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Short-term spatio-temporal spring grassland fire effects on soil colour, organic matter and water repellency in Lithuania

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Abstract

The aim of this work was to study the short-term effects (first 9 months after the fire) of a low-severity spring boreal grassland fire on soil colour, soils organic matter (SOM) and soil water repellency (SWR) in Lithuania. Three days after the fire we designed a plot of 400 m^2 in a control (unburned) and unburned area with the same geomorphological characteristics. Soil water repellency analysis were assessed through the 2 mm mesh (composite sample) and in the subsamples of all of the 250 samples divided into different soil aggregate fractions of 2–1, 1–0.5, 0.5–0.25 and < 0.25 mm, using the Water Drop Penetration Time (WDPT) method.

The results showed that fire darkened the soil significantly during the entire study period due to the incorporation of ash/charcoal into the soil profile. Soil organic matter was significantly higher in the first two months after the fire in the burned plot, in comparison to the unburned plot. Soil water repellency (SWR) of the composite sample was higher in the burned plot during the first two months after the fire. However, considering the different aggregate fractions studied, the SWR was significantly higher until 5 months after the fire in the coarser fractions (2–1 mm, 1–0.5 mm) and 7 months after in the finer (0.5–0.25 mm and < 0.25 mm), suggesting that the leachability of organic compounds is different with respect to soil aggregate size fractions. This finding has implications for the spatio-temporal variability of fire effects on SWR. SOM was significantly negative correlated with SWR (composite sample) only in the two months after the fire. These results demonstrated that in the first two months the hydrophobic compounds produced by fire were one of the factors responsible for the increase in SWR. Subsequently repellent compounds were leached, at different rates, according to particle size. The impacts of this low severity grassland fire were limited in time, and are not considered a threat to this ecosystem.

1 Introduction

Fire is a natural phenomenon important to many worldwide ecosystems. It is accepted that fire plays an important role in plant adaptations and ecosystem development and distribution (Pausas and Kelley, 2009). It is well known that fire is a common occurrence and important disturbance in boreal ecosystems and a factor in the forest ecology of the region (Vanha-Majamaa et al., 2007). These ecosystems are strongly adapted to fire disturbance (Granstrom, 2001; Hylander, 2011; Pereira et al., 2013a, b). However, the recent climate change, land-use change and fire suppression policies, may have important implications on the fire regime, fire severity and the role of fire in boreal environments (De Groot et al., 2013; Kouki et al., 2012; Van Bellen et al., 2010). Among all the boreal ecosystems, fire plays a particularly important role in grasslands. Without the presence of fire, the area extent of boreal grasslands would decline significantly (Bond et al., 2005).

Despite the recognized importance, little research has been carried out on fire effects on boreal grassland ecosystems (Pereira et al., 2013a, c), especially on soil properties. Fire has been recognized to be a soil forming-factor (Certini, 2013). The majority of the studies on fire impacts on grassland soil have been carried out in tropical (Bird et al., 2000; Coetsee et al., 2010; Fynn et al., 2003; Michelsen et al., 2004; Miranda et al., 1993), sub-humid (Knapp et al., 1998), desert (Ravi et al., 2009a; Withford and Steinberger, 2012), arid (Vargas et al., 2012), semiarid (Dangi et al., 2010; Ravi et al., 2009b; Snyman et al., 2002; Xu and Wan, 2008; White et al., 2011), temperate (Harris et al., 2007) and Mediterranean environments (Marti-Roura et al., 2013; Novara et al., 2013; Romanya et al., 2001; Úbeda et al., 2005).

After fire, the degree of direct and indirect impacts on soils (e.g. ash and soil erosion, moisture, organic matter, hydrophobicity, ash nutrient input, organic matter consumption, microbiological changes) have consequences for the complex spatio-temporal nutrient distribution and availability for plant recovery (Busse et al., 2013; Gimeno-Garcia et al., 2011; Kinner and Moody, 2010; Malkinson and Wittenberg, 2011; Moody et al., 2013; Pereira et al., 2011, 2013a; Ravi et al., 2009b; Sankey et al., 2012; Shakesby, 2011; Smithwick et al., 2012). The spatio-temporal extent of these impacts depends on the fire severity, topography of the burned area and the meteorological post-fire conditions.

Fire can change soil colour. In fires of high severity the temperatures increase soil redness, especially when temperatures are > 300–$500\,^{\circ}$C (Terefe et al., 2008) or $> 600\,^{\circ}$C (Ketterings and Bigham, 2000; Ulery and Graham, 1993), which is attributed to the destruction of the organic matter and increase in iron oxides such as hematite (Terefe et al., 2005). Low severity fires darken the soil as a result of the incorporation of ash/charcoal into the soil matrix (Eckmeier et al., 2007). These authors observed that soil lightness had a significant negative correlation with charcoal carbon. Despite this knowledge, little is known about the soil changes in the immediate period after the fire, when the major changes in soil properties and ash transport happen (Pereira et al., 2013a; Scharenbroch et al., 2012). In addition, few comparisons have been carried out with nearby unburned plots. Eckmeier et al. (2007) studied the effects of a slash-and-burn fire in comparison with a control plot. However, the study was carried out immediately after the fire and one year after the fire. Major changes were not observed in detail in the year after the fire. The changes in soil colour after fire can have implications for temperature (albedo increase or decrease) and microbiological activity (Certini, 2005; Gomez-Heras et al., 2006). Thus it is important to have high-resolution studies of fire effects on soil colour.

Fire affects also soil organic matter (SOM) chemical composition, quantity and quality. Fire can increase or decrease SOM depending on the type of fire and severity, which considers the effects of biophysical variables such as topography, soil and type of species and ecosystem affected (Certini et al., 2011; González-Peréz et al., 2004; Knicker, 2007). Low severity fires can increase SOM in the immediate period after, due to the incorporation of charred material (De Marco et al., 2005), and high severity fires tend to decrease SOM due to the high temperatures, which volatilize all SOM, decreasing considerably its amount in the soil (Neff et al., 2005). Depending on the topography, some months after fire important amounts of SOM can be also lost by erosion (Novara et al., 2011).

It widely known that fire can induce soil water repellency (SWR), with implications for soil infiltration, water and nutrient availability and an increase of runoff and erosion (Debano et al., 2000; Mataix-Solera et al., 2013; Varela et al., 2005). The fire impacts on SWR depend on type of soil affected, temperature reached, fire severity, fire recurrence, time of residence, type and amount of vegetation combusted, ash produced and pre- and post-fire soil moisture content (Bodí et al., 2011; Doerr et al., 2000; Jordán et al., 2011; MacDonald and Huffman, 2004; Mataix-Solera and Doerr, 2004; Tessler at al., 2012; Vogelman et al., 2012). Previous studies observed that after fire, SWR is especially changed in soils that are wettable before fire compared those that are hydrophobic (Gimeno-Garcia et al., 2011). In wettable soils fire increases SWR (Granged et al., 2011; Mataix-Solera and Doerr, 2004), meanwhile in hydrophobic soils, fire can slightly reduce or have no impact on SWR (Doerr et al., 1998; Jordán et al., 2011; Neris et al., 2013). However this effect depends on fire severity. Rodriguez-Alleres et al. (2012) reported that moderate to high severity fires can increase SWR in naturally repellent soils.

Spring grassland fires are frequent in Lithuania. After the winter, farmers burn the dead grass in order to improve fields for spring and summer crops (Pereira et al., 2012a). Thus, it is important to know the effects of these fires on soil properties in order to understand the impacts of this practice, especially in an environment where few studies have been carried out. Moreover, this use of fire for landscape management is forbidden in Lithuania, and normally, farmers set fires and leave the area until the fires are extinguished, leading on many occasions to property loss (Mierauskas, 2012; Pereira et al., 2012a).

The aim of this work is to study the short-term effects of a low severity spring grassland fire on some soil properties: soil colour, SOM content and SWR.

2 Materials and methods

2.1 Study site and plot design

The fire occurred on 15 April 2011, near Vilnius (Lithuania) at 54°42′ N, 25°08′ E, 158 m.a.s.l and affected approximately 20–25 ha. The characteristics of the study area are described in Table 1. The fire severity was considered low based on the predominance of black ash and unburned patches (Pereira et al., 2013a). Three days after the fire, we designed a plot of 400 m^2 (20 m × 20 m, with 5 m space between sampling points) in a control (unburned) and burned area with the same geomorphological characteristics (flat area). Samples were collected in the top soil (0–5 cm) immediately, and at 2, 5, 7 and 9 months after the fire. We studied the upper soil layer because we aim to know the effects of fire in the first centimetres of soil. Previous studies showed that the fire effects on soil are especially limited to the first 5 cm (Marion et al., 1991; Blank et al., 2003). In low severity fires, soil temperatures rarely exceed 100 °C in the surface and 50 °C at 5 cm (Agee, 1973). In total we collected 25 samples in the unburned and 25 in the burned plot in each sampling period (50 samples).

2.2 Laboratory analysis

Samples were collected, stored in plastic bags, taken to the laboratory and air-dried for 24 h. Subsequently, the samples were carefully sieved through a 2 mm mesh. Soil colour, including hue, value and chroma, was assessed using the Munsell color chart (Ketterings and Bigham, 2000; Viscarra Rossel et al., 2006) in order to quantify the effects of fire on soil colour (Terefe et al., 2008; Úbeda et al., 2009). Soil organic matter was estimated by loss-on-ignition using approximately 1 g of soil heated to 900 °C for 4 h (Avery and Bascomb, 1974) after drying at 105 °C for 24 h for remove the moisture. Soil texture of unburned samples was analysed using the Bouyoucos method (Bouyoucos, 1936) and pH with 1 : 2.5 deionised water (Table 1). Soil water repellency was assessed in the samples sieved through the 2 mm mesh (composite sample) and in the subsamples of all of the 250 samples divided into different soil aggregate fractions of 2–1, 1–0.5, 0.5–0.25 and < 0.25 mm, as used in previous studies (Mataix-Solera and Doerr, 2004; Jordán et al., 2011). In total we analysed 1250 SWR sub-samples. Between 5–7 g of soil of each sample and subsample were placed in 60 mm diameter plastic dishes and exposed to a controlled laboratory environment (temperature of 20 °C and 50 % of air relative humidity) for one week in order to avoid potential effects of atmospheric conditions on SWR (Mataix-Solera et al., 2013). The persistence of SWR was measured with the Water Drop Penetration Time (WDPT) method that involves placing three drops of distilled water onto the soil surface and registering the time required for the drop complete penetration (Wessel, 1988). The average time of the three drops was used to assess the WDPT of each sample and subsample. Water Drop Penetration Time classes were assessed according to Doerr (1998) (Table 2).

2.3 Statistical analysis

Data normality and homogeneity of the variances were tested with the Shapiro–Wilk test (Shapiro and Wilk, 1965) and Levene test respectively. Data were considered normal and homogeneous at a $p > 0.05$. Original data did not follow the normal distribution and heteroscedasticity. Soil colour chroma value and SOM value data respected normality after a neperian logarithmic (ln) transformation. Soil water repellency data only followed the normality and heteroscedasticity after a squared root transformation. Differences between treatments (control vs. burned plot) and among sampling periods were observed using repeated measures Anova test. In the case of soil fractions, the repeated measures Anova tested the differences of SWR among treatments and time in each fraction. Differences among fractions in each treatment at each period were assessed with one-way Anova test. If significant differences were identified a Tukey HSD post-hoc test was applied. Significant differences were considered at a $p < 0.05$. In this work data are presented as original values (untransformed). However, comparisons were carried out with the transformed data. Correlations among the variables were carried out with the Pearson coefficient of correlation. In the case of SWR, the coefficient of correlation just considered the composite sample. Significant correlations were considered at a $p < 0.05$. Statistical analyses were carried out with STATISTICA 6.0 (Statsoft Inc., 2006).

3 Results

3.1 Soil colour and soil organic matter content

The soil colour in the burned and unburned plots was in the soil Munsell 10YR hue for all the samples. The soil chroma value was significantly different between treatments ($F = 67.18$, $p < 0.001$), time ($F = 3.70$, $p < 0.01$) and time vs. treatment ($F = 4.35$, $p < 0.01$). Soil colour was significantly darker (lower Munsell chroma value) in the burned than in the unburned plot in all sampling periods (Fig. 1). The great differences were observed immediately and 2 months after the fire. Despite the statistical significance, the differences between the two plots decreased with time. Among periods significant differences were identified only in the burned plot, between the immediate period after the fire and the subsequent time periods (Fig. 1).

SOM was significantly different between treatments ($F = 24.97$, $p < 0.001$), time ($F = 3.28$, $p < 0.05$), but not between time vs. treatment ($F = 1.64$, $p > 0.05$). Soil organic matter was significantly higher in the burned plot than in the unburned plot in the two first sampling periods (after the fire and two months after the fire) (Fig. 2). The largest differences were observed after and 2 months after the fire. The differences among periods were significant only in the burned plot. In both plots the trend with time is very similar.

3.2 Soil water repellency

The SWR of the composite samples was significantly different between treatments ($F = 133.37$, $p < 0.001$), time ($F = 49.20$, $p < 0.001$) and time vs. treatments ($F = 45.94$, $p < 0.001$) (Fig. 3). The differences between treatments were higher in the burned plot, especially evident immediately and 2 months after the fire. Five, 7 and 9 months after the fire no significant differences were identified among treatments. With time we observed a decrease of SWR in the burned area (Fig. 3).

In relation to the analysed soil fractions, significant differences were observed between treatments ($F = 16.22$, $p < 0.001$), among the different fractions ($F = 11.72$, $p < 0.001$) and time vs. treatment ($F = 10.64$, $p < 0.001$) in SWR. The SWR was especially high in the finer fractions (0.5–0.25 and < 0.25 mm). We identified significant differences in SWR among all studied periods in the finer fractions in the burned area. In the coarser fractions (2–1 and 1–0.5 mm) between 2 and 5 months after the fire no significant differences were observed. No differences were identified among time in any fractions in the unburned plot (Table 3). Differences between the studied fractions in the different plots were observed immediately after, 2 and 5 months after the fire. Seven months after the fire significant differences were only observed in the SWR finer fraction. Nine months after the fire, no significant differences were observed in the SWR any of the studied fractions (Table 3).

We observed significant differences in the studied fractions in each plot during the studied period in SWR (Table 4). Immediately after, 2 and nine months after the fire in the unburned and burned plot the finer fraction (< 0.25 mm) was significantly higher than in the other size fractions. Five months after the fire no significant differences were observed between the coarser fractions (2–1 and 1–0.5 mm) and the finer (0.5–0.25 and < 0.25 mm) in both plots. Seven months after the fire we observed significant differences among all fractions in the burned and unburned plot (Table 4).

In the unburned plot, in all the sampling periods and fractions analysed samples were predominantly wettable (Fig. 4a, c, e, g and i). In the burned plot SWR was classified mainly as "low" (Fig. 4b, d, f, h and j). However, after the fire in the composite and studied soil fractions, SWR was classified as strong and severe, especially in the finer fraction (< 0.25 mm). With time SWR persistence was reduced in all the fractions and 9 months after the fire the samples were all wettable (Fig. 4i and j).

3.3 Correlation among variables

In the unburned area the correlations between soil colour and SOM were always negatively significant at a $p < 0.05$. The correlations between soil colour vs. SWR and SOM vs. SWR were not significant in any case (Table 5). The correlations between soil colour vs. SOM in the burned area were negatively significant in all sampling periods. However, in the correlations of soil colour vs SWR and SOM vs. SWR, the correlations are only significant immediately after and 2 months after the fire. The coefficients of correlation decrease with the time in all the cases (Table 5).

4 Discussion

4.1 Soil colour and SOM

Fire darkened soil colour, especially in the immediate period after the fire. Incomplete fuel combustion produces black ash (Úbeda et al., 2009), especially in low severity fires, as in the present one, where the temperatures do not reach high values (Keeterings and Bigham, 2000). Normally, black ash is incorporated into the soil or can be eroded in the weeks following the fire (Pereira et al., 2013b), contributing to the darkening of the soil following the fire and the reduction of Munsell chroma values as observed in this study and in previous reports (Ketterings and Bigham, 2000; Ulery and Graham, 1991). With time, despite the significant differences of soil colour among treatments, in the burn plot the soil became lighter. This can be attributed to leaching after rainfall that solubilises ash elements and reduces soil darkness (Eckmeier et al., 2007; Pereira et al., 2012b, 2013c; Woods and Balfour, 2011). The ash leaching into the soil profile increases and changes the type and amount of nutrients in the soil, as observed in other studies (Chambers and Attiwill, 1994; Marion et al., 1991; Pereira et al., 2011, 2013d).

The black ash cover in the immediate period after the fire decreases albedo and increases soil temperature (Bowman et al., 2009; Moody et al., 2013; Scharenbroch et al., 2012), and changes the microbiological activity and diversity (Raison and McGarity, 1980; Badia and Marti, 2003; Dooley and Treseder, 2012). These environmental conditions, together with the nutrient availability, high rainfall amount after the fire, and warmer temperatures during the spring season, can explain the fact that two months after the fire vegetation recovered totally in this burned area (Pereira et al., 2013a). As a result of vegetation recovery, two months after the fire the effects of soil colour on soil temperature may have been reduced. As in other grassland ecosystems, the fast vegetation recuperation is an indicator that the ecosystem is resilient to fire impact, and it is considered to have beneficial effects on biodiversity (Morgan, 1999; Lewis et al., 2009; Bond and Parr, 2010; Wu et al., 2013). In this context the studied fire is was not considered a threat to the ecosystem.

Soil organic matter was high in the burned plot, especially in the first two months after the fire. In low severity fires, as in the one studied, SOM increases temporarily due to the incorporation of ash and charred material into soil profile (González-Peréz et al., 2004). Short-term increases of SOM in the immediate period after low and medium severity fires were documented in other studies (Gimeno-Garcia et al., 2000; Mataix-Solera et al., 2002; De Marco et al., 2005; Vogelman et al., 2012). The decrease of SOM with the time in soil surface can be also attributed to incorporation into deeper layers due to leaching (Czimczik et al., 2004; Hockaday et al., 2006; Knicker et al., 2013) and plant nutrient consumption and recovery, especially in the first two months, when the plant regrowth was remarkable.

The correlation between soil colour and SOM was always significantly negative, especially high in the immediate period after the fire in both plots. Darker soils correspond to low Munsell chroma values (Viscarra Rosell et al., 2006; Shields et al., 1968; Conant et al., 2011), independent of the area being affected by fire or not. In burned areas, soil became darker with the increasing content of aromatic carbon, highly present in charred material produced by fires (Dumig et al., 2009). In soils affected by low severity fires, the colour is darker due the incomplete organic matter combustion, and richer in SOM (Terefe et al., 2008).

4.2 Soil water repellency

Soil water repellency in the composite samples was significantly higher in the burned plot than in the control plot in the two first months after the fire. Fire induced SWR was documented in previous works in areas affected by low severity fire (Gleen and Finley, 2010; Granjed et al., 2011; Stoof et al., 2011). The rapid decrease of SWR in the immediate period after the fire can be attributed to the amount of rainfall that leached ash/charchoal and soil hydrophobic compounds into the soil profile as observed in previous works (Granjed et al., 2011; MacDonald and Huffman, 2004). In the two first months post-fire precipitation totalled more than 80 mm (Pereira et al., 2012b) and this could have contributed to the leaching of hydrophobic compounds. It is very likely that the direct impacts of fire (e.g. temperature) were minimal since in the immediate period after the fire no significant differences were observed in soil moisture between burned and unburned plot (Pereira et al., 2012b). The high SWR in the burned plot can be attributed to the indirect effect of ash deposition on the soil surface. The ash produced at low fire severity has been demonstrated to can be hydrophobic (Bodí et al., 2011) and once deposited onto the soil surface can contribute strongly to SWR increases. As previous works on this plot have demonstrated, the ash collected in this burned area was hydrophobic (Pereira et al., 2012a), thus it is very likely that contributed to this short term increase in SWR.

In the control and burned plot, SWR was higher in the finer fraction (< 0.25 mm), especially in the first 7 months after the fire. Rodriguez-Alleres et al. (2007) observed that grassland soils presented a high hydrophobicity in the finer fraction as we identified in this study. Bisdom et al. (1993) also observed that finer sized fractions were more hydrophobic than the coarser fractions. The results obtained in this study are in accordance with previous works in burned areas, which identified that the finer soil fraction was more repellent than the coarser fraction (Mataix-Solera and Doerr, 2004; Gimeno Garcia et al., 2011; Jordán et al., 2011).

Soil water repellency is mainly attributed to soils with coarser textures that are more susceptible to developing repellent surfaces, due to the smaller specific surface area in relation to fine textured soils (Blas et al., 2010; Doerr et al., 2000). However it has been found that when a soil is hydrophobic, the finer fraction is usually more water repellent that the coarser ones (Mataix-Solera et al., 2004; Jordán et al., 2011). In the present study SWR was especially severe in the finer fraction in the immediate period after the fire in the burned area. This can be attributed to the existence of hydrophobic ash smaller than < 0.25 mm and/or the presence of hydrophobic interstitial organic matter that influenced the SWR (Mataix-Solera and Doerr, 2004).

In the composite samples significant differences between treatments were only identified in the two months after the fire. Nevertheless in the burned plot, significant differences among fractions were observed until 9 months after the fire. In the finer fractions differences were significant in all measurement periods (Table 3). This shows that the leaching of ash hydrophobic substances attached to soil fractions may be different with time and the leaching from the coarse fractions is higher than from the finer ones. Between each fraction in the different treatments significant differences were observed in the coarser fractions (2–1 and 1–0.5 mm) until 5 months after the fire and in the fine fractions (0.5–0.25 and < 0.25 mm) until 7 months after the fire. Soil texture is an important variable in nutrient leaching (Borchard et al., 2012).

The nutrients are leached faster from coarser than from finer fractions due to the lower water retention and smaller specific surface area, as reported in previous studies (Gaines and Gaines, 1994; Leinweber et al., 1999; Nguyen and Marschner, 2013). This can explain why the organic hydrophobic substances were leached faster from the coarser fractions. The results suggest that the time for the burned plot to return to previous conditions depends also on the aggregate size fraction because the leaching of organic substances is not equal across the fractions. Accordingly, the spatial and temporal distribution of aggregate size fractions in burned areas may be important to understand the rate of leaching of organic hydrophobic substances from the upper soil layer.

Fire can have important impacts on soil particle and aggregate size. High severity wildfires can reduce the sand sized aggregates, and consume completely the organic matter, leading to a destruction of the soil aggregates (Giovannini et al., 1988; Mataix-Solera et al., 2011; Ulery and Graham, 1993). Low temperature/severity fires, normally do not significantly change particle and aggregate size (Certini, 2005; Mataix-Solera et al., 2011). Changes in particulate size occur at temperatures around 500 °C and in aggregate stability at temperatures around 200 °C (Ketterings et al., 2000; Mataix-Solera et al., 2011). Thus in the studied fire, particle and aggregate sizes may be not different between unburned and burned area. However it is important to know if there were some changes with time, because these changes may have an influence on the persistence of SWR in space and time. The differences of each fraction in each treatment are similar in all sampling periods, suggesting that fire did not change the differences among the studied fractions.

In the control area, the correlations between soil colour vs. SWR and SOM vs. SOM were weak and non-significant. In the burned area the correlations were significant only in the first two months after the fire. This suggests that fire and the type of ash produced may be responsible for the increase of SWR. In unburned and burned areas SOM can be correlated (Lozano et al., 2013; Martínez-Zavala and Jordán-López, 2009; Mataix-Solera et al., 2002; Mataix-Solera and Doerr, 2004) or not correlated (Blas et al., 2010) with the amount of SOM. The presence of hydrophobic compounds may be related to a certain type of organic material and not with the total SOM (Doerr et al., 2000). Also, hydrophobicity may be affected by the ionic strength of the soil solution that induces an approximation of charged functional groups in SOM (Hurraß and Shaumann, 2006). These results suggest that the soil became hydrophobic from the substances produced during the fire, as organic coatings that covered the soil particles and aggregates that with time were leached, especially from the coarser fractions. The nutrients leached from ash and soil that normally occurs in the immediate period after the fire (Pereira et al., 2013d; Úbeda et al., 2005) may also contribute to the rapid reduction in SWR.

5 Conclusions

Fire darkened the soil and increased for a short period the SOM (first two months after the fire). This increase was due to the input of partially burned ash into the soil profile that produced an increase in the SWR, due to the characteristics of the burned material. However, this increase was not homogeneous across all aggregate size fractions. Finer fractions were more hydrophobic than the coarser ones. In comparison with the control plot, the SWR of the finer fractions in the burned area was more persistent with the time (7 months after the fire) than in the coarser fractions (5 months).

This spring fire had a short-term effect on the studied variables and would not be considered a serious threat to Lithuanian grasslands.

Future research is needed to understand the persistence of the SWR in different soil size fractions, and the factors that control this dynamic. The different responses of aggregate size fractions to SWR after fire induce an important spatio-tempral variability of fire impacts on SWR and hydrologically related parameters such as infiltration, runoff and soil erosion.

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Main characteristics of the study area.

Geological substrate (Kadunas et al., 1999)	Glacio-lacustrine deposits
Soil type (WRB, 2006)	*Eutric podzoluvisols*
[a, b]Texture (% sand, silt and clay)	9.4, 63.5, 27.1 (Silt loam)
[a]pH	7.2
[a]Organic matter content (%)	6.5
Mean annual rainfall (mm) (Bukantis, 1994)	735
Mean annual temperature (°C) (Bukantis, 1994)	8.8
Dominant vegetation	*Leontodon autumnalis* and *Anthoxanthum odaratum*

[a] Values based on control (unburned) soil samples ($N = 25$).

[b] Sand: 2–0.05 mm, silt: 0.05–0.002 mm, clay: < 0.002 mm.

Table 2. Water Drop Penetration Time (WDPT) classes used in this work. Water Drop Penetration Time measured in seconds (s) (according to Doerr, 1998)

	Wettable	Water repellent								
		Low			Strong			Severe		
WDPT classes	≤ 5	10	30	60	180	300	600	900	3600	> 3600
WDPT interval (s)	≤ 5	6–10	11–30	31–60	61–180	181–300	301–600	601–900	901–3600	> 3600

Table 3. Summary of ANOVA results and Tukey HSD test for soil water repellency according to the analysed soil fractions. Statistical comparisons were carried out among time (upper case) and between treatments (the same fraction in different plots) (lower case) during the studied period. Different letters represent significant differences at $p < 0.05$. Tukey's mean separation A > B > C > D > E. Water Drop Penetration Time measured in seconds (s).

Period	Treatment	Fraction	Mean	SD	Minimum	Maximum
After the fire	Control	2–1	1.73Ab	0.78	1	5
		1–0.5	2.02Ab	1.91	1	11
		0.5–0.25	3.12Ab	7.29	1	38
		< 0.25	15.44Ab	37.42	1	178
	Burned	2–1	65.74Aa	133.01	1	574
		1–0.5	101.13Aa	165.66	1	695
		0.5–0.25	159.65Aa	301.90	2	1363
		< 0.25	500.44Aa	657.81	17.33	2777.1
2 Months	Control	2–1	1.57Ab	0.58	1,41	3
		1–0.5	1.62Ab	0.74	1,33	4
		0.5–0.25	1.78Ab	1.36	1.39	7.21
		< 0.25	3.21Ab	4.86	1.22	23.67
	Burned	2–1	6.60Ba	4.05	1	16
		1–0.5	12.24Ba	15.14	2	75
		0.5–0.25	17.88Ba	26.53	2	129.39
		< 0.25	119.13Ba	237.27	4.66	1221.21
5 Months	Control	2–1	1.72Ab	0.62	1.11	3.21
		1–0.5	1.73Ab	0.61	1.16	3.33
		0.5–0.25	2.69Ab	3.69	1	20.11
		< 0.25	11.66Ab	16.02	1	59.66
	Burned	2–1	6.70Ba	5.02	1.66	17.66
		1–0.5	8.08Ba	7.32	1.66	34.34
		0.5–0.25	9.13Ca	9.86	2	40.33
		< 0.25	39.33Ca	46.50	2.33	185.22
7 Months	Control	2–1	2.12Aa	0.79	1.33	4.33
		1–0.5	2.25Aa	1.92	1	10.66
		0.5–0.25	2.70Ab	2.42	1	11.33
		< 0.25	11.93Ab	15.56	1.33	77.66
	Burned	2–1	3.24Ca	1.89	1	8.11
		1–0.5	3.61Ca	2.67	1	9.66
		0.5–0.25	4.60Db	4.29	1	18.33
		< 0.25	19.04Db	25.45	2	106.11
9 Months	Control	2–1	1.05Aa	0.15	1	1.66
		1–0.5	1.08Aa	0.22	1	2
		0.5–0.25	1.02Aa	0.09	1	1.33
		< 0.25	1.33Aa	0.25	1	2
	Burned	2–1	1.10Da	0.30	1	2.33
		1–0.5	1.36Da	1.20	1	6.66
		0.5–0.25	1.09Ea	0.34	1	2.66
		< 0.25	1.57Ea	0.85	1	4.33

Table 4. Summary of ANOVA results and Tukey HSD test for soil water repellency according to different size fractions in the same treatment, during the study period. Different letters represent significant differences at $p < 0.05$. Tukey's mean separation $A > B > C > D$.

Period	Treatment	P		2–1 mm	1–0.5 mm	0.5–0.25 mm	< 0.25 mm
After the fire	Control	$F = 2.80$	< 0.05	B	B	BA	A
	Burned	$F = 12.18$	< 0.001	B	B	B	A
2 Months	Control	$F = 25.13$	< 0.001	B	B	B	A
	Burned	$F = 24.21$	< 0.001	B	B	B	A
5 Months	Control	$F = 8.01$	< 0.001	B	B	A	A
	Burned	$F = 9.81$	< 0.001	B	B	A	A
7 Months	Control	$F = 26.97$	< 0.001	D	C	B	A
	Burned	$F = 22.42$	< 0.001	D	C	B	A
9 Months	Control	$F = 26.41$	< 0.001	B	B	B	A
	Burned	$F = 23.81$	< 0.001	B	B	B	A

Table 5. Coefficients of correlation among the studied variables in the burned area. Significant at $< 0.05^a$, $< 0.01^b$ and $< 0.001^c$.

Period		Soil colour vs. SOM	Soil colour vs. SWR	SOM vs. SWR
After the fire	Unburned	-0.63^c	$-0.01^{n.s}$	$0.01^{n.s}$
	Burned	-0.74^c	-0.81^c	0.75^c
2 Months	Unburned	-0.62^c	$-0.01^{n.s}$	$0.02^{n.s}$
	Burned	-0.56^b	-0.39^b	0.34^a
5 Months	Unburned	-0.47^b	$-0.08^{n.s}$	$0.17^{n.s}$
	Burned	-0.45^b	$-0.23^{n.s}$	$0.22^{n.s}$
7 Months	Unburned	-0.50^b	$-0.10^{n.s}$	$0.18^{n.s}$
	Burned	-0.45^b	-0.32^a	$0.17^{n.s}$
9 Months	Unburned	-0.41^b	$-0.01^{n.s}$	$0.01^{n.s}$
	Burned	-0.42^b	$-0.22^{n.s}$	$-0.07^{n.s}$

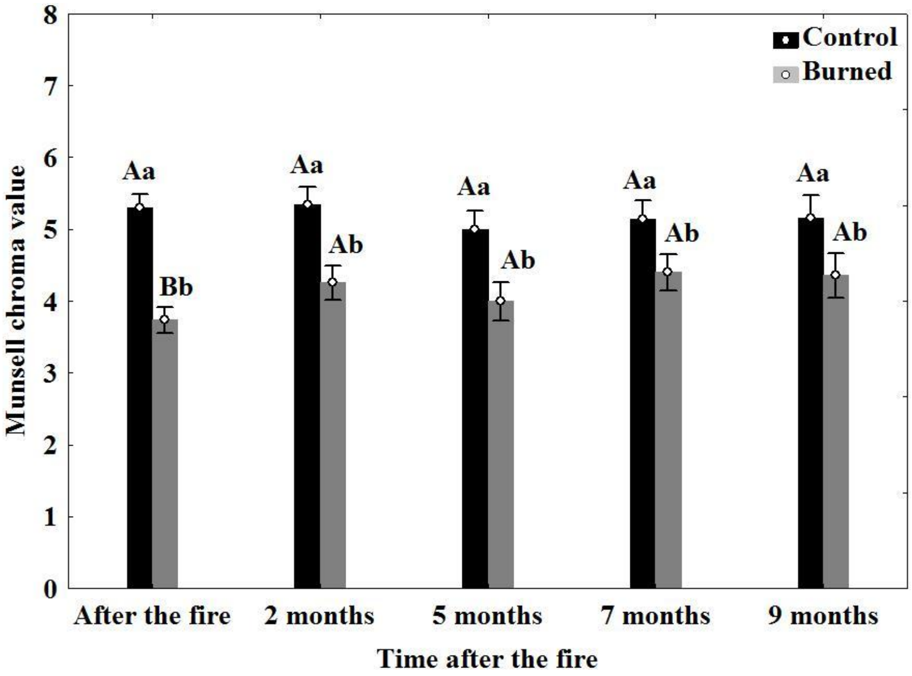

Fig. 1. Evolution of soil Munsell chroma value in the unburned and plot in the post-fire period (bars represent 95 % confidence intervals). Different letters indicate significant differences ($p < 0.05$) among time (upper case) and treatments (lower case).

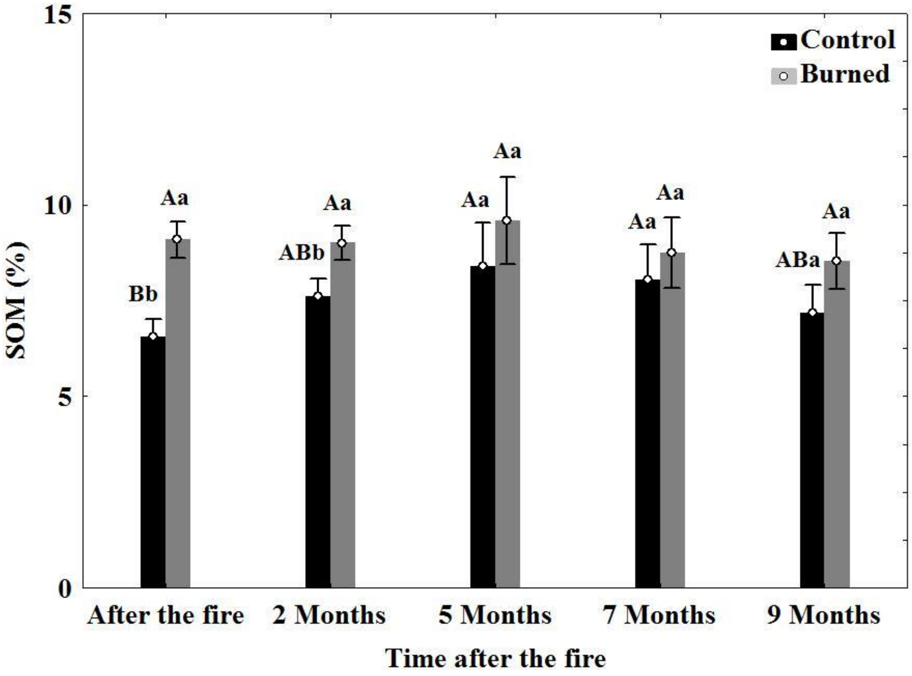

Fig. 2. Evolution of SOM content in the unburned and plot in the post-fire period (bars represent 95 % confidence intervals). Different letters indicate significant differences ($p < 0.05$) among time (upper case) and treatments (lower case).

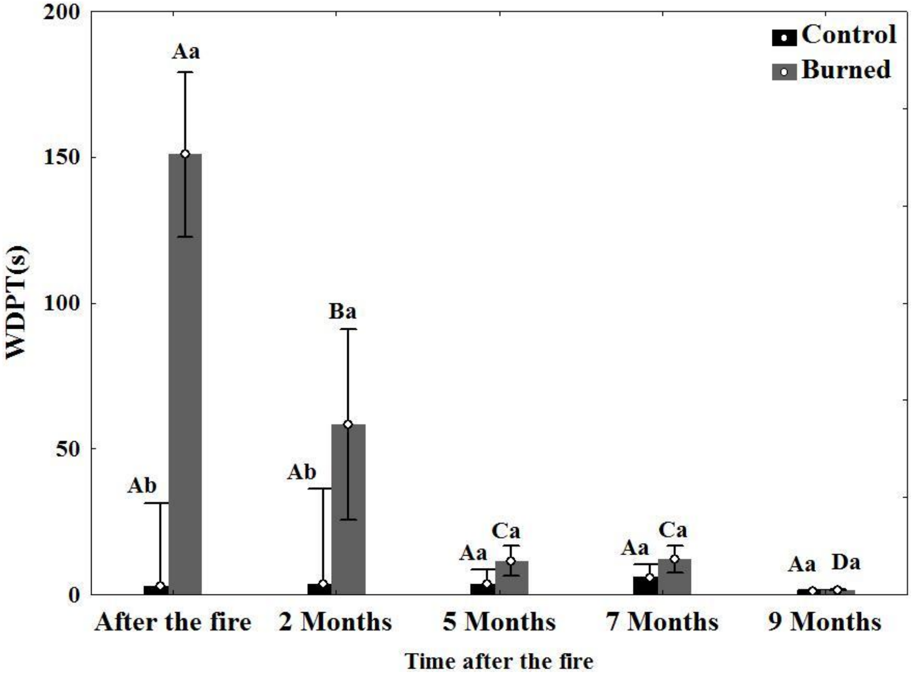

Fig. 3. Evolution of SWR (composite sample) in the unburned and plot in the post-fire period (bars represent 95 % confidence intervals). Different letters indicate significant differences ($p < 0.05$) among time (upper case) and treatments (lower case).

Title Page
Abstract Introduction
Conclusions References
Tables Figures
I◀ ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

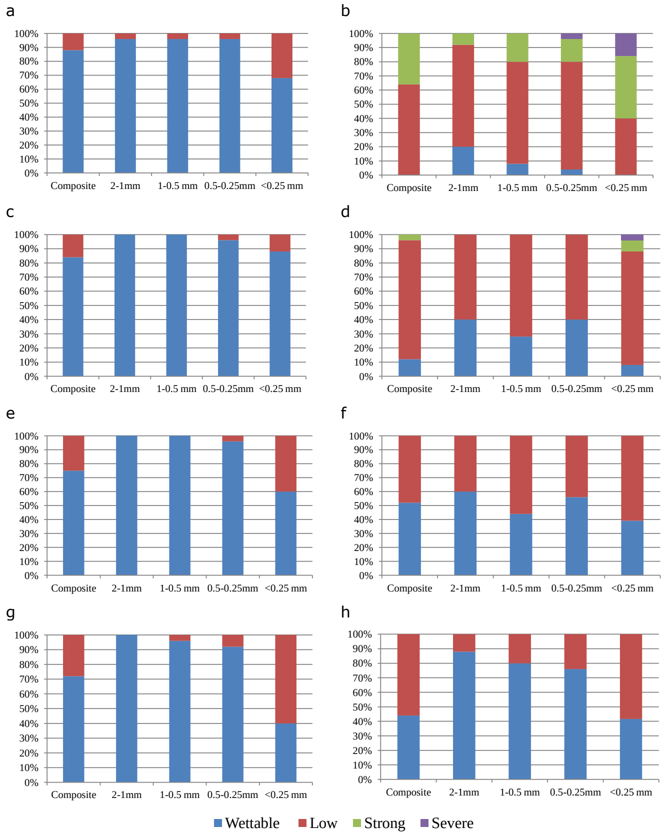

Fig. 4. Relative frequency of SWR for composite and sieved soil fractions, **(a)**: unburned, after the fire, **(b)**: burned after the fire, **(c)**: unburned 2 months after the fire, **(d)**: burned 2 months after the fire, **(e)**: unburned 5 months after the fire, **(f)**: burned 5 months after the fire, **(g)**: unburned 7 months after the fire, **(h)**: burned 7 months after the fire, **(i)** unburned 9 months after the fire and **(j)**: burned 9 months after the fire.

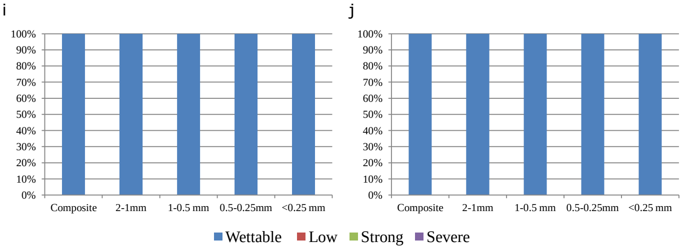

Fig. 4. Continued.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion