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Spatial models for monitoring the spatio-temporal evolution of ashes after fire – a case study of a burnt grassland in Lithuania

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Abstract. Ash thickness is a key variable in the protection of soil against erosion agents after planned and unplanned fires. Ash thickness measurements were conducted along two transects (flat and sloping areas) following a grided experimental design. In order to interpolate data with accuracy and identify the techniques with the least bias, several interpolation methods were tested in the grided plot. Overall, the fire had a low severity. However, the fire significantly reduced the ground cover, especially on sloping areas, owing to the higher fire severity and/or less biomass previous to the fire. Ash thickness depended on fire severity and was thin where fire severity was higher and thicker in lower fire severity sites. The ash thickness decreased with time after the fire. Between 4 and 16 days after the fire, ash was transported by wind. The greatest reduction took place between 16 and 34 days after the fire as a result of rainfall, and was more efficient where fire severity was higher. Between 34 and 45 days after the fire, no significant differences in ash thickness were identified among ash colours and only traces of the ash layer remained. The omni-directional experimental variograms showed that variable structure did not change significantly with time. The ash spatial variability increased with time, particularly on the slope, as a result of water erosion.

1 Introduction

After fires, especially in severe crown fires and in grassland fires, the ash and the remaining vegetation cover on the soil surface are the main protection against erosion agents. The wash of the ash depends on the rainfall characteristics and the ash properties (Cerdà and Doerr, 2008). Ash characteristics depend upon the plant species burned, amount of biomass, fuel moisture content, temperature and residence time of the flames (Ulery et al., 1993; Úbeda et al., 2009; Pereira et al., 2009). Ash plays an important role in post-fire runoff and erosion. Some studies have shown that ash can enhance runoff and erosion by sealing the soil surface (Gabet and Sternberg, 2008; Onda et al., 2009), or decrease runoff as result of water storage (Cerdà and Doerr, 2008; Woods and Balfour, 2008; Zavala et al., 2009), or both (Woods and Balfour, 2010). For example, Woods and Balfour (2010) observed that a < 10 cm ash layer overlying a coarse soil led to clogging of the larger pores, enhancing the runoff response in relation to pre-fire conditions. On the other hand, the same ash overlying a fine textured soil did not have any effect on pore clogging. Cerdà (1998a) found that the infiltration rates of recently fire-affected soils were high due to the protective cover of the ash. These authors observed that ash layer water storage increased with ash thickness and that this storage likely prevented or reduced runoff.

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The protection of the soil by ash and vegetative residues is of major importance until vegetation recovers (Cerdà 1998a; Woods and Balfour, 2008). The capacity of ash to protect soil depends upon the topography of the burned area, meteorological conditions post-fire, and ash thickness. High fire severity can reduce the thickness of the litter layer cover (Cerdà and Doerr, 2008; Pereira et al., 2010). Several studies have been conducted on the effects of ash on soil properties in burned areas (Cerdà and Doerr, 2008; Gabet and Sternberg, 2008; Larsen et al., 2009; Leighton-Boyce et al., 2007; Mallik et al., 1984; Onda et al., 2008; Woods and Balfour, 2008, 2010; Zavala et al., 2009) and some of these studies considered ash thickness as a key variable to understanding the post-fire ecosystem evolution (due to the control ash exert on soil fertility), and soil and water conservation. We consider that ash thickness is the key variable for soil protection from runoff and erosion for the reasons mentioned above. Nevertheless, few studies have been conducted on the spatial and temporal evolution of ash thickness and the factors that control this evolution (Pereira et al., 2012b). This is probably due to the fact that ashes are ephemeral features of the fire-affected landscapes. The study of ash thickness shows the degree of soil protection in the immediate period after the fire, and how it changes in space and time. This will have implications on soil nutrient status that can change quickly due to ash removal, ash erosion, infiltration and type of ash. With ash, nutrients are also transported. Ash mobility after the fire has important implications on soil properties and a better understanding of ash movement in soil is important and needed. The primary factors that control ash thickness are the spatial variability of fuels and fire severity. After a fire, it has been observed that the ash layer is gradually reduced (Bodí et al., 2011) and (re)distributed at different rates as a result of the effects of erosion by wind and water, topography of the burned area, dissolution, compaction, and incorporation into the soil profile (Pereira et al., 2010).

Using interpolation methods to understand the spatial distribution of environmental variables and their pattern across the landscape can result in significant financial and time gains. Mapping variables involves estimating values at unsampled areas with interpolation methods. However, the effectiveness of the method used depends on the accuracy of the spatial interpolation, as mentioned in several studies which also discuss the most appropriate methods for the interpolation of variables (Erdogan, 2009; Palmer et al., 2009; Simbahan et al., 2006; Sun et al., 2009; Xie et al., 2011). Independently of the scale of analysis, accurate spatial predictions are fundamental in the evaluation of the effects of fire on the landscape and strategies to mitigate their impacts. Some studies have been conducted on the spatial distribution of ash properties after fire and have shown that these can be highly variable, even in small plots. The spatial variability of ash thickness may be affected by intrinsic factors such as soil properties and ash texture, which depend on fire temperature, fire severity, vegetation moisture, amount and type of biomass and fuel distribution, as well as extrinsic factors such as wind, water erosion and rain splash (Pereira et al., 2010).

This study aims to quantify the ash thickness spatial and temporal evolution in the immediate period, and factors that control it, following low severity grassland fire in boreal ecosystem of Lithuania. Ash thickness was analysed in two topographic areas, flat and sloping, using two different methodologies of collecting data, transect and grid. In the transect areas, ash thickness was compared with the contiguous non-burned litter in order to quantify the impact of this low prescribed fire in soil protection. In the grided area we tested several interpolation methods in order to observe the best method. In addition, ash thickness was calculated according to ash colour, which is frequently used to measure fire severity (Goforth et al., 2005; Pereira et al., 2012a; Smith and Hudak, 2005), in order to determine if the impact of fire in the soil system depended upon fire severity.

2 Materials and methods

2.1 Study site and data collection

The study area is located near Vilnius (Lithuania) at 54.42° N and 25.26° E and 154 m a.s.l. in an urban/forest interface area. The fire started on 14 April 2010 from unknown causes and affected an area of about 4 ha of a recently abandoned agricultural field. The soil is developed from glaciofluvial sediments and is classified as a Cambic Arenosol (Kadunas et al., 1999). Based on 15 samples collected in the study area, the mean soil particle size distribution was 86 % sand, 6 % silt and 8 % clay. Mean annual temperature was 5.8 °C, the mean total precipitation 735 mm (data from 1961–1990) and the annual and spring prevailing winds from the northwest (Bukantis, 1994). The vegetation is mainly composed of common dandelion (*Taraxacum officinale*) and buffalo grass (*Anthoxanthum odoratum*).

Prior to the ash thickness measurements, we designed two transects that integrate part of the area affected by the fire and part of the unburned area, used as a control plot. The first transect was taken from west to east, in a flat area with a total length of 182 m (101 m in the burned area and 81 m in the control area) and the second transect was taken on a south-facing slope with an inclination of 14 % and was 115 m long (62 m in the burned area and 53 m in the control area). Ash thickness measurements require several precautions. Before the start of the measurements of ash or litter thickness it was very important to take care where we stepped, especially in the burned areas, in order to avoid inducing errors in the ash thickness measurements. For both transects we first selected a starting point and marked it carefully. Subsequently we measured the ash thickness every meter using an iron bar 50 cm long. Since transects were long, marks were placed every 2 m in order to avoid errors in locating the measurements points. Prior to the beginning of each ash thickness measurement, we checked if the transect length and marks were correctly placed. We measured ash thickness only after careful verification of the control points. In the other part of the burned area we designed a 27 m × 9 m space grid with an orientation of north–south on a flat area and took samples every 3 m (in this case control points were placed every 3 m), for a total of 40 sampling points. Coordinates of the sampling points were taken with a GPS receiver *i* Blue, model 747 (accuracy of ± 3 m). The methods used for the ash thickness measurements were the same as described above. More detailed information about ash thickness measurements is available in Cerdà and Doerr (2008), Pereira et al. (2010) and Woods and Balfour (2010). We classified the fire severity based upon the ash colour in accordance with Úbeda et al. (2009). Ash thickness measurements were carried out 4, 16, 34 and 45 days after the fire, until vegetation covered the soils. To determine the effects of precipitation on ash thickness dynamics and vegetation recovery, daily rainfall at the Vilnius (Zirmunai, 54.41° N–25.17° E and 148 m.a.s.l.) meteorological station located 1 km from the study area where analysed.

2.2 Statistical analysis

Prior to data analysis, data normality was checked with the Shapiro-Wilk test (Shapiro and Wilk, 1965), and the homogeneity with the Levene test. Normal distribution and homogeneity were considered at a $p>0.05$. The distributions of ash thickness measured in both transects (with the exception of the control plot from the slope transect) did not follow a normal distribution and the homogeneity of the variances, even after neperian logarithmic (ln), and Box-Cox transformations (Box and Cox, 1964). Therefore, in order to observe differences between sample periods, we applied a non-parametric Friedman ANOVA test. An analysis of the ash thickness differences within ash color in each sample period was carried out with the non-parametric test Kruskall-Wallis ANOVA test (K-W). In those cases where significant differences at a $p<0.05$ were identified, we applied a Tukey HSD post-hoc test (Conover, 1980; Sokal and Rohlf, 1995). The comparison between transects was carried out with the non-parametric Factorial ANOVA test on rank-transformed data because the normality and homogeneity of the variances were not achieved, even after the natural logarithmic and Box-Cox transformations. A similar procedure was applied to compare ash thicknesses among sample periods in the grid area. However, with the exception of ash thickness measured 16 days after the fire, all data conformed to a normal distribution. After ln transformation all distributions conformed to the Gaussian distribution. Thus, we applied repeated measures of ANOVA. If significant differences were identified at a significance level of $p<0.05$, a Tukey HSD test was applied. All graphics in the figures are presented with original data. Statistical analyses were performed with STATISTICA 6.0 (Statsoft Inc., 2006) and SPSS 18.0 (SPSS Inc., 2009).

2.3 Spatial structure, interpolation methods and assessment criteria

Spatial patterns of ash thickness in the grid area were interpreted with variogram modelling, which was used to evaluate the spatial continuity of ash thickness among data points and identify the range of spatial dependence. In this study the modelled variograms are omni-directional (which considers that the variability is equal in all directions) as according to Webster and Oliver (2007), and at least 150 data points are needed to reliably identify the presence of anisotropy. When possible, variable dependence was calculated with the nugget/sill ratio. According to Chien et al. (1997), if the ratio is less than 25 %, the variable has strong spatial dependence, between 25 % and 75 %, the variable has moderate spatial dependence, and greater than 75 %, the variable shows only weak spatial dependence. Normally, strong spatial dependence is attributed to intrinsic factors and weak spatial dependence to extrinsic factors (Cambardella et al., 1994).

To characterize the spatial variation of ash thickness in the grid area, we tested several well-known interpolation methods in order to identify the most accurate. This methodology has been applied previously to studies of ash (Pereira and Úbeda, 2010), soil properties (Robinson and Metternicht, 2006) and precipitation distribution (Diodato and Ceccarelli, 2005; Moral, 2010). The interpolation methods vary in their assumptions, from global to local perspectives, and whether processes are deterministic or stochastic in nature. For more detailed information, interested readers can consult Goovaerts (1999); Isaaks and Srivastava (1989); Smith et al. (2009); or Webster and Oliver (2007). In this study we tested interpolation precision with nine interpolation methods: the deterministic methods inverse distance to a power (IDP), with the power of 1, 2, 3, 4 and 5, local polynomial (LP) with the power of 1 (LP1) and 2 (LP2), spline with tension (SPT), completely regularized spline (CRS), multiquadratic (MTQ), inverse multiquadratic (IMQ) and thin plate spline (TPS). We also considered some geostatistical methods, ordinary kriging (OK) and simple kriging (SK). For each interpolation method we included a total of 15 neighbours and applied a smoothing factor of 0.5. These interpolation methods are extensively described in the literature (Chaplot et al., 2006; Pereira et al., 2010; Xie et al., 2011). The interpolation methods' assessment criterion was based on the errors produced by each method (observed-predicted) observed with the cross-validation method. With these data we calculate the mean error (ME) and root mean square error (RMSE).

The best interpolation method is the one that has the lowest RMSE. Further explanations of these indexes can be found in Mardikis et al. (2005), Pereira and Úbeda (2010), and Pereira et al. (2010). In addition we compared the observed

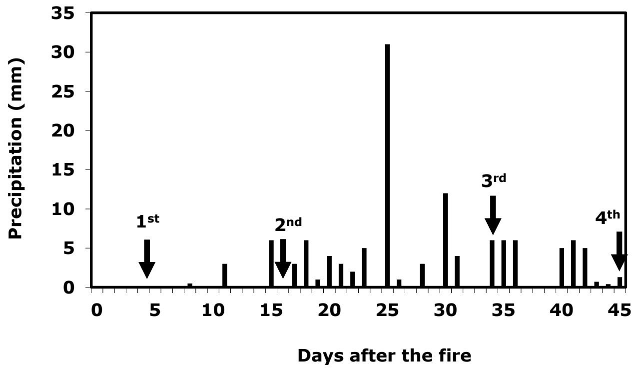

Fig. 1. Daily precipitation throughout the study period. Arrows point to days when measurements were collected and the numbers above the arrows indicate the measurement period.

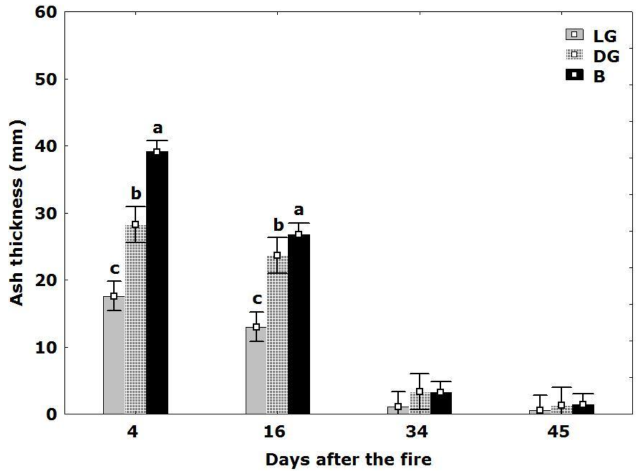

Fig. 2. Evolution of mean ash thickness in the flat area the post-fire period (bars show 95 % confidence intervals). Different letters indicate significant differences ($p<0.05$) between ash types (DG, dark grey ashes; B, black ashes; LG, light grey ashes).

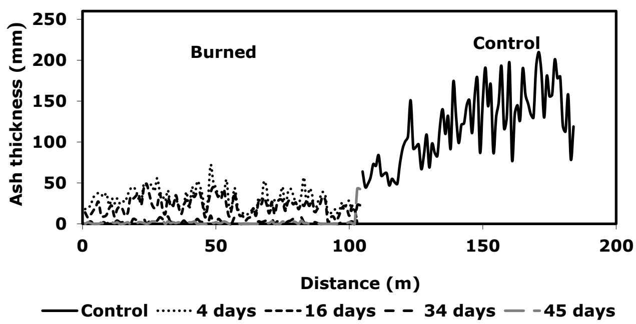

Fig. 3. Litter and ash thickness across all flat area transects in the different measurement periods (burned) and control area. The correlations only consider burned area. (Control $n = 80$, Burned plot $n = 101$).

and estimated distributions with a paired t test, identified at a significance level of $p<0.05$, and related them through a Pearson correlation coefficient also identified at a significance level of a $p<0.05$. Variograms were performed with Surfer 9.0 (Golden Software) and interpolation tests with ArcGis 9.3 (ESRI) (ESRI, 2008), for Windows.

3 Results

3.1 Rainfall post-fire

The first rainfall event occurred 8 days after the fire (5 mm). Between 4 and 16 days after the fire there was a total of 10 mm of rainfall. The major rainfall occurred between 16 and 34 days after the fire (81 mm), mainly during the 25th day after the fire when in 24 h, it rained 31 mm. Between 34 and 45 days after the fire it rained 30 mm. In total during the study period the total rainfall was approximately 120 mm (Fig. 1).

3.2 Flat area

In the flat area transect we identified ash with three colours: black (10YR 2/1) 51.96 %, dark grey (10YR 4/1) 19.61 % and light grey (10YR 7/1) (28.43 %). Black ash represents low fire severity, dark grey means fire severity and light grey high fire severity. The Friedman ANOVA results showed that the difference between litter or ash thickness and time identified at a significance level of $p<0.001$ (Table 1). We observed that the ash thickness diminished with time and that this reduction was the greatest between 16 and 34 days after the fire. Nevertheless, this reduction was different according to ash colour (i.e.: fire severity) as can be observed in Fig. 2, especially 4 (K-W =62, $p<0.001$) and 16 days after the fire (K-W = 37 $p<0.001$). Between 34 and 45 days after the fire we did not identify significant differences between ash colours. The ash thicknesses in the flat transect profile in the burned and control areas are shown in Fig. 3. It is visible that for some points the second measurement ash was thicker than for the first. We did not identify any measured point without ash cover 4 and 16 days after the fire. Only after 34 and 45 days were some points bare (18 % and 40 % respectively). The coefficient of variation (CV%) was of 37 % in the control, 41 % 4 days after the fire, 46 % 16 days after the fire, 87 % 34 days after the fire, and 113 % 45 days after the fire.

3.3 Slope area

In the slope transect we identified ash with four colours: black (10YR 2/1) 40.94 %, followed by dark grey (10YR 4/1) 29.03 %, white (10YR 8/1) 16.13 % and light grey (10YR 7/1) (12.90 %). White ash represents high fire severity. The Friedman ANOVA results showed significant differences between litter and ash thickness at a $p<0.001$. As in the previous transect, the main differences in ash thickness were observed between 16 and 34 days after the fire (Table 2).

Table 1. Summary of Friedman ANOVA and Tukey HSD test, for ash thickness in a flat area in all measurement periods. Different letters mean significant differences at a $p<0.05$. Data in mm. (*a = higher mean, d = lower mean*).

	mean	SE	min	max	Friedman ANOVA
Control	119.5^a	5	45	210	
4 days	30.9^b	1.2	10	72	
16 days	22.2^c	1.0	2	49	Chi Sqr.=308.04, $p<0.001$
34 days	2.6^d	0.2	0	10	
45 days	1.1^d	0.1	0	5	

Table 2. Summary of Friedman ANOVA and Tukey HSD test, for ash thickness in slope area in all measurement periods. Different letters mean significant differences at a $p<0.05$. Data in mm. (*a = higher mean, c = lower mean*).

	Mean	SE	Min	max	Friedman ANOVA
Control	92.1^a	4.2	29	176	
4 days	23.1^b	1.7	3	53	
16 days	16.2^b	1.4	0	39	Chi Sqr.=154.61, $p<0.001$
34 days	2.2^c	0.4	0	8	
45 days	0.8^c	0.2	0	4	

Among ash colours, differences in depths were registered between the first two ash thickness measurements at 4 (K-W = 51, $p<0.001$) and 16 days after the fire (K-W =29, $p<0.001$). Between 34 (K-W =3, $p>0.05$) and 45 days (K-W = 3, $p>0.05$) no differences were identified among ash colours (Fig. 4). Figure 5 shows the ash thickness profile for the sampling periods and in the control area. We observed that, as in the flat area, the major reduction occurred 34 days after the fire. As in the flat transect, we identified in some places where ash was thicker in the second measurement. On the slope transect all measured points were still covered by ash 4 days after the fire. Sixteen days after the fire, 11 % throughput the measured points had no ash, increasing to 52 % after 34 days and up to 67 % after 45 days. The CV % was of 33 % in the control, 57 % 4 days after the fire, 69 % 16 days after the fire, 133 % 34 days after the fire, and 167 % 45 days after the fire.

The comparison between sites showed significant differences between days ($F = 246\,699$, $p<0.001$), place ($F = 13\,272$, $p<0.001$) and the interaction between days x place ($F = 12$, $p<0.001$). The litter thickness was higher in the flat area than in the sloped area and at 4 and 16 days after the fire the ash layer was significantly thicker in the flat area. Thirty-four and 45 days after the fire no significant differences were observed in ash thickness in time and between the flat and slope transects (Fig. 6).

3.4 Grided area

In the grided area we identified black (57.50 %) and dark grey ash (42.50 %). The results of the ANOVA test showed signif-

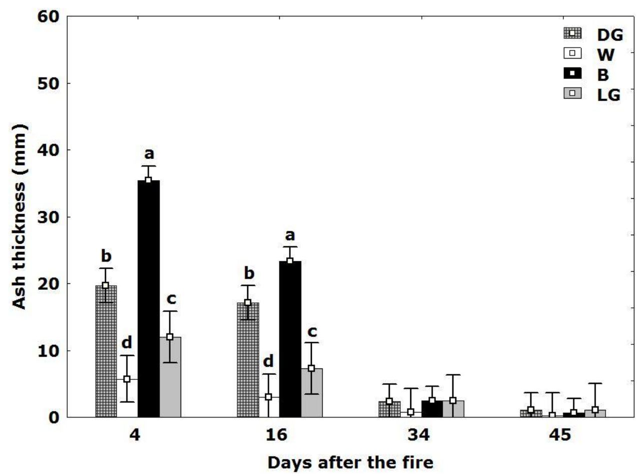

Fig. 4. Evolution of mean ash thickness in the sloping area the post-fire period (bars show 95 % confidence intervals). Different letters indicate significant differences ($p<0.05$) between ash types (DG, dark grey ashes; B, black ashes; LG, light grey ashes).

icant differences in ash thickness among ash colour ($F = 5$, $p<0.05$), days ($F = 328$, $p<0.001$) and ash colour and days ($F = 6$ $p<0.05$). The greatest reduction of ash thickness was observed between 16 and 34 days after the fire. Significant differences between ash colours were only observed 4 and 16 days after the fire (Fig. 7). As in the flat transect, all points measured 4 and 16 days after the fire were covered by ash. Only after 34 and 45 days were some points were bare (17 % and 40 % respectively). The CV % was 34 % 4 days after the fire, 37 % 16 days after the fire, 75 % 34 days after the fire,

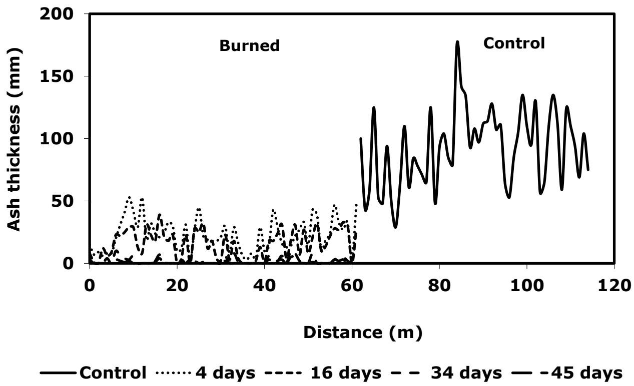

Fig. 5. Litter and ash thickness across the slope transects in the different measurement periods (burned) and control area. The correlations only consider burned area. (Control $n = 53$, Burned plot $n = 60$).

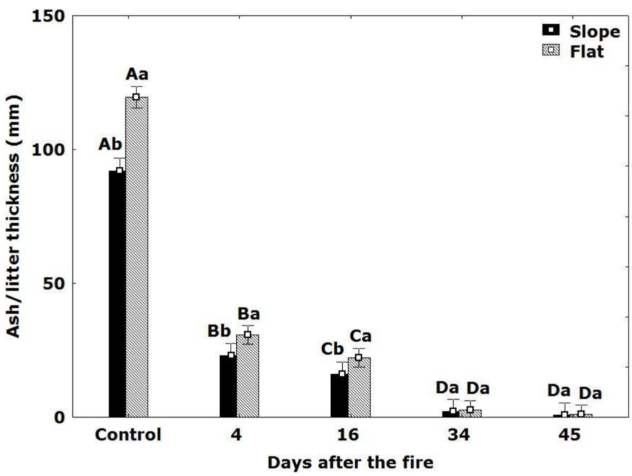

Fig. 6. Evolution of mean litter and ash thickness from the flat and sloping area in the post-fire period (bars show 95 % confidence intervals). Different letters indicate significant differences ($p<0.05$) between dates (capital letters) and ash types (low-case letters).

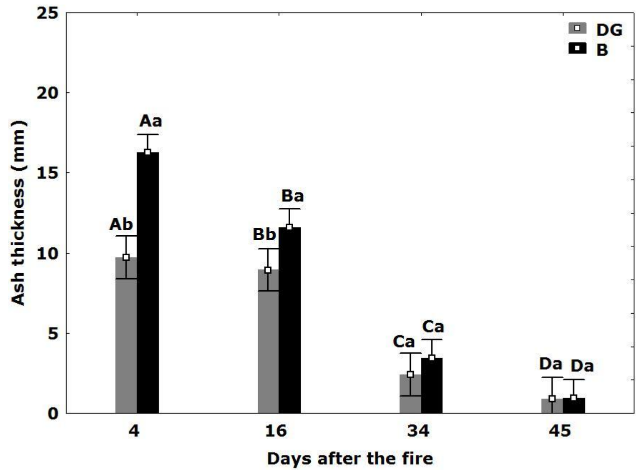

Fig. 7. Evolution of mean ash thickness from the grid plot in the post-fire period (bars show 95 % confidence intervals). Different letters indicate significant differences ($p<0.05$) between dates (capital letters) and ash types (low-case letters). DG, dark grey ashes; B, black ashes; LG, light grey ashes.

and 99 % 45 days after the fire. The temporal and spatial evolution of vegetation recovery in the grided area is shown in Fig. 8. It is clear that the burned area recovered quickly, especially one month after the fire (Fig. 8c). Forty-five days after the fire, hardly any visual vestiges of the fire impact remained.

The linear model gave the best fit for the experimental variograms calculated for ash thickness measured 4 days after the fire (Fig. 9a) with a nugget effect of 13.35 and a slope of 1.42 (Table 3), 16 and 45 days after the fire, (Fig. 9b and d) a nugget effect of 7.31 and 0.80 and a slope of 0.60 and 0.49, respectively (Table 3). The spherical model fitted the experimental variogram calculated with the data collected 34 days after the fire and showed a nugget effect of 0.80, a sill of 6.90 along a range of 7.22 m. The nugget/sill ratio (0.11) showed that ash thickness had a strong spatial dependence.

Prior to the ash thickness modelling we tested the data normality distribution. The next step was to test, using the normalized data, several interpolation methods and model their spatial distribution. The data of the ash measurements of 4, 34 and 45 days after the fire had a Gaussian distribution. Sixteen days after the fire data normality was only achieved after natural logarithmic transformation. Thus in this case we used ln transformed data for modelling.

The results of the tested interpolation methods for all measurement periods are shown in Table 4. Four days after the fire, LP1 was the most accurate for interpolating the ash thickness (RMSE, 4.3) and the least precise was TPS (RMSE, 6.3) (Table 4a), 16 after the fire, the most precise technique was SK (RMSE 0.34) and the least accurate was the LP2 (RMSE 0.47) (Table 4b), after 34 days most accurate was IMTQ (RMSE 1.8) and the least precise was IDW1 (RMSE, 2.144) (Table 4c) For the 45 days data the most accurate method was CRS (RMSE, 0.67) and the least precise was IDW1 (RMSE, 0.86) (Table 4d). The methods tested were considered unbiased, since ME is always very close to 0 and no differences were observed and predicted values (Table 4). Four days after the fire, the correlation coefficient between observed and predicted values was only significant in LP1, meanwhile 16 days after the fire we observed significant correlations between the two distributions in almost methods (with the exception of IDW1, IDW2, LP2 and TPS). Thirty four days after the fire, the correlations were significant in all techniques tested and 45 days. Only IDW1 correlations between observed and predicted values were not significant (Table 4).

Table 3. Best-fitted omnidirectional variogram models of ash thickness and corresponding parameters.

Time	Model	Nugget effect	Slope/Sill	Range (m)	Nug/sill ratio
4 days	Linear	13.35	1.42	10	–
16 days	Linear	7.31	0.60	10	–
34 days	Spherical	0.80	6.90	7.22	0.11
45 days	Linear	0.30	0.49	10	–

Fig. 8. From left to right and up down. View of the study site 4, 16, 34 and 45 days after the fire.

The spatial interpolation of ash thickness data was carried out with the most accurate method as identified in the previous section and is shown in Fig. 10. We identified that 4 days after the fire there was a decreasing trend in ash thickness from northeast to southwest of the plot (Fig. 10a). Sixteen days after the fire, the ash thickness persisted according to the trend identified in the earlier data in the northeastern and central parts of the plot, and the ash was less thick in the eastern and southeastern part of the plot. Thirty four days after the fire the ash distribution pattern changed substantially, the eastern part of the plot was thinner at some points in the southeastern, western and northwestern parts of the plot. In the last ash thickness measurement period (45 days after the fire) only trace amounts of ash remained and at a great number of the points we did not observe any ash cover. Thicker ash deposits were identified in the eastern part of the plot and the areas without ash cover were in the northeastern and southwestern portions of the plot.

4 Discussion

Ash is a key variable for soil protection and landscape recuperation after fire. Some studies have reported ash thicknesses up to 70 mm in an oak forest burned by wildland fires (Ulery et al., 1993), 60 mm in a mixed pine forest (Goforth et al., 2005), and 17 mm in a mixed fir and larch forest (Woods and Balfour, 2008). However little information is available about fire severity effects on ash thickness and its temporal evolution, and no studies have been conducted on this topic on boreal grassland ecosystems.

Overall, the studied fire had low severity, nevertheless, it induced a significant reduction on ground cover. Ash colour

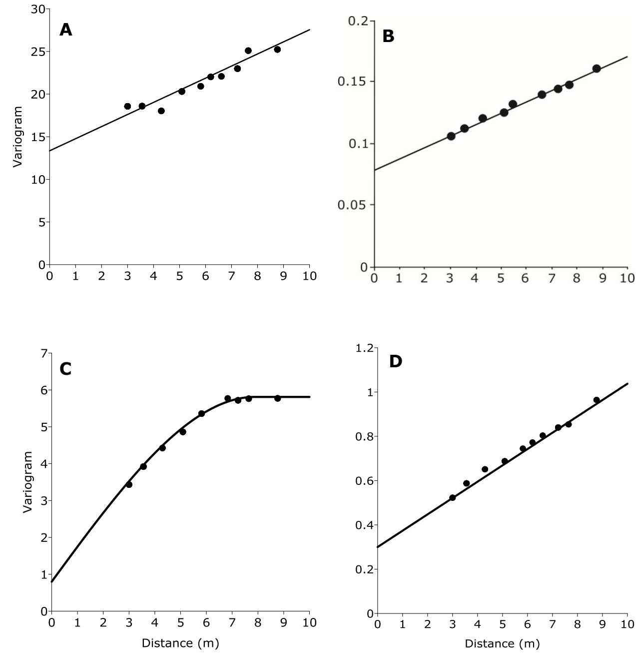

Fig. 9. Omni-directional variograms calculated for ash thickness distributions at **(A)**, 4; **(B)** 16; with Ln data, **(C)** 34; and **(D)** 45 days after the fire.

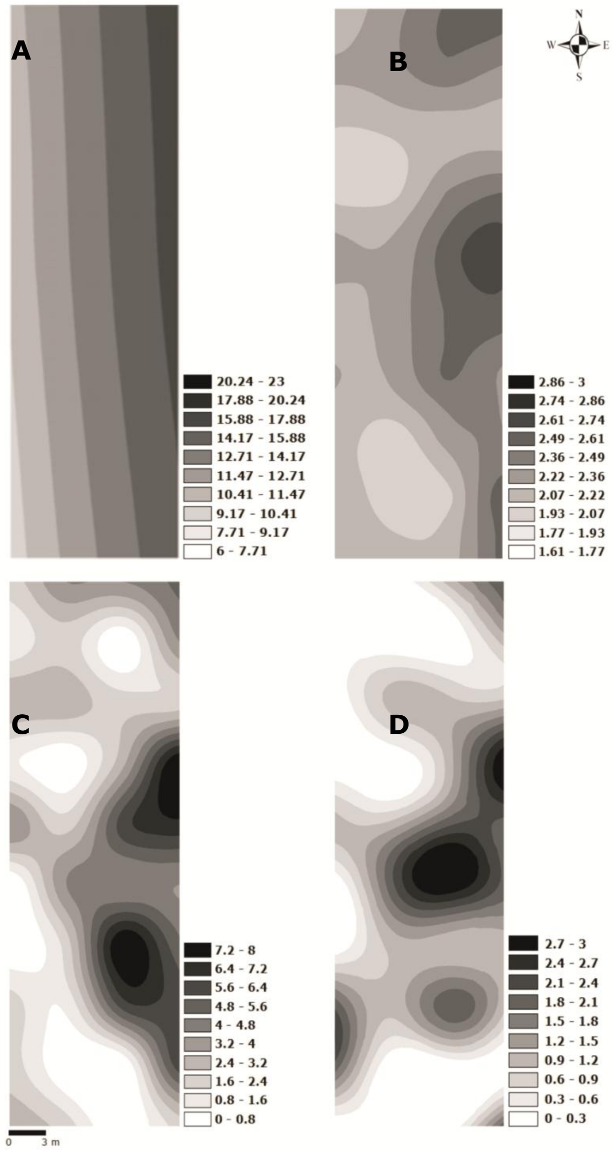

Fig. 10. Ash thickness interpolations according to the most accurate technique. From left to right. **(A)** 4 (LP1), **(B)** 16 (SK) with Ln data, **(C)** 34 (IMTQ) and **(D)** 45 days after the fire (CRS), data in mm, ln data for 16 day after the fire.

is a key variable to understanding fire severity (Smith and Hudak, 2005; Goforth et al., 2005; Úbeda et al., 2009) and is a clear tracer of ash thickness as we observed here, which confirms previous research in the Mediterranean type ecosystems (Pereira et al., 2011). In all studied plots, black ash was thicker than the light grey or white ash due to the lower degree of combustion that leaves a greater amount of organic material in the ash. In planned and unplanned fires, fire severity is very heterogeneous across the landscape and depends on the fuel type, structure, arrangement on the soil surface, moisture, burned area topography and meteorological conditions (Knapp and Keeley, 2006; Keeley, 2009). Fire severity was higher in the sloped areas than in the flat areas, indicated by the presence of white ash. Fires tend to burn upslope, and steeper slopes will burn with a higher intensity because the heat released by the fire will pre-heat the fuel prior to combustion. In addition, fire is very likely to be more severe on sloping areas which are drier than flat areas, where moisture is higher (Maingi and Henry, 2007). The slope where we measured ash thickness was south-facing, thus more exposed to insolation and radiation. The vegetation and litter thickness were also less in comparison with flat portions in the burned area, based on measurements from the control area, thus the vulnerability to fire was high (Fig. 6).

Sixteen days after the fire we observed on average a reduction of ash thickness in all studied areas in relation to the previous measurement. In some points there was reduced ash cover, and in others ash was thicker than in the previous measurement. The ash cover reduction was observed especially where we identified light grey and white ash very likely due the wind erosion. Between 4 and 16 days after the fire no major rainfall occurred, thus it is very likely that ash compaction and wind erosion induced the transport and (re)distribution of ash across the landscape and contributed to ash thickness reduction (Fig. 1). However, this question needs further detailed studies, since it was not possible to collect wind data in the studied area. Hence it is probably another factor that contributes to the changes in the ash morphology and depth.

Table 4. Summary statistics of the accuracy of interpolation methods. Numbers in bold indicate the least biased method. **(A)** 4 days after the fire, **(B)** 16 days after the fire, **(C)** 34 days after the fire and **(D)** 45 days after the fire. Correlations between observed and estimated values significant at $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$ and n.s (not significant at a $p<0.05$).

	Method	Min	Max	ME	RMSE	Obs vs Est	*r*
A	IDW 1	−10.609	7.566	0.0195	4.572	0.9788	0.10 n.s
	IDW 2	−10.961	7.246	−0.04	4.573	0.9567	0.16n.s
	IDW 3	−11.223	7.019	−0.05922	4.662	0.9371	0.17n.s
	IDW 4	−11.389	7.096	−0.06172	4.775	0.9360	0.16n.s
	IDW 5	−11.490	7.424	−0.0602	4.867	0.9388	0.16n.s
	LP 1	**−10.235**	**6.696**	**−0.03826**	**4.323**	**0.9562**	**0.35***
	LP 2	−12.131	8.971	0.03093	5.512	0.9722	0.03n.s
	SPT	−10.911	6.912	−0.01973	4.661	0.9790	0.19n.s
	CRS	−11.068	7.526	−0.02713	4.804	0.9720	0.17n.s
	MTQ	−11.873	9.073	−0.05668	5.267	0.9467	0.12n.s
	IMTQ	−10.542	7.362	0.0469	4.530	0.9847	0.17n.s
	TPS	−12.466	11.040	−0.05317	6.394	0.9588	0.008n.s
	OK	−10.791	6.946	0.01863	4.539	0.9796	0.22n.s
	SK	−10.701	6.688	−0.03476	4.475	0.9615	0.25n.s
B	IDW 1	−0.7715	0.7126	−0.003097	0.3609	0.9575	0.16n.s
	IDW 2	−0.7754	0.7046	−0.007328	0.3514	0.8970	0.27n.s
	IDW 3	−0.7750	0.7075	−0.007567	0.3480	0.8926	0.32*
	IDW 4	−0.7730	0.7134	−0.006422	0.3484	0.9089	0.33*
	IDW 5	−0.7711	0.7185	−0.005271	0.3497	0.9254	0.34*
	LP 1	−0.6446	0.7533	0.0386	0.3591	0.5036	0.33*
	LP 2	−0.8045	1.6942	0.008538	0.4700	0.9102	0.10n.s
	SPT	−0.7200	0.7121	−0.001585	0.3475	0.9774	0.33*
	CRS	−0.7128	0.7121	−0.00147	0.3498	0.9791	0.34*
	MTQ	−0.7246	0.7008	0.0007356	0.3655	0.9900	0.32*
	IMTQ	−0.7283	0.7173	−0.0007262	0.3467	0.9896	0.33*
	TPS	−0.8182	0.8249	0.009062	0.3969	0.8873	0.30n.s
	OK	−0.7411	0.7086	−0.007969	0.3488	0.8872	0.32*
	SK	**−0.7299**	**0.7068**	**−0.004116**	**0.3464**	**0.9412**	**0.34***
C	IDW 1	−4.819	3.242	0.03467	2.144	0.9200	0.37*
	IDW 2	−4.323	3.104	−0.07788	1.944	0.8035	0.50***
	IDW 3	−.301	3.114	−0.0571	1.916	0.8533	0.53***
	IDW 4	−4.156	3.086	−0.0641	1.879	0.8323	0.55***
	IDW 5	−4.077	3.066	−0.06249	1.863	0.8350	0.56***
	LP 1	−4.038	3.415	0.1101	1.856	0.7125	0.57***
	LP 2	−4.038	3.546	0.1242	1.897	0.6864	0.55***
	SPT	−3.679	3.005	−0.01504	1.811	0.9589	0.60***
	CRS	−3.721	3.016	−0.01452	1.809	0.9602	0.60***
	MTQ	−3.593	3.008	−0.015	1.832	0.9594	0.59***
	IMTQ	**−3.797**	**3.028**	**−0.009278**	**1.802**	**0.9745**	**0.60*****
	TPS	−3.853	3.460	0.02984	1.912	0.9228	0.59***
	OK	−3.641	3.105	−0.001916	1.813	0.9947	0.59***
	SK	−3.723	3.092	−0.04579	1.825	0.8762	0.58***
D	IDW 1	−1.960	1.086	0.04005	0.8689	0.774	0.31n.s
	IDW 2	−1.826	1.103	0.006488	0.8141	0.960	0.45**
	IDW 3	−1.796	1.107	−0.01071	0.7907	0.933	0.48**
	IDW 4	−1.906	1.088	−0.01735	0.7827	0.890	0.50***
	IDW 5	−1.958	1.064	−0.01948	0.7793	0.876	0.51***
	LP 1	−1,852	1.393	−0.05376	0.8264	0.686	0.41**
	LP 2	−2.266	1.299	−0.01511	0.871	0.914	0.39*
	SPT	−1.903	1.162	−0.009115	0.7729	0.941	0.54***
	CRS	**−1.728**	**1.360**	**0.0007761**	**0.6706**	**0.994**	**0.72*****
	MTQ	−1.774	1.676	0.01107	0.7504	0.929	0.67***
	IMTQ	−1.898	1.174	−0.008938	0.7516	0.931	0.58***
	TPS	−2.482	1.462	−0.02202	0.8297	0.869	0.51**
	OK	−1.674	1.268	0.006854	0.7877	0.956	0.49**
	SK	−1.778	1.264	−0.004127	0.7846	0.973	0.50**

The major reduction in mean ash thickness that occurred between 16 and 34 days post-fire was caused by erosion and compaction of the ash layer by rainfall. Other authors have already pointed out that rainfall has an important role in controlling the decrease in ash thickness after a fire (Cerdà, 1998a, 1998b; Pereira et al., 2010a). It is very likely that wind promoted ash transport and (re)distributed it. Rain splash compacted the ash (Onda et al., 2008) and facilitated incorporation into soil profile. (enhanced by the absence of trees that could intercept rain drops) that was particularly effective in locations where fire severity was higher. High severity fires reduce surface fuels to small particulates that are easy to transport and leach into the soil profile. Thus, it is very likely that ash produced at higher temperatures induced the first effects on soil properties, since smaller particles are more easily incorporated into the underlying soil. Ash incorporation into the soil profile also depends on soil properties, mainly texture (Woods and Balfour, 2010). Since the soil at the study site is primarily composed of sand, ash incorporation into the underlying soil probably happens readily. Among all plots the ash depletion happened quickly on the sloping area due to topography. Water erosion might be the main cause of ash thickness reduction in sloping area.

Other mechanisms of ash reduction, (re)distribution and incorporation into the soil profile can be through bioturbation (Fig. 11). Soil invertebrates can survive after grassland fire and these fires rarely achieve the needed severity to affect these populations (Neary et al., 1999). Wikars and Schimmel (2001) observed that fire impacts on invertebrates depend on the amount of organic matter consumed. Invertebrates that live in deeper soil are less affected than those that live in vegetation. The authors observed that after the fire some species of beetles, *Atomaria pulchra* (*Cryptophagidae*), *Corticaria rubripes* (Lathridiidae), rapidly colonized the burned plot. Jerome and Andersen (2001) observed that after experimental burnings in Australian tropical savanna, beetle abundance and richness were greater in burned plots than in the control. We do not know if ants were responsible for the changes in ash thickness in our study, however they can contribute with their nests to remove or cover the ash from the soil surface (Cerdà and Doerr, 2010; Pereira et al., 2012) as we observed in this study (Fig. 11). This is due to the intense activity of ants after forest fires. The lack of ash at some sampling points 34 days after the fire may be also evidence of this process.

The omni-directional experimental variograms allow us to understand the spatial structure of ash thickness in the studied periods. Sixteen and 45 days after the fire, a linear model was the best fit and this means that the spatial variability of the variable increased with distance and inside the studied area the variance did not reach the range. This situation was not observed 34 days after the fire, where the variogram showed a great spatial dependence (Table 6). The spatial structure of the ash thickness distribution in the grid area was very similar and changed little during the study, as the grid was designed in a flat area where no major water transport occurred and ash incorporation into the soil profile was favoured.

Fig. 11. Effects of ant mount build on ash (indicated with arrows) (re)distribution 16 days after the fire in the studied plot.

The test of the different interpolation methods allows us to have an accurate idea of the spatial distribution of ash thickness after the fire. Four days after the fire we observed that LP1 was the most precise method. LP methods are sensitive to neighbouring distance and they are especially accurate when the data show a short-range variation (Smith et al., 2006). This means that if the data do not have significant spatial variations, LP is a good interpolator. This method gives us indirect evidence of the probable fire line progression from northeast to southwest and the attendant fire severity. Litter consumption is a tracer of fire severity and temperature (Úbeda et al., 2009). It is also widely recognized that fire temperature rises with the distance covered by the fire line (Gimeno-García et al., 2004; Marcelli et al., 2002), especially if there are no changes in vegetation structure and composition such as we observed in the control and burned area.

Sixteen days after the fire, the most accurate method was SK. Kriging and/or other geostatistical methods that rely on the theory of regionalized variables which assumes that the variability of the variable is homogenous across the studied area (Webster and Oliver, 2007). Thus we observed that ash thickness follows a determined spatial pattern that was easily identified with SK. No major changes were identified in ash thickness between 4 and 16 days after the fire. Since little rainfall occurred, it is very likely that the spatial distribution of the ash thickness was affected by wind transport and may also have an impact in other areas outside the burned plot. However, the fire severity was low in this grassland fire, and wind erosion of the relatively large ash particles is expected to be less effective than wind erosion of finer particles produced during high severity wildland fires (Pereira et al., 2011; Pereira et al., 2012b). Thirty four and 45 days after the fire, the most accurate interpolation methods were IMTQ and CRS, and the integrated group of Radial Basis Functions that are deterministic interpolators (not based on regional patterns). Some local patterns are distinguished that are very likely to be induced by different rates of ash incorporation into the soil profile at the different measured points.

Soil protection is more variable in the burned area than in the control. The fire creates a highly variable pattern of ash distribution, due to the different conditions of combustion. As expected, with time this variability increases especially in the sloping area where surface wash and wind erosion are more efficient. The ash thickness reduction and the increase of spatial variability will induce a heterogeneous soil protection pattern over time, weaker in some areas and strong in others as a result of ash compaction and (re)distribution. This means that soil is differentially exposed to erosion agents and the small-scale variability is high with implications for the spatial distribution of the post-fire hydrological response. In the present case, erosion was not a major problem, because of the rapid vegetation regrowth. Also runoff patterns can be substantially changed as a result of ash thickness variability. For example, runoff decreased in areas where ash was thicker, as observed by Cerda and Doerr (2008) and Woods and Balfour (2010). The increase of ash spatial variability with time will also have important implications on the type and amount of nutrients availability for plant growth (Pereira et al., 2012a).

5 Conclusions

The studied fire was of low severity, yet it produced a significant reduction in vegetation cover, especially in the sloping area. The ash layer was thinner in the points where fire severity was high. The greatest ash thickness reduction was observed between 16 and 34 days after the fire due rainfall. In the period after the fire the ash thickness decreased due to wind (re)distribution and compaction (driven by raindrops impact), and leaching into the soil profile in the grided and flat transect area. In the sloped area water erosion might be the main driver of ash thickness reduction. Other mechanisms such as bioturbation might be also involved, as we observed visually. Ash thickness reduction was especially effective where we identified light grey and white ash.

Vegetation recovered very quickly and soil was rapidly protected from erosion, even after the ash thickness decreased. The interpolation methods carried out allow us to estimate indirectly the probable fire line evolution, which was from northeast to southwest and attendant fire severity during the first post-fire measurements. Ash spatial variability increased over time, especially in the sloping area, as a result of water erosion. Further studies with better temporal resolution and the impacts of fauna on ash (re)distribution are needed.

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