severity (the relationship between the temperature reached and the exposure time) (Keeley, 2009).

Previous studies to delineate the main soil changes concerning temperatures during fires have shown distinguishable temperature variations in this system in similar environments (Santín and Doerr, 2016; Mataix-Solera et al., 2011). As regards slash-and-burn fire, the soil temperatures generally reached are between 150 and 700 °C (Thomaz, 2017a; Ketterings et al., 2000; Hartford and Frandsen, 1992; Chandler et al., 1983; Wells et al., 1979; Sertsu and Sanchez, 1978; Masson, 1948). Fire severity is critical to post-fire soil system response. However, nothing is known about the dynamics of the controlling factors that define the variation of fire temperatures in this system.

Therefore, the present study aimed to evaluate the characteristics of temperature variation in the first five centimeters of soil layers in a slash-and-burn system in southern Brazil. For this assessment, data from three published works (secondary data) and three other recent fires carried out in the same system in the region were evaluated. We sought to identify the main variables determining fire severity under the same burning conditions in different soils.

Materials and Methods

Study areas

The climate in the burned areas is classified according to Köppen (1948) as Cfb (temperate climate, mild summer) and Cfa (subtropical climate, hot and humid summer). This climate has average temperatures during the coldest month of 14 °C (mesothermal), cool summers with average temperatures during the hottest month below 23 °C, and no dry season. Annual rainfall averages range from 1445 to 1880 mm, and evapotranspiration from 900 to 1000 mm (Nitsche et al., 2019).

Data from fires carried out in the slash-and-burn agricultural system in the southeast of the State of Paraná were used (Figure 1). Six data sets were used, with three of them based on secondary data found in the literature - Cambisol 1, Cambisol 2, and Cambisol 3 and were from

Prudentópolis, Paraná in southern Brazil (25°23′37″ S; 51°06′27″ W) altitude 807 m (Table 1). The other three come from direct primary data on fires carried out in 2018 and 2019 by farmers in rural communities were: Ferralsol - Guarapuava, Paraná (25°19′42″ S; 51°15′37″ W) altitude 1175 m, Cambisol 4 - Prudentópolis, Paraná (25°07′10″ S; 51°05′05″ W) altitude 755 m and Regosol - Ivaí, Paraná (25°00′08″ S; 50°53′44″ W) altitude 648 m (Table 1).

The procedures required for the preparation of the areas are: a) clearing the area to be burned (secondary forest); b) drying the cut vegetable matter (one month); c) burning dry matter; d) planting beans or corn, and e) harvesting and leaving fallow for three to eight years. According to the farmers, the controlled burnings follow the same pattern each year, with the same proportions of cut vegetation and a similar fallow

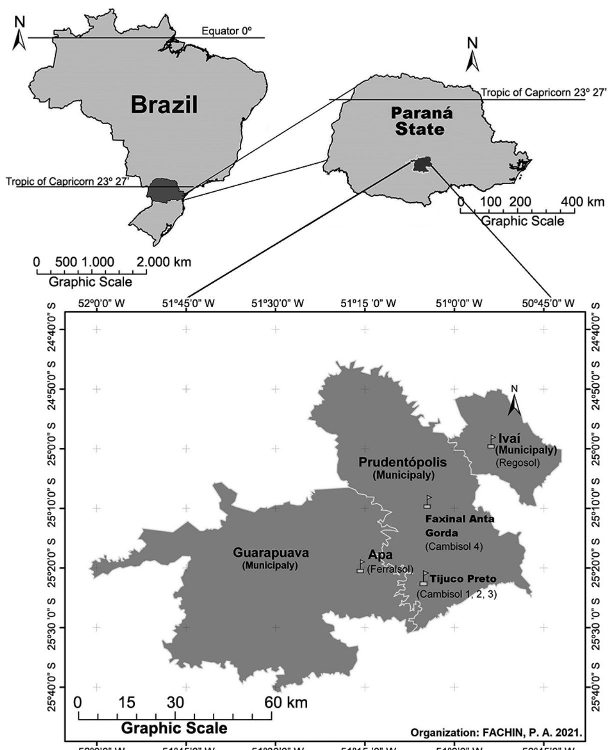

Figure 1 – Location of study areas.

period (> 4 years). At least one month between cutting and burning is needed to allow the biomass and litter to dry out, so that burning may be carried out with low surface moisture. Fires are set during the late afternoon with little wind to reduce the risk of wildfire spreading to other areas.

The temperatures of soils burned were monitored (Table 1), and were then classified as Ferralsol (Guarapuava), Cambisol (Prudentópolis), and Regosol (Ivaí) (FAO, 2015).

Experimental design

The experimental procedure for obtaining temperatures was similar in the three situations evaluated. Areas ± 1000 m^2 with five years of fallow (secondary vegetation) were chosen for the development of the experiments. The biomass was cut, dried, and burned in the three areas for subsequent planting of beans following the local agricultural system. Four small trenches (± 10 cm deep) were opened in each area before the burning, approximately 10 m apart. In each trench, three sets of thermocouples with a datalogger (thermocouple probe type k) were installed at depths of 0 cm, 2.5 cm, and 5 cm for checking temperatures every second (Figure 2).

Biomass was estimated at four points in each soil within an area of 1 m^2, from which the material was cut and weighed. The material consisted of trunk, branches, leaves, and litter. The three areas had been in fallow for five years, having previously passed through two fire cycles. After cutting the vegetation, the areas showed an average of dry biomass between 4.5 and 7.2 kg m^{-2}.

Subsequently, each trench was closed with soil and covered with dry biomass on the surface (6 kg m^{-2}) at the points evaluated for the three fires (Figure 2). This amount of dry biomass was defined based on Thomaz et al. (2014), who found that land with an average of five years of fallow in this location produces approximately 6.2 kg m^2.

Soil moisture was around 18 % (Table 1). The flames reached between 2 and 5 m in height, taking between 21 and 41 min to burn the entire areas, and after the burning, there were irregular patches of ash in white, gray, and black colors, with more than 60 % white ash in the three areas.

Table 1 – Soil surface horizon characteristics. Soil depth (0-5 cm). Soil type according to FAO (2015).

Soil parameters	Ferralsol	Regosol	Cambisol 1[a]	Cambisol 2[b]	Cambisol 3[c]	Cambisol 4
Clay content (g kg^{-1})	690	430	358	490	345	470
Silt content (g kg^{-1})	263	310	487	290	331	290
Sand content (g kg^{-1})	47	260	155	220	323	240
Aggregate stability[2] (%)	70 ± 9.4	49.8 ± 6.9	55.4 ± 13.0	60.2	82	93.8
Organic matter[3] (g kg^{-1})	72	60	62	48	28	50.7
Gravimetric soil moisture before burning (%)	20	16	19	n/i	n/i	n/i

[1]Wet sieving method (Kemper and Rosenau, 1986); [2]Walkley and Black (1934); Mean ± standard deviation (n = 6); n/i = no information; Letters indicate secondary data obtained from: [a]Thomaz (2017a), [b]Thomaz (2017b), and [c]Thomaz et al. (2014). Ferralsol – Guarapuava, Regosol – Ivaí, Cambisol 1, 2, 3, 4 – Prudentópolis.

Results

The peak temperatures measured at three depths (0 cm; 2.5 cm and 5 cm) in soils during slash-and-burn agricultural fires generally ranged from 32 to 673 °C. There was an abrupt reduction in the peak temperature measured at depth. While at the surface (0 cm) the minimum peak temperature was 185 °C (Regosol), the maximum peak at 2.5 cm deep was 92 °C (Cambisol 4), and on average, the reduction in peak temperature between these depths was 84 %. The peak temperature reduction to 5 cm deep in the soil was 88 % compared to the surface and 30 % compared to 2.5 cm in depth (Table 2).

Considering the soil surface (0 cm) among the evaluated soils, Ferralsol showed a higher average peak temperature than Cambisol (30 % lower) and Regosol (48 % lower). Among the Cambisols, there was a temperature difference since Cambisol 1 resulted in higher peak temperatures compared to Cambisol 2 (28 % lower), Cambisol 3 (32 % lower) and Cambisol 4 (63 % lower).

The peak temperature variation in depth was proportional to the peak temperature identified on the surface. The soils that showed the highest peak temperature resulted in more significant reductions. Furthermore, temperatures measured at 2.5 and 5.0 cm showed low variation between soil types (standard deviation of 19.9 °C) compared to surface temperatures (standard deviation of 179.7 °C).

There was an inverse relationship between temperature and time of exposure on the soil surface, where the highest temperatures had the shortest duration, and the lowest had the most extended exposure times (Figure 3). An obvious distinction was also identified between the results of exposure times to temperatures found in the primary and secondary data (Cambisol 1; 2 and 3).

As regards the duration times of the heating peaks at the soil surface presented in Table 3, the secondary data were longer than the primary data by approximately 212 % in Regosol, 166 % in Cambisol, and 119 % in Ferralsol.

In Cambisol 1, 2 and 3 the duration of the highest temperatures (> 500 °C) remained during burning for a maximum of 255 s, and the lowest temperatures (< 200 °C) remained on the soil surface for up to 1050 s. For Thomaz et al. (2014), the temperature of 534 °C remained for 240 s, while the temperature of 142 °C remained for 1350 s.

In general, there were differences between temperatures and exposure times in fires in areas with the

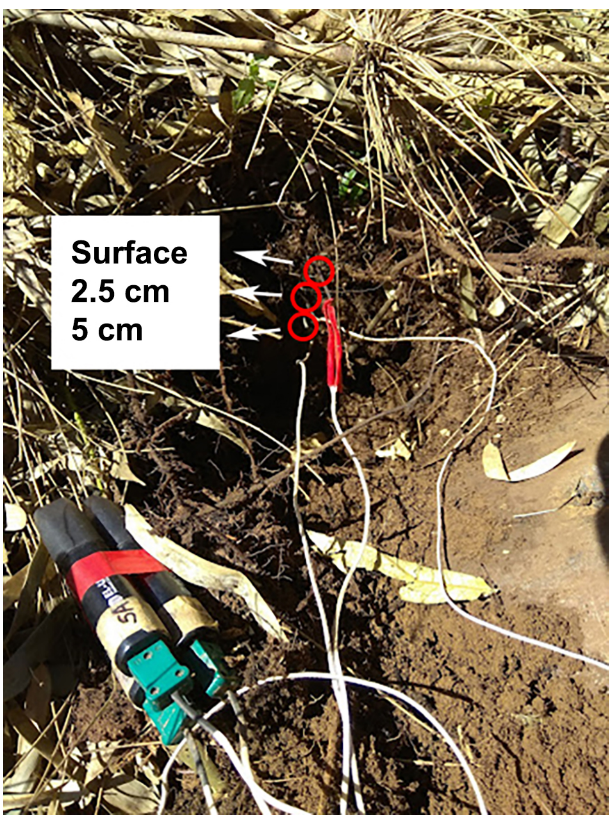

Figure 2 – Thermometers installed at depths (0; 2.5; 5.0 cm) to monitor the temperatures produced by the burning.

Table 2 – Temperatures reached at depths of 0; 2.5 and 5 cm during burning in the three slash-and-burn systems areas.

Soil type	Soil depth		
	0	2.5	5
		cm	
Cambisol 1[a]	673 °C	42 °C	n/i
Cambisol 2[b]	484 °C	56 °C	n/i
Cambisol 3[c]	460 °C	84 °C	49 °C
Cambisol 4	249 °C	92 °C	32 °C
Ferralsol	355 °C	65 °C	59 °C
Regosol	185 °C	48 °C	39 °C

n/i = no information. Letters indicate secondary data obtained from: [a]Thomaz (2017a), [b]Thomaz (2017b), and [c]Thomaz et al. (2014). Ferralsol – Guarapuava, Regosol – Ivaí, Cambisol 1, 2, 3, 4 – Prudentópolis.

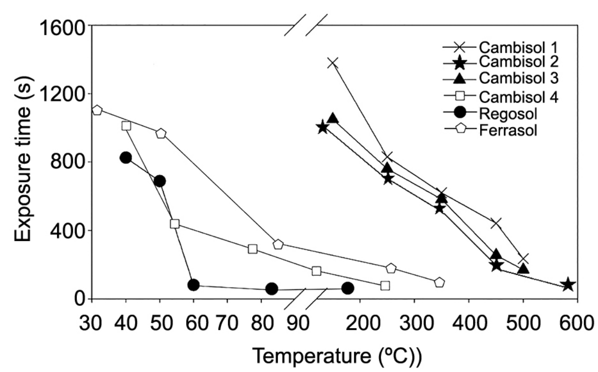

Figure 3 – Residence time according to surface temperature class (0 cm).

same fallow times. Between the areas evaluated in this study, there are differences in vegetation characteristics and litter load (the average dry biomass ranged from 4.5 to 7.2 kg m^{-2}). The Regosol is further north, close to the transition from Cfb (temperate climate, mild summer) to Cfa (subtropical climate, hot and humid summer), allowing for faster, denser, and larger regeneration of shrub vegetation than in other areas. This aspect is evident in the greater number of stumps (cut trunks) (Figure 4). In the same area, a greater thickness was observed in the litter layer accumulated on the surface, which is also more preserved.

Discussion

In the present study, the temperatures measured at the surface were higher than those at 2.5 and 5 cm deep, similar to the results observed in the secondary data. This temperature behavior transfer within the soil is expected in different types of fires since soils are poor conductors of heat (DeBano, 2000); thus, during a fire, there is a large temperature gradient in the depth of the soil (Úbeda and Outeiro, 2009). Thus, higher temperatures remain on the surface for a shorter time, for a few minutes only (Bento-Gonçalves et al., 2012), while in the inner soil layers the temperature decreases but the exposure time increases (DeBano et al., 1998; Doerr and Cerdà, 2005).

Soils with different textures may show variations in heat conduction capacity. In our study, soils with sandy textures showed more significant heating in depth. Higher levels of sand have a higher thermal conductivity than clayey soils due to quartz's influence, which has twice the thermal conductivity of other minerals (Campbell, 1985).

In the present study, soils with higher levels of organic matter (Ferralsol and Regosol) had the lowest temperatures at the 2.5 cm depth, as the soil organic matter (SOM) content also influences the propagation of temperature within the soil ground. SOM has less thermal diffusion in order of magnitude than other minerals and slightly less than water (Farouki, 1981). For this reason, high levels of SOM can act as a thermal insulator, since structurally and in conditions of high content, it causes lower soil porosity and inhibits the thermal conductivity of heating (Adams, 1973; Decharme et al., 2016).

In addition to mineral composition and organic matter content, soil moisture is a determining factor. Under dry soil conditions, soil heating tends to be slow, while high moisture conditions contribute to rapid warming. This is mainly due to the high-speed movement of water through the pores when evaporated by heating, releasing, and transferring heat to the soil (Neary et al., 1999; Hirschi et al., 2011). Other elements, such as soil bulk density and fire severity, influence heat transmission through the soil (Lombao et al., 2015; Certini, 2005; Badía et al., 2017).

In our study, the three fires had lower surface temperatures than those found by Thomaz et al. (2014) and Thomaz (2017a, b), indicating no severity pattern in controlled fires under the same conditions in this system. Factors such as fallow times, soil moisture, dry biomass load, litter moisture, and identical atmospheric conditions did not guarantee that the fires were homogeneous, showing that other variables determine fire severity in this system.

Among the controlling factors, the biomass load is considered the main one. However, we observed that fallow times with similar biomass loads produce different

Table 3 – Exposure time reached at the maximum temperature peak at each depth according to the data in Table 2.

Soil type	Soil depth		
	0	2.5	5
	cm		
Cambisol 1[a]	90 s	n/i	n/i
Cambisol 2[b]	255 s	n/i	n/i
Cambisol 3[c]	470 s	n/i	n/i
Cambisol 4	102 s	194 s	356 s
Ferralsol	124 s	157 s	637 s
Regosol	87 s	641 s	128 s

s = seconds. n/i = no information; Letters indicate secondary data obtained from: [a]Thomaz (2017a), [b]Thomaz (2017b), and [c]Thomaz et al. (2014). Ferralsol – Guarapuava, Regosol – Ivaí, Cambisol 1, 2, 3, 4 – Prudentópolis.

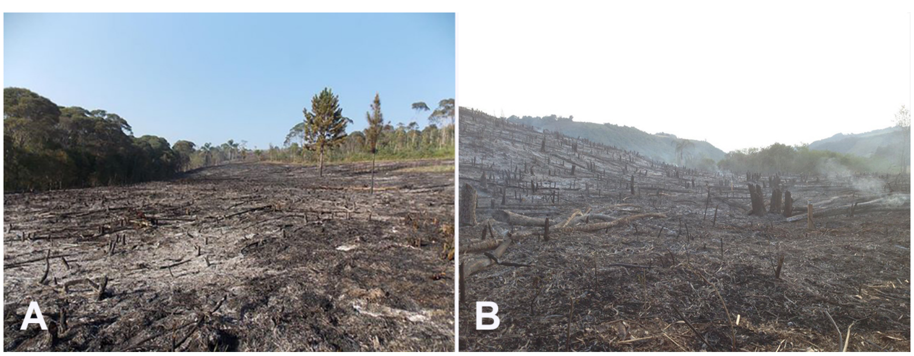

Figure 4 – Number of trunks showing differences in vegetation densities. A) area with Cfa climate according Köppen (1948), Prudentópolis municipaly - Cambisol; B) area transitioning from above Cfa to Cfb with more density vegetation, Ivaí municipaly - Regosol.

intensities. This is due to a set of factors, among which the variation in plant species that develop in different places have different physical and chemical aspects and flammability.

Within the same ecosystem with the same soil, rainfall, and atmospheric temperature, variations in vegetation density occur due to differences in edaphic, altimetric, topographic, and slope exposure (Wildi, 2002; Chazdon et al., 2007). Ecosystems of Mixed Ombrophilous Atlantic Forest predominant in the areas of this study, when located in different climates, tend to develop different varieties of plant species. Warmer and wetter climates tend to concentrate vegetation of greater volume and density in this ecosystem, and contribute to the formation of biomass and litter with greater density and volume. Biomass loads with the same weight but different volumes can produce variations in the severity of the burning. Thus, equal fallow periods within the same ecosystem may present different fire intensities.

Little or nothing is known about litter's influence on soil temperature during a slash-and-burn fire in this system. The studies compared in this work did not measure litter volume, but visually (Figure 4), it was possible to observe that in areas with denser regeneration vegetation, the biomass volume, the height and duration of the fire flames and the litter layer were higher, but soil temperatures were lower. By the end of the fire, the biomass had been completely burned, and the larger layers of litter were better preserved, as they were not completely burned, thereby preventing the flames from having contact with the soil surface.

The thickness and density characteristics of low-flammability litter can play a key role in protecting or insulating the temperature generated by above-ground burning (Ketterings et al., 2000; Hartford and Frandsen, 1992). According to Mondal and Sukumar (2014), this depends on factors such as the degree of flammability of the affected species, layer moisture, volume of living and dead material, wind severity during the fire, current solar radiation, and origin of the fire (spontaneous, induced, controlled, uncontrolled).

The thickness and moisture of the litter layer are controlling factors of fire severity at the top of the soil (Cochrane and Ryan, 2009). Several studies of fire dynamics at the ground surface found no correlation between surface temperatures and litter load in dry eucalyptus forests (*Eucalyptus marginata*) in Australia (Wotton et al., 2012). In the present study, Mixed Ombrophilous Atlantic Forests produce a high amount of litter, with an average of 6.097 t ha^{-1} yr^{-1} (Antoneli and Thomaz, 2012), with a lower number of species that produce resins and other fuel elements, conferring a low level of flammability and combustion (Santos et al., 2018). This indicates that larger litter layers in this system can be used as fire protection elements from the top of the soil. In addition, fires in this system in southern Brazil are usually set in a short period of drought, making it possible to retain moisture at the top of the soil in the deep part of large volumes of litter and thus prevent its burning.

In addition, biomass loads in fallow areas should be reduced to ensure lower fuel concentration and low-severity fires. We recommend annual thinning of branches and leaves to reduce biomass and increase organic matter and litter layer to improve the thermal insulation of the fire in the ground. Combining these elements can bring lesser effects of fire degradation on the soil and greater sustainability of this agricultural system.

There still needs to be a model to predict the possible behavior of a fire in this system. Given the complexity of the factors that define fire behavior, it is difficult to predict the severity of fires in a stated ecosystem (Bento-Gonçalves et al., 2012; Doerr and Cerdà, 2005; Neary et al., 1999).

Therefore, it is essential to characterize fire intensities for a region to assess the potential impact on the ecosystem and design appropriate fire management plans (Mondal and Sukumar, 2014). Advances in studying fire severity conditions in slash-and-burn agriculture may result in empirical models in the form of a continuous function to predict fire behavior. This would be a powerful tool for providing information to help manage fire and reduce impacts on the ground.

Conclusions

Controlled fires under the same fallow conditions, soil moisture, dry biomass load, litter moisture, and atmospheric conditions present differences in severity. In addition, differences in soil texture did not influence surface temperatures. However, soils with higher sand content showed more significant temperature transfer at depth.

The load of burned biomass is not the main factor determining the severity of burning in the soil but are characteristics of the litter. Thus, different types of vegetation produce different layers and volumes of litter, causing similar fallow times in different vegetation types to have variations in burning intensities.

In general, the results of these studies indicate that more extended fallow periods can produce more significant litter accumulation and isolation from ground fire in a Humid Atlantic Forest ecosystem.

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Authors' Contributions

Conceptualization: Fachin, P.A. **Data curation:** Fachin, P.A. **Formal analysis:** Fachin, P.A. **Funding acquisition:** Fachin, P.A. **Methodology:** Fachin, P.A.; Thomaz, E.L. **Project administration:** Fachin, P.A.; Thomaz, E.L. **Resources:** Fachin, P.A.; Thomaz, E.L. **Supervision:** Fachin, P.A.; Thomaz, E.L. **Writing-original draft:** Fachin, P.A. **Writing-review and editing:** Fachin, P.A.; Thomaz, E.L.

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