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The signs of past wildfires encoded in the magnetic properties of forest soils

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ABSTRACT

Among the main environmental factors, which influence the functioning of the soil system are wildfires. Their impact on vegetation cover and mineral soil has long been studied in relation to carbon cycling and preservation of soil health. Information about the changes caused by past wildfires in two forest soils, Umbrisol and Albic Luvisol, were obtained by environmental magnetic studies, combined with diffuse reflectance spectroscopy, x-ray diffraction, and Fe and C selective chemical analyses. Maghemite was identified as a main ferrimagnetic carrier of both pedogenic and fire-induced signals. The presence of goethite in the fire-affected depths of the two profiles indicated that the maximum temperature reached in the mineral soil during wildfires was lower than the transformation temperature of goethite (250–300 °C). Therefore, we suggest that the strong magnetic enhancement of the burnt soils (upper 1–2 cm) was caused mainly by the magnetic fraction contained in the vegetation ashes. Higher iron content in coniferous species, probably, was responsible for the higher degree of fire-induced magnetic enhancement of the Umbrisol as compared to less iron incorporated in the broadleaf vegetation at Albic Luvisol. No relationship between the degree of fire-induced magnetic enhancement and time since fire was observed.

1. Introduction

Fire is among the major environmental factors in Earth's surface processes, which is becoming increasingly important during the last century of intensified anthropogenic greenhouse gas emissions and climate change. Moreover, fire-affected soils are characterized by significant changes in their physical and mineralogical properties, leading to change in their capacity to sequester carbon and thus, their role in the global carbon cycle. Incomplete combustion of organic matter during low severity wildfires results in production of pyrogenic carbon, whose stability and preservation under varying climate conditions is a matter of debate (Singh et al., 2012; Egli et al., 2012; Jiménez-González et al., 2016). Along with the changes in carbon stock, physical and mineralogical properties of the fire-affected soils are also prone to short- and long-term changes (Mataix-Solera et al., 2011; Armas-Herrera et al., 2016; Santín and Doerr, 2016). The specific properties of Amazonian Archeological Black Earth soils (terra preta) have been assigned to the anthropogenic activities in prehistoric times, leading to the formation of dark organic-rich soils with significant content of pyrogenic carbon. Studies of iron oxides in the clay fraction of such soils from southern Amazonas (de Aquino et al., 2016) reveal no difference between the content and properties of goethite and hematite in anthropic horizons versus natural (non-affected by fire) Brasilian soils. Thus, the source of higher magnetic signal in terra preta soils needs further research. On the other hand, higher magnetic enhancement of agricultural soils utilized for sugarcane cropping with burning of straw fields is reported (Barrios et al., 2017) as compared to sugarcane cropping without burning. All these issues raise the question on the origin of the fire-affected soil magnetic enhancement. The effect of fire for the establishment of magnetic signature of soils has been proposed long ago by Le Borgne (1955), at the beginning of environmental magnetic studies. Commonly, the occurrence of maghemite in soils from temperate belt has been ascribed to the effect of past wildfires, which cause thermal transformation of soil oxyhydroxides to maghemite (Campbell et al., 1997; Cornell and Schwertmann, 2003; Clement et al., 2011; Mataix-Solera et al., 2011). On the other hand, some studies report insignificant magnetic enhancement of fire-affected soils, thus rejecting the hypothesis that past fires are responsible for the observed magnetic enhancement in soils (Roman et al., 2013). The presence or absence of pedogenic magnetic enhancement of different soil types give also valuable information on the genesis, environmental conditions and iron geochemical cycling at the Earth's surface conditions (Jordanova, 2016). The aim of the present study is to further explore these controversial findings by studying magnetic signature along with other multidisciplinary analyses as diffuse reflectance spectroscopy (DRS), selective chemical extraction, elemental

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concentration, or carbon and nitrogen content of wildfire-affected forest soils. Furthermore, we want to check their ability to preserve information about past fire intensity as well as the dynamics of soil recovery after fire.

2. Materials and methods

Two soil profiles of Umbrisols (Dark mountainous soils) from Rila mountain – burnt and non-burnt locations – were sampled in July 2015. The burnt soil profile (site M) experienced severe wildfire event in year 2000 and natural vegetation recover occurred since then. It resulted in development of a 2 cm new post-fire organic horizon, overlying charred 15 cm thick humic horizon. The latter most probably has thickened due to sedimentation of ashes and charred mineral soil from upslope positions. Because the location is situated within natural reserve area, no restoration has been applied. The non-burnt location (site MO) has lower altitude and represents typical profile of an Umbrisol with 15 cm dark humic horizon, followed by AC-horizon. The parent rock is represented by weathered granite. Climate conditions are characterized by mean annual temperature (MAT) of 4.8 °C and mean annual precipitation (MAP) of 960 mm. The original vegetation is representative for the timberline between the coniferous forest and high-mountain meadow, consisting of herbaceous species and coniferous forest, dominated by *Pinus mugo*. The distance between the two locations is 1.5 km with 255 m difference in the altitude. Profiles' descriptions are given in Table 1.

A third profile of an Albic Luvisol (Leached Cinnamonic forest soil) (soil profile SL) from Strandja mountain (SE Bulgaria) was sampled as well. It is developed under mixed broadleaf forest vegetation (mainly *Fagus orientalis* L. and *Carpinus betulus*). Wildfire occurred in 2012, burning down the original vegetation. No reforestation measures have been undertaken until sampling in 2015. Parent rock is represented by Palaeozoic argillites and metasandstones, climate in the area is Mediterranean with MAT of 12 °C and MAP of 771 mm. Profile's description is given in Table 2.

Fig. 1 shows the locations of the soil profiles studied.

After cleaning the vertical wall of the outcrop, high-density sampling was performed – continuous sampling at 0.5 cm interval for the uppermost 8 cm, 1 cm sampling interval for the next 10 cm and 2 cm – until the bottom part of the BC-horizon. Loose material of about 50 g mass was taken using non-magnetic spatula and sealed in plastic bags. The samples were air dried in the laboratory at room temperature, gently crushed and sieved through a mesh with 1 mm openings.

Powdered material was used for magnetic susceptibility and hysteresis measurements. Remanence measurements of isothermal and anhysteretic magnetizations were carried out on cubic 2 × 2 × 2 cm samples, prepared in plastic boxes by mixing 2 g of soil material, some gypsum powder and water. After hardening, boxes were removed. A blank gypsum sample was prepared and measured in line with the rest of the samples in order to subtract the effect of gypsum component on the total magnetization of the cubic samples.

Magnetic susceptibility (K) of the bulk soil was measured on Kappabridge MFK-1 (Agico, Brno) at an applied field of 200 A/m and single low frequency. Mass-specific susceptibility (χ) was calculated using sample's mass, measured on an analytical balance KERN ABJ with precision of 0.0001 g Frequency-dependent magnetic susceptibility (χ_{fd}) was measured on Bartington dual frequency sensor MS2B (Bartington Ltd., UK) with frequencies of 0.47 kHz and 4.7 kHz. Percent frequency-dependent magnetic susceptibility was calculated as normalized difference between low-frequency (χ_{lf}) and high-frequency (χ_{hf}) magnetic susceptibility values: $\chi_{fd}\% = 100 * (\chi_{lf} - \chi_{hf}) / \chi_{lf}$ (Mullins and Tite, 1973). Anhysteretic remanent magnetization (ARM) was acquired by using a Molspin AF-tumbling demagnetizer with 100mT maximum amplitude of the alternating field and ARM attachment with applied weak direct current (DC) field of 0.1 mT (Molspin Ltd., UK). Anhysteretic susceptibility (χ_{arm}) was calculated as $\chi_{arm} = ARM/H/\rho$, where H is the intensity of the DC-field and ρ - bulk density. Isothermal remanent magnetization (IRM) was acquired in ASC pulse magnetizer (ASC Scientific, USA) at 2 T field and back-field remanence at 300mT was imparted for calculation of the S-ratio ($S = -IRM_{300mT} / IRM_{2T}$). Stepwise thermal demagnetization of composite IRM, acquired along the three perpendicular sample's axes (according to the method proposed by Lowrie (1990)) was used for identification of magnetic minerals. High-coercivity magnetic minerals were magnetized along z-axis by applying a DC field of 5 T. Applying a field of 600mT along y-axis isolated middle – coercivity ferrimagnetic minerals such as titanomagnetites, but also low-coercivity hematite may be present. For separation of low-coercivity magnetic fraction a field of 200mT was applied along x-axis. Remanence measurements were carried out using Molspin Minispin (Molspin Ltd., UK) magnetometer. Magnetic hysteresis measurements were carried out on Micromag 3900 (Princeton Measurements Corporation, USA) with maximum applied field of 1 T using the facilities at the University of Bucharest. Set of magnetic characteristics were determined: saturation magnetization (M_s); saturation remanence (M_{rs}); coercive force (B_c) after correction for paramagnetic contribution and coercivity of remanence (B_{cr}) – by using back-field DC demagnetization.

Soil pH was measured with a Hanna 213 pH-meter (HANNA Instruments, USA) in water (1:5 soil: water ratio with sample holding time of 1 h).

The reflectance spectra of powdered samples were obtained using a Cary 5000 UV–VIS-NIR spectrophotometer (Varian Inc., California)

Table 1
Description of the two profiles of Umbrisols studied.

Profile	Description
Umbrisol (MO)	0–2 cm O-horizon, coarse crumby structure, silty, dark brown color 7.5 YR 3/3 moist, abundant fine roots
N 42°12′49.0″	2–25 cm Ah horizon, loose crumby structure, silty, brown color 7.5 YR 4/4 moist, coarse fragments from the parent rock 2%, sharp transition to the
E 23°23′15.3″	lower AC horizon
H = 1733 m a.s.l.	25–45 cm AC horizon, medium crumby structure, silty, strong brown color 7.5 YR 4/6 moist, coarse fragments from the parent rock 1%
Natural, non-burnt soil	
Umbrisol (M)	0–2 cm post-fire O horizon, medium crumby structure, silty, light brown color 7.5YR6/4 moist, abundant fine roots
N 42°11′53.4″	2–15 cm Ah charred horizon, crumby structure, silty-clayey, black color 7.5YR2.5/1 moist, pieces of charred wood of 2-3 mm size, smooth
E 23°22′52.5″	transition to the lower transitional horizon with decreasing number of char.
H = 1977 m a.s.l.	15–25 cm AC horizon, crumby structure, sandy, dark brown color 7.5YR3/4 moist, coarse fragments from the parent rock 2%
Fire-affected soil	
Wildfire in year 2000	
no reforestation	