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Fire-induced changes in the geotechnical properties of a volcanic soil

Modifications des propriétés géotechniques d'un sol volcanique causées par le feu

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ABSTRACT: Wildfires have been observed to significantly impact hillslope stability through the combustion of vegetation and changes in soil properties, mainly resulting in an increased proneness to post-fire rainfall-induced erosion and debris flows. In this regard, the existing literature on the fire-induced effects on soil properties has yielded divergent results mainly due to the inherent site-specificity that characterizes both wildfire and post-fire soil mobilization phenomena. To shed a light into the post-fire changes in both physical and hydromechanical properties of volcanic soils, an experimental laboratory study was conducted on soil samples collected from the Mt. Saro area in the Sarno municipality (Pizzo d'Alvano massif, Campania region, Italy). Here, a wildfire occurred on March 23, 2022. The experimental campaign pursued the geotechnical characterization of three classes of soil samples i) unburned, ii) wildfire-burned, and iii) laboratory thermally treated. The results unveiled pronounced changes in soil properties under both wildfire- and laboratory-burned conditions. In general, the fire-affected soil showed decreasing values of soil organic matter content, root content by weight, and soil shear strength when compared to the unburned control samples. Conversely, as the severity of the fire increased, we observed increases in soil hydraulic conductivity and cumulative infiltration. These findings can provide novel insights to enhance the comprehension of those processes presiding over post-fire slope instability and erosion in similar geo-environmental contexts.

RÉSUMÉ: Les feux de forêt ont été observés pour avoir un impact significatif sur la stabilité des versants par le biais de la combustion de la végétation et des modifications des propriétés du sol, principalement résultant en une plus grande propension à l'érosion induite par les pluies post-incendie et aux coulées de débris. Cependant, la littérature existante sur les modifications induites par le feu des propriétés du sol a produit des résultats divergents principalement en raison de la spécificité intrinsèque du site qui caractérise à la fois les phénomènes de feu de forêt et de mobilisation du sol après l'incendie. Afin d'éclairer les modifications post-incendie des propriétés physiques et hydromécaniques des sols volcaniques, une étude expérimentale en laboratoire a été menée sur des échantillons de sol prélevés dans la région du Mont Saro, dans la commune de Sarno (massif de Pizzo d'Alvano, région de Campanie, Italie). Dans cette région, un incendie s'est produit le 23 mars 2022. La campagne expérimentale visait à la caractérisation géotechnique des sols distingués en trois classes d'échantillons: i) non brûlés, ii) brûlés par le feu de forêt, et iii) soumis à un traitement thermique en laboratoire. Les résultats ont révélé des modifications marquées des propriétés du sol dans les conditions de feu de forêt et de traitement thermique en laboratoire. En général, le sol affecté par le feu a montré des valeurs décroissantes de la teneur en matière organique du sol, de la teneur en racines en poids, et de la résistance au cisaillement du sol par rapport aux échantillons témoins non brûlés. En revanche, à mesure que la gravité de l'incendie augmentait, nous avons observé des augmentations de la conductivité hydraulique du sol et de l'infiltration cumulative. Ces découvertes apportent de nouvelles perspectives qui renforcent la compréhension de la stabilité des pentes après un incendie et de l'érosion dans des contextes géoenvironnementaux similaires.

Keywords: Wildfires; laboratory testing; slope instability.

1 INTRODUCTION

Wildfires can affect hydrologic slopes response by burning vegetation and inducing changes in soil properties (Certini, 2005). Indeed, several literature studies recognize wildfire-burned watersheds as having an increased susceptibility to rainfall-induced surficial soil failures (e.g., Rengers et al., 2020). In the context of climate change scenarios, in which both frequency and intensity of wildfires are expected to increase, coupled with predicted shifts in precipitation patterns towards more frequent short-duration/high-intensity rainfall events, it is anticipated that the Mediterranean region, and particularly the southern Italy, will experience increasing post-fire surficial failures (Sousa, 2015). Thus, it is important to address the possible threats that such events can pose to people, property, and infrastructure located downstream of the fire-affected area. In this regard, the geotechnical characterization of burned soil is key in providing quantitative information on post-fire soil behavior, as well as in trying to understand the triggering mechanisms of surficial failures on fire-affected slopes. The literature reveals that the possible fire-induced changes in soil properties are to be considered site-specific since both soil and wildfire characteristics can vary site by site according to local conditions such as geology, topography, and climate (Ulery and Graham, 1993; Certini ,2005).

Fire can impact soil organic matter (SOM) content. SOM may increase, decrease, or not change (Ulery and Graham, 1993). Key role is played by the temperature/duration conditions reached during wildfire, as well as by the types and characteristics of the affected SOM. Moderate to severe fires can permanently alter the grain size distribution (GSD) of the affected topsoil layer (Ulery and Graham, 1993). Similar to SOM, grain size may increase, decrease, or not change, mainly depending on soil type and its mineralogy. Generally, increases in GSD have been attributed with aggregation of fine particles into coarser composite stable particles (Ulery and Graham, 1993; Ketterings et al., 2000).

Although still limited, the existing literature on the effects of fire on soil mechanical properties highlights that the soil-root systems can lose their initial strength post-fire, by lowering the cohesion contribution to soil shear strength (Peduto et al., 2022a, 2022b).

For specific soil types and under certain thermal exposure conditions, soil-water repellency (SWR) may occur at a certain depth along the soil profile, which likely results in a decrease of rainwater infiltration, subsequently increasing the slope susceptibility to flooding and runoff-initiated soil mobilization phenomena (De Bano, 2000). The appearance of SWR in surficial topsoil layers can be related to i) the pore clogging by post-fire residues (e.g., ash, charcoal, burned leaves) (Woods and Balfour, 2006); ii) the temperature gradients experienced along the soil profile (De Bano, 2000). Literature studies suggest that an exposure temperature of 220-250 °C for a duration of 5-7 minutes is ideal conditions for the SWR formation. In contrast, more severe heating conditions (i.e., either longer duration or higher temperature) are reported to destroy either the intrinsic or the fire-induced SWR layer. Indeed, some studies also showed increases in soil infiltration and hydraulic conductivity because of the occurrence of severe wildfires, mainly due to the fire-induced loss of soil structure, attributable to roots and SOM burning (Peduto et al., 2022a, 2022b).

Given the site-specific nature of the possible fire effects on soil properties, this study focuses on the fire-induced changes in the physical and hydromechanical properties of the coarse-grained pyroclastic topsoil covering the Mt. Saro area (Pizzo d'Alvano massif, Campania region, Italy). Here, a wildfire occurred on 23 March 2022 (Figure 1). The slopes of the Pizzo d'Alvano massif are highly susceptible to fast-moving landslides and are also frequently affected by wildfires. Relatively thin pyroclastic soil layers, which derive from the past explosive activity of the nearby Somma-Vesuvius volcanic complex, cover the underlying bedrock (Rolandi et al., 1998).

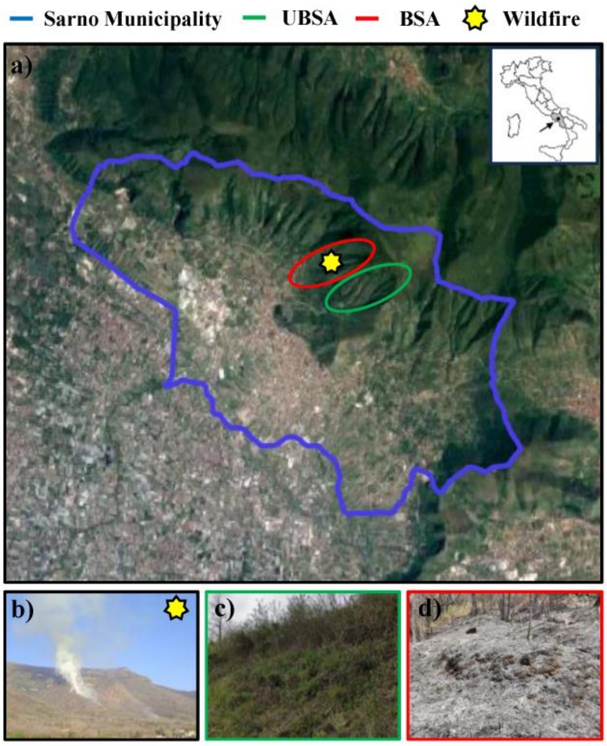

Figure 1. a) Overview of the study area with the indication of the sampling locations (i.e., UBSA: Unburned Sampling Area, BSA: Burned Sampling Area). b) Photo of the active wildfire taken on 23/3/2022. c) Photo of the UBSA. d) Photo of the BSA.

Soil sampling in undisturbed condition was conducted at 0-5 cm depth to limit the analyses to the shallow fire-affected topsoil layer. Both wildfire-burned and unburned soil samples were collected. In addition, laboratory burning treatments were carried out on unburned soil samples. For the purpose of data analysis, three different sample classes were distinguished i) "unburned", ii) "wildfire-burned", and iii) "laboratory thermally treated". Studies such as the one presented here can be useful to investigate mechanisms controlling post-fire erosion/instability slope responses in similar areas and to provide input data for implementing prediction models and planning *in situ* monitoring systems.

2 EXPERIMENTAL PROGRAMME AND TESTING PROCEDURES

The sampling activity involved both burned (B-j) samples collected within the area affected by the 23 March 2022 fire (i.e., BSA: Burned Sampling Area) and unburned (UB-j) samples collected in the nearby control area (UBSA: Unburned Sampling Area), characterized by similar soil and vegetation conditions (Figure 1). Some of the samples from the UB-j class were also subjected to two different thermal treatments in the laboratory by using a propane burner placed 5 cm above the soil surface for 15- and 30-minutes duration, namely P15-j and P30-j sample classes, respectively.

For each sample class, we investigated the following soil characteristics i) soil grain size distribution (GSD) via particle-size by dry-sieving tests (ASTM D422-63, 2007); ii) root content by weight (RCW) through the procedure proposed by Schuurman and Goedewaagen (1965), iii) soil organic matter (SOM), via loss-on-ignition (LOI) tests (ASTM D7348-08, 2011) and specific gravity (G_s) tests (ASTM D 854, 2014), iv) soil shear strength through direct shear tests in saturated condition (ASTM D3080, 2011), v) soil saturated hydraulic conductivity following the standard method (ISO, 2004), and vi) soil infiltration via mini disk infiltrometer (MDI) tests (Robichaud et al., 2008).

Table 1. Performed laboratory tests and investigated soil properties.

Laboratory Tests	Soil Property
Particle-size by dry sieving	GSD
Schuurman and Goedewaagen (1965)	RCW
G_s and LOI	SOM
Direct Shearing	Shear strength
Constant head permeability	K_{sat}
Mini Disk Infiltrometer	K_{unsat} and infiltration

LOI and G_s tests were carried out to investigate indirectly any fire-related changes in SOM content. Basically, LOI tests involve the destruction by heat (i.e., exposure time of two hours at 550 °C) of SOM. The impact of increasing exposure temperatures on SOM and GSD was assessed. Specifically, LOI, G_s, and sieving tests were carried out on fixed soil material of the UB-j class. The tests were also performed on soil samples from the UB-j class after they were subjected to specific muffle furnace treatments. The latter involved heating soil samples for a duration of 30 minutes at progressively increasing temperatures, ranging from 100 to 600 °C. Direct shear tests were performed on saturated specimens at relatively low vertical pressures (i.e., 2, 10, 20, 30 kPa), given that fire can only affect the very surficial portion of the topsoil layer. To investigate any possible changes in soil infiltration characteristics for different post-burn conditions, we performed MDI tests by using the *Decagon Mini Disk Infiltrometer*.

3 RESULTS

Decreasing LOI and increasing G_s values were found as temperature increased (Figure 2a, 2b). Moreover, a decreasing trend in LOI was observed as G_s increased (Figure 2c). Relatively low LOI values (i.e., relatively high G_s values) are generally associated with low SOM contents (Schulte and Hopkins, 2015).

The obtained results reveal that the SOM decay increased at increasing temperatures, thus burned soil is expected to contain less organic matter than unburned soil.

The structure of the topsoil layer is generally dependent upon SOM content and GSD. By consuming SOM and altering soil GSD, fire can weaken soil structure (Gonzaléz Pérez et al., 2004). This may result in increased bulk density, reduced porosity, and decreased water storage capacity of the soil (Peduto et al., 2022a). Accordingly, along with the removal of ground cover, surface litter, and/or duff, a loss of SOM can significantly accelerate runoff resulting in increased susceptibility to erosion. Moreover, the percentage of soil material passing the 0.15 mm diameter sieve increased as the temperature of exposure increased. This finding could be linked to the thermal-induced weakening and subsequent disaggregation of the pumice particles that are typically found in pyroclastic soils. This statement agrees with past research findings on the topic (e.g., Stoof et al., 2011; Peduto et al., 2022a). Overall, the average RCW was found lower in the fire-affected samples (see table in Figure 3).

Accordingly, we can argue that both the wildfire and the laboratory thermal treatments caused the combustion of the existing soil-root systems and changed their initial characteristics. These findings can be related to the negative impacts of fire on soil shear strength arising from the obtained direct shear tests results (Figure 3). Indeed, a general reduction in the shear strength of B-j and P15/P30-j vs. UB-j samples was found. Notably, the shear strength envelopes exhibited up to almost 50% fire-induced decreases in soil cohesion values with respect to the control unburned samples. In contrast, the effective friction angle value did not significantly change among the tested sample classes.

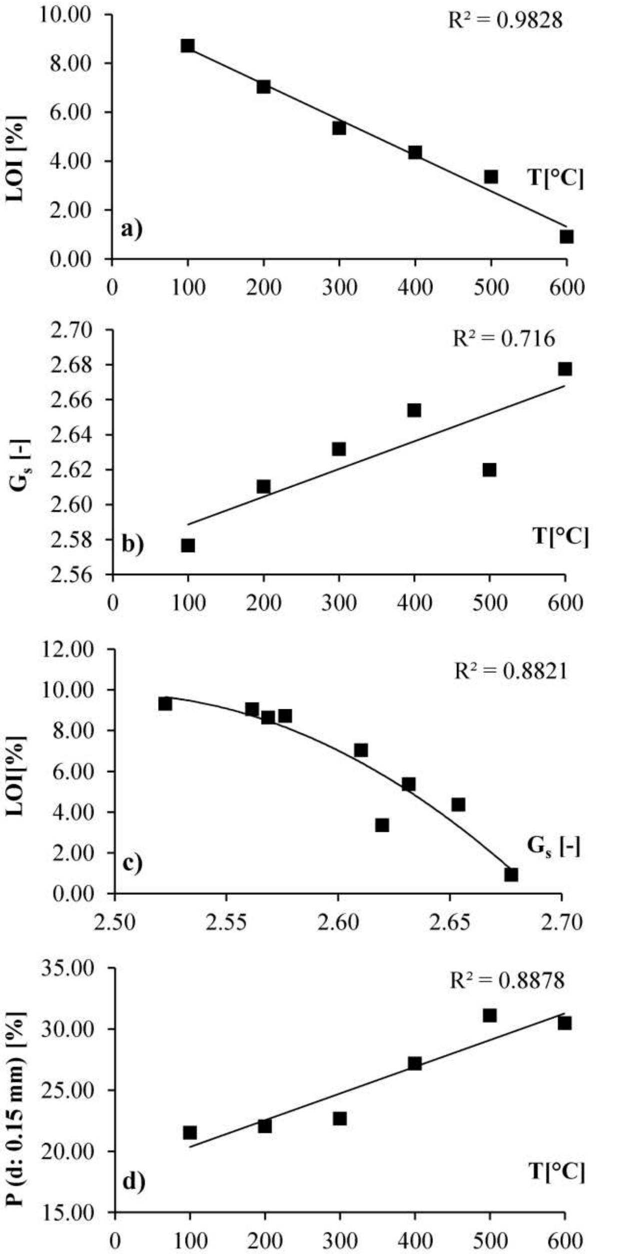

Figure 2. a) LOI, and b) G_s vs. T [°C]. c) LOI vs. G_s. d) percentage of soil passing 0.15 mm diameter sieve vs. T [°C]. The initial soil weight is fixed to 100 g for each heating treatment.

The investigated soils are loose and of pyroclastic origin, in a way that only their root systems and SOM aggregates may provide a cohesive contribution under saturated conditions (Peduto et al., 2022a, 2022b). The results reveal that fire can weaken surficial roots, reducing the associated contribution to the soil shear strength.

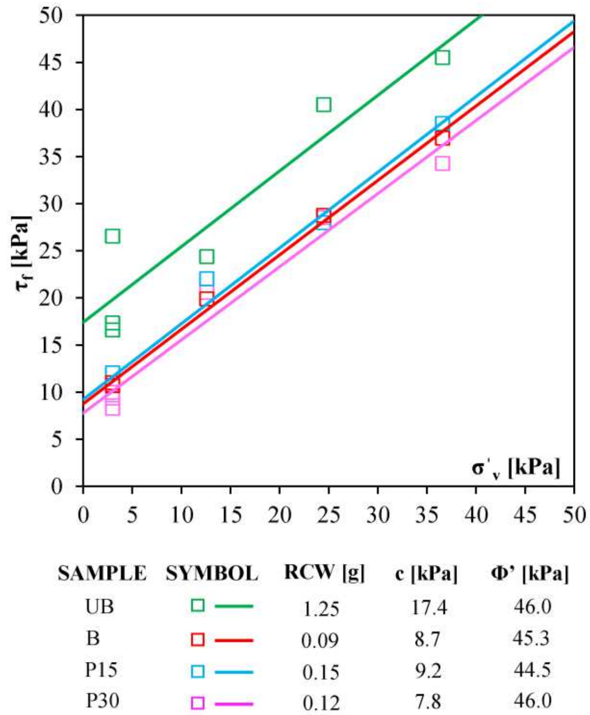

Figure 3. Results from the direct shear tests in terms of shear strength failure envelopes for all the tested soil sample classes. "c" and "Φ'" are the soil cohesion, and the soil effective friction angle, respectively.

From the hydraulic point of view, the tested soil exhibited progressive fire-induced increases in soil cumulative infiltration, in contrast to most literature studies that report the occurrence of SWR (e.g., De Bano, 2000). However, it is worth noting that intensity and persistence of SWR usually differs with fire temperature and duration, vegetation type, soil moisture and texture, as well as time since burning (Huffman et al., 2001).

Overall, since wildfire impacts, vegetation cover, soil texture, and antecedent soil moisture all differ across a burned area, the occurrence and the spatial distribution, depth, and thickness of SWR may also differ considerably (Doerr and Moody, 2004; Woods et al., 2007). Indeed, the spatial distribution of water-repellent soils can range from isolated patches to discrete layers with discontinuities (Jackson and Roering, 2009), to continuous layers (Woods et al., 2007).

Moreover, increases in soil hydraulic conductivity, under both unsaturated and saturated conditions, were observed for fire-affected soil with respect to unburned soil (Figures 4a, 4b). We attributed the increases in both infiltration and hydraulic conductivity to the fire-related development of macropore flow pathways, mainly caused by the combustion of SOM and roots, as well as to alteration of soil GSD. This ends up creating post-fire interface priority flows.

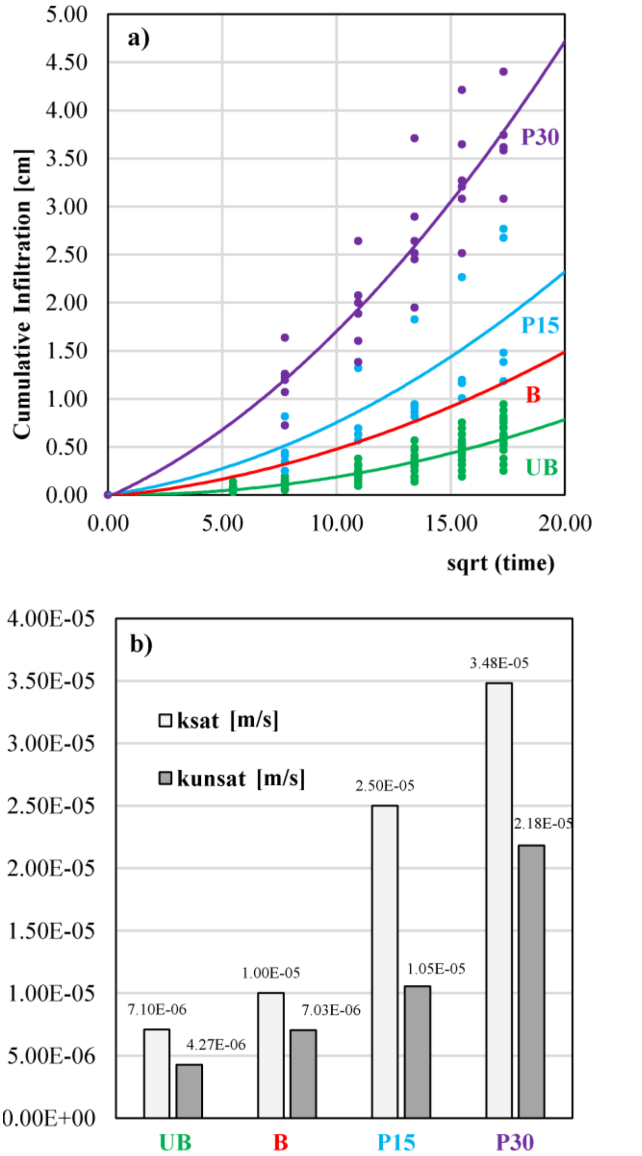

Figure 4. a) Cumulative infiltration vs. sqrt(time), derived from MDI tests. b) Average results in terms of hydraulic conductivity, in both saturated and unsaturated condition (i.e., k_{sat}, k_{unsat}), obtained through soil permeability and MDI tests, respectively.

4 CONCLUSIONS

The experimental results showed changes in the properties of soil sampled in the Mt. Saro wildfire-affected area or treated with laboratory burnings.

In general, the burned soil exhibits decrease in SOM content, RCW, and, consequently, soil shear strength. On the other hand, the increases in soil hydraulic conductivity and infiltration may be linked to the possible formation of macropore flow pathways induced by the burning of roots and SOM. In summary, we found that key role is played by SOM and RCW. By exposing the soil to increasing temperature, a reduction of SOM occurs, along with a possible weakening of the soil root systems, with consequences on both the soil mechanical and hydraulic properties. In turn, this may lead to an increase of the proneness to post-fire surficial soil failures. However, the tests carried out did not consider changes in mineralogy of the burned soil that could have affected GSD, LOI, and G_s.

Although deserving further deepening, the presented results could provide useful information for understanding the initiation mechanisms and assessing the susceptibility to post-fire soil mobilization phenomena.

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