On the wildfire-induced changes in the properties of a vegetated clayey slope cover

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ABSTRACT

Wildfires are generally believed to be detrimental to slope stability, by both damaging the vegetation and altering the hydro-mechanical properties of soil cover through burning action. However, the extent to which wildfires may impact on state of the vegetation and soil state is still an open issue, as it depends on several factors such as fire intensity, on the soil and vegetation state and type.

The research activity was carried out with reference to in-situ test-site, the Pisciolo hillslope, where selected vegetation has been seeded and farmed, with the aim to assess its effectiveness in reducing surface water infiltration. The test site caught fire in September 2023, during which most of the vegetation was burned down.

Pre and post fire soil properties were evaluated using laboratory and in-situ methods including Loss-on-Ignition (LOI), water drop penetration time (WDPT), and in-situ seepage tests (i.e., by means of Guelph permeameter and double ring infiltrometer). Furthermore, the wildfire-induced thermal stress in the soil was monitored with a thermocouple recording soil temperature within 15 cm b.g.l..

Monitoring results showed that significant wildfire-induced temperature variations were limited to the very near-surface soil layer, up to 25 cm; the soil organic matter decreased after the fire exposure; the hydraulic behaviour was also affected but only to a minor extent, since the coefficient of saturated permeability was found to change only slightly.

The logged information may be used for a better understanding of the soil and vegetation post-fire evolution states. Indeed, this research activity is expected to impact the modelling of the slope-vegetation-atmosphere interaction at the ground surface, which is the factor mainly controlling the current activity of several weather-induced landslide in both fine and coarser slopes.

Keywords: Wildfire; Vegetated test field site; Soil-Vegetation-Atmosphere interaction; In-situ monitoring.

1. Introduction

In Europe, Mediterranean regions are the most susceptible areas to wildfires; this is mainly due to the land-use change that has promoted land abandonment with consequent accumulation of biomass (fuel) in forest and natural land, resulting in an increased fire density and intensity, economic damage, and land degradation (Colantoni et al., 2020). Moreover, wildfires are generally considered to be detrimental to slope stability, since those damage the vegetation and alter the properties of shallow soil cover as consequence of the fire-induced thermal stress and burning action (Rengers et al., 2020).

However, the extent to which wildfires may impact on vegetation condition and soil state over depth is still not fully clear, as it depends on several factors, such as fire intensity and duration, as well as the soil and vegetation state and type. Although it would be crucial to establish a physically based model of post-wildfire soil behavior, study on the fire-induced effect on their physical hydro-mechanical properties are still few (Peduto et al., 2022a, b). Fire may impact on the chemo-physical properties of the soil, including its wettability, porosity, infiltration rate, and retention capacity (Coppola et al., 2024).

Typically, laboratory tests are generally preferred to field testing in quantifying the effect of wildfires because of high site-specificity, the variability of the hydro-mechanical response of the top layer, and the difficulty of measuring soil properties in the field prior to the wildfires, which are generally unexpected.

In September 2023, a wildfire occurred at the Pisciolo hillslope (Tagarelli & Cotecchia, 2019, 2020), being a prototype of several other slopes, where a weather-induced slow landslide activity was monitored. At the toe area of this landslide process, a full-scale experiment involving both spontaneous crops and selected vegetation (Tagarelli & Cotecchia, 2022) was realized to investigate the soil-vegetation-atmosphere interaction. The wildfire nearly caused the complete burning of the vegetation. This circumstance, together with the large archive of field data recorded before the wildfire, represents an interesting research opportunity, to carry out a comparison between the pre-fire and the post-fire condition with reference to both the soil cover layer and the vegetation.

Furthermore, a continuously recording monitoring system in the field (Stasi, 2024) was active when the wildfire struck (19/09/2023); this allowed to record monitoring data pertaining to the wildfire process, in terms of soil temperature variation within the first 15 cm of soil, by means of thermocouples.

Hence, the recorded field data during the fire propagation, together with the monitoring of the pre- and post-wildfire hydraulic properties of the soil cover may represent a contribute to shed light on the wildfires-induced effects on the soil cover state.

2. The case study: the Pisciolo hillslope

The Pisciolo slope (Melfi, Italy) is a prototype of several slopes' that are location of weather-induced landslide activity, within the southern central to eastern Italian Apennines (Cotecchia et al., 2014). In this geo-hydro-mechanical context, field monitoring data and numerical modeling (Cotecchia et al., 2014; Tagarelli & Cotecchia 2020) demonstrated that the fluctuation of the piezometric heads recorded in the slopes are connected to the weather action. Indeed, the weather at the top slope boundary drives the water infiltration over time, that is then responsible for the hydraulic head fluctuations in the slope at depth. In this perspective, the thermo-hydro-mechanical constitutive properties of the soil cover are relevant for all the processes occurring at the slope top boundary that represent the soil-vegetation-atmosphere (SVA) interaction. The latter influence the whole stress-strain response at the slope scale, resulting in a slope-vegetation-atmosphere (SLVA) interaction. This is especially the case since both the energy and the hydraulic gradients due to the weather exhibit their maximum intensity at very shallow depths (i.e., from ground level to 3-4 metres depths), where the exchanges of liquid, gas and energy between the soil and the atmosphere mainly take place.

With the aim to further deepen the knowledge on the thermo-hydro-mechanical processes of the SVA interaction and its effect on the slope conditions at the crop scale, a full-scale experiment involving spontaneous vegetation and a selected vegetation seeded and farmed in 2019 (Tagarelli & Cotecchia, 2022) was realized.

The vegetated topsoil cover (i.e., up to 1.5-2 m b.g.l) at Pisciolo is a clay with sandy silt (Stasi 2024) that is locally interbedded by coarser strata and fractured rocky clusters; whereas the selected vegetation is mainly Gramineae grass (i.e., Poacee) that is characterized by a gravitropic vegetative growth with a fibrous root system able to reach water and nutrients at depth below ground level. The final purpose of the field test site is to assess the impact of the selected vegetation in modifying the thermo-hydraulic balance at the ground surface and to quantify any potential decrease in the amount of water infiltrating the slope top cover.

Furthermore, the hydro-mechanical characterization of the soil cover has been carried out through both laboratory field testing. The behavior of the soil cover as response to the weather action and the conditions of the vegetation portion (e.g. leaves and roots, Stasi 2024) varying over the years have been monitored in the field, together with the weather forcing action itself. Indeed, the field test site was equipped with a system to monitor all the main variables involved in the thermo-hydraulic balances, i.e., suction, volumetric water content, soil temperature, solar radiation, wind speed, by means of an advanced network of probes and sensors (Tagarelli et al., 2022, Stasi 2024).

Right after the wildfire occurrence in September 2023, an in-situ survey has been carried out, during which also aerial images of the test site being involved (of about 40 hectares, Figure 1) have been taken. The surveys has allowed to recognize that the wildfire has caused the combustion of dry grass and leaves. The wildfire has been classified as grazing fire, for which the propagation speed is generally of about 5–10 m/min, with a flame height limited to less than1 meter and a still low flame front intensity between 100 and 800 KW/m^2 (De Zorzi et al., 2009).

Figure 1. a) Pisciolo hillslope surveyed after the wildfire with a drone; photo in the test site in which selected vegetation were present b) pre- and c) post fire event with a d) detail of the burnt area.

3. Methods

Pre and post wildfire soil properties have been evaluated using laboratory and in-situ testing methods including Loss-on-Ignition (LOI) tests (ASTM D7348-08, 2011), water drop penetration time (WDPT) tests (Doerr et al., 2004), and in-situ infiltration rate tests with Guelph permeameter (Soil moisture Equipment Corp. 2008) and Double Ring Infiltrometer (DRI) (ASTM D3385).

The LOI tests have been carried out to investigate the wildfire-induced change in the soil organic matter (SOM) content. The test consists of heating up (550°C) the sample for two hours, causing the destruction of all organic matter in the soil.

The WDPT method was used to investigate qualitatively any induced changes in the soil water repellency, which possibly reduce the infiltration rate by forming water resistant layer along the soil profile. This investigation was carried out with 80 µL distilled water droplet placed onto the soil surface. The time to let the droplet infiltrate was recorded, giving an indication of the soil repellency rate.

The Guelph permeameter test has been used to investigate the infiltration rate into the soil cover before and after the wildfire occurrence. The testing procedure prescribes the application of a transient seepage of water recharge into the unsaturated soil cover inside a surficial cylindrical well hole, in which a water head of 0.25 m is kept constant, until a steady state condition of the seepage in the soil is reached (Soil moisture Equipment Corp., 2008).

The DRI makes use of two open stainless-steel cylinders, of which one is placed inside the other. Once the rings are water-filled, the water level is recorded by a floating device in the inner ring at regular times until the steady state condition is reached and the infiltration rate is determined (Ronnqvist, H. 2018).

As already mentioned, during the wildfire occurrence, the soil temperatures was continuously recorded within 15cm b.g.l. by means of a Type E thermocouple (Campell Scientific, TCAV) which resulted from an average of the soil temperatures recorded at four probes located at 0.5, 5.5, 10.5, 15.5 cm depth into the soil. This allowed to record the increase in soil temperature due to the wildfire strike.

4. Analysis of the tests and monitoring results

The Figure 2 shows the results of the LOI tests carried out on 4 different samples on both pre- and post-fire condition, reported in grey and black respectively. For all the specimens, a lower LOI value is found after wildfire exposure. On average, the LOI decreases from values pre-fire of about 10 % to values post-fire of about 7 %. Low values of LOI are generally associated with a low SOM content (Schulte and Hopkins 2015); hence, burned soil is expected to have a lower SOM content than that of the unburned soil, in turn increasing the bulk density, which is then expected to reduce porosity (Peduto et al., 2022a). In principle, this would then cause the soil at the ground surface to be less permeable, increasing the runoff potential intensity.

From the results of the soil characterization by means of WDPT method carried out on both pre- and post-fire soil, it can be concluded that the tested soil is classified as wettable, with measured WDPT values of about one second, indicating no changes in the repellency of the soil surface, although a wooden embers cover was found (Figure 1d). However, these results may be also affected by the initial dry soil state condition , as well as the short heat exposure due to the short wild fire duration. Indeed, the latter has been determined by means of the soil temperature monitoring data (Figure 3) that show a significant temperature variation in the soil within 15cm b.g.l. which is experienced only of about half an hour, meaning that the wildfire was of short duration and not very persistent.

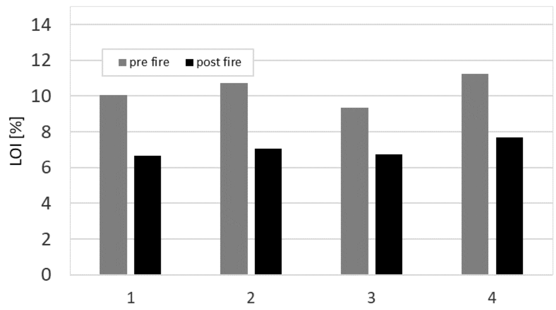

Figure 2. LOI tests results for pre- and post-fire characterization in the vegetated tests area.

The in-situ monitoring data revealed that the soil temperature within 15cm depth was found to sharply increase from about 25 °C (19/09/2023 15:40) up to 355°C (15:55) and then by a quite rather fast decrease within the following hours, reaching then a soil temperature of about 30°C, consistent with the soil temperature in the pre-fire conditions.

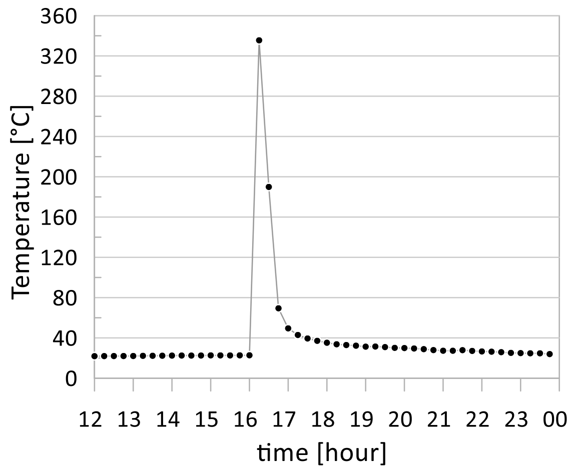

Figure 3. Monitored temperature within the first 15.5 cm of soil b.g.l. that have followed the wildfire process on 29 September 2023.

The hydraulic behaviour of the rooted soil has been investigated by means of the in-situ tests conducted pre and post the strike of the wildfire. In particular, a total of four Guelph tests were conducted at 0.3 m depth with the single-head method, two with reference to the pre-fire condition, already reported by Tagarelli et al., (2023) and two tests for the after the wildfire occurrence. The initial state of the soil was determined in the laboratory through tests on the undisturbed soil samples collected right before the execution of the Guelph tests. The soil initial states, in terms of void ratio, e, suction, s, degree of saturation, S_r, are reported in Table 1. The data show that the soil in the post-fire condition is characterized by higher suction values, and corresponding lower degree of saturation. However, it is worth mentioning that the pre-fire soil states reported in Table 1 do not correspond to the condition immediately prior to the fire occurrence. Indeed, pre-fire soil states correspond to data recorded when the Guelph tests were carried out in the past, and date back in May 2022 (Tagarelli et al., 2023). As such, the data in Table 1 should not be commented as the effect of the wildfire strike, but rather those data were of use to inform the finite element numerical back-analysis of the Guelph tests carried out (Tagarelli et al., 2023). The plot in Figure 4a shows the results in term of water flux infiltrating the soil cover with time as recorded during the Guelph tests before the wildfire occurrence (full and empty dots), and after the wildfire strike (full and empty squares).

Overall, similar steady state infiltration rates at the end of the pre and post fire tests were recorded to be between 0.18-0.28 cm/min. Although, a lower infiltration rate of about 0.03 cm/min was found for the Test 2 post fire. However, this latter value is believed to fall within the high hydraulic heterogeneity that characterize the soil cover at Pisciolo (Tagarelli & Cotecchia, 2020).

It can be concluded that the hydraulic soil properties at about 30 cm b.g.l, appear not to be modified by the wildfire strike, and this seems to be reasonable, since the thermal stress at in the soil at the investigated depth was limited.

Table 1. Initial state of the soil sampled inside the vegetated area before and after the wildfire affected at the beginning of the Guelph's permeability test.

	Pre fire		**Post fire**	
	Test 1	Test 2	Test 1	Test 2
Unit weight, γ [kN/m^3]	15.6	14.9	18.3	18.09
Natural water content, w_n [%]	17.9	22.28	18.2	10.0
Void ratio, e [-]	0.71	0.78	0.71	0.59
Degree of saturation, S_r [%]	68.5	78.7	69.1	45.6
Suction, s [kPa]	589	532	1306	3713

Slightly smaller values of the steady state water flux have been recorded during the Dual ring infiltrometer tests (Figure 4b), being about 0.02-0.05 cm/min, with respect to those of the Guelph tests post-fire.

It is worth mentioning that this circumstance is probably due to the different portion of the soil cover that is investigated by means of the Guelph test, usually at a depth of about 30 cm b.g.l., and the one investigated by means of the Dual ring infiltrometer test, which is basically at the ground surface. Furthermore, as already discussed, the wildfire-induced thermal stress in the soil affected shallow depths (i.e., about 15 cm, Figure 3), making the ground surface the most impacted soil cover portion by the wildfire.

This is the reason why DRI tests have been also carried out since those induce a seepage process from the ground surface downward in the soil cover. Hence, this field test is believed to be the most appropriate to investigate the soil hydraulic properties when affected by wildfire.

Overall, it is recognised that the wildfire occurrence has slightly modified the hydraulic behaviour of the soil cover but only at very shallow depth, since slower infiltration rate have been recorded in the in-situ tests by means of DRI. This conclusion is corroborated by field and laboratory data reported in the literature, that show the same trend of reduction of the infiltration, despite being with reference to pyroclastic soils (Iervolino et al., 2023; Coppola et al., 2024).

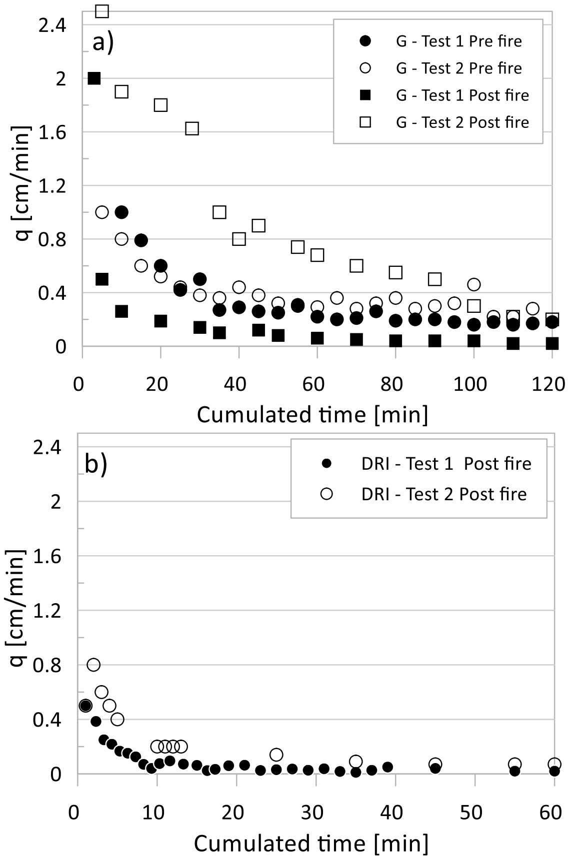

Figure 4. Infiltration rates derived by means of in-situ tests of a) Guelph permeameter; b) Double ring infiltrometer tests.

5. Conclusions and future perspectives

The preliminary field data recorded just right after the strike of the wildfire and here reported may contribute to enrich the needed database to shed light on the extent to which wildfires impact the vegetation and the soil properties.

Furthermore, these data also represent a valuable set of information which may be of use to carry out a back-analysis of the wildfire forcing action within a thermo-hydro-mechanical numerical modelling.

It is believed also that this set of data may inform better the numerical predictions with reference to future scenarios of the processes within the slope-vegetation-atmosphere interaction in the view of climate change adaptation. The impact that future climate scenarios may have on activity of landslide controlled by the slope-vegetation-atmosphere interaction needs to be computed by also accounting for the wildfire occurrence, since those are expected to be more frequent as the mean earth temperature increases.

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