**Spatio-temporal distribution of ashes in a Lithuanian burned grassland, evaluating different data collection and interpolation methods**.

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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 grid experimental design. In order to interpolate data with accuracy and identify the techniques with the least bias, several interpolation methods were tested in the grid plot. Overall, the fire had a low severity. 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 depends on fire severity and is 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 major 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 shown that variable structure did not change importantly with the time. The ash spatial variability increased with the time, particularly on the slope, as a result of water erosion.

**Keywords:** Ash thickness, Fire severity, Interpolation methods, Grassland, Lithuania

# Introduction

After fire, 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). The characteristics of the ash 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 <1cm 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.

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 (Mallik et al. 1984; Leighton-Boyce et al. 2007; Cerdà and Doerr, 2008; Gabet and Sternberg, 2008; Onda et al. 2008; Woods and Balfour, 2008, 2010; Larsen et al. 2009; Zavala et al. 2009) and some of these studies considered ash thickness as a key variable to understand 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 (Bodi 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 (Schloeder et al. 2001; Erxleben et al. 2002; Robinson and Metternicht, 2006; Simbahan et al. 2006; Sun et al. 2009; Erdogan, 2009; Palmer et al. 2009; Xie et al. 2011). Independent 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; and 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 were analysed in two topographic areas, flat and slope, and using two different methodologies of collecting data, transect and grid. In transect areas, ash thickness were compared with the contiguous non-burned litter in order to quantify the impact of this low prescribed fire in soil protection. In the grid area we tested several interpolation methods in order to observe the best method. In addition, ash thickness were calculated according to ash colour, that is frequently used to measure fire severity (Smith and Hudak, 2005; Goforth et al. 2005; Pereira et al. 2012a), in order to determine if the impact of fire in the soil system depends upon fire severity.

# Materials and methods

* 1. **Study site and data collection**

The study area is located near Vilnius (Lithuania) at 54.42ºN and 25.26ºE and 154 m.a.s.l. in an urban/forest interface area. The fire started on April 14, 2010 from unknown causes and affected an area of ≈4ha of a recently abandoned agricultural field. The soil is developed on glaciofluvial sediments and is classified according to FAO as a Cambic Arenosol (Kadunas et al. 1999). Based on 15 samples collected in the study area, the soil texture is composed of 86% sand, 6% silt and 8% clay. Mean annual temperature is 5.8ºC, the mean total precipitation is 735 mm (data from 1961-1990) and the annual and spring prevailing winds are 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 181 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 114 m long (62 m in the burned area and 53 m in the control area). Ash thickness measurements have to be made using several precautions. Before the start of the measurements of the 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 in length. 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. In the other part of the burned area we designed a 27x9 m grid with an orientation of north – south on a flat area and took samples every 3 meters (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. The methods used for the ash thickness measurements were the same as discussed 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 color 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, 54.41ºN - 25.17ºE and 148 m.a.s.l.) meteorological station located 1 Km from the study area where analysed.

* 1. **Statistical analysis.**

Prior to data analysis, data normality was checked with the Shapiro and Wilk (1965) test, 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 ln 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. All statistical analyses were performed with STATISTICA 6.0 (Statsoft Inc) and SPSS 18.0.

**2.3. Spatial structure, interpolation methods and assessment criterion**

Spatial patterns of ash thickness in the grid area were observed with variogram modelling. It was developed 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), at least 150 data points are needed to reliably identify the presence of anisotropy. When possible, variable dependence was calculated with the Nug/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 Isaaks and Srivastava (1989); Goovaerts (1999); Webster and Oliver (2007); or Smith et al. (2009). 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 and 2, 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; Yilmaz, 2007; Smith et al. 2009; Pereira and Úbeda, 2010; 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 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), for Windows.

# 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 precipitated a total of 41 mm. The major rainfall occurred between 16 and 34 days after the fire (380 mm), mainly in the 25th day after the fire where in 24 hours, rained 300 mm. Between 34 and 45 days after the fire rained 190 mm. In total during the study period the total rainfall was 1065 mm (Fig. 1).

## 3.2 Flat area

In the flat area transect we identified ash with three colours: black (51.96%), dark grey (19.61%) and light grey (28.43%). 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 =62.23, p<0.001) and 16 days after the fire (K-W=37.37 p<0.001). Between 34 and 45 days after the fire we did not identify significant differences, since the results of K-W test were K-W =8.53 p>0.05 and K-W=7.18, p>0.05, respectively. The ash thicknesses in the flat transect profile in the burned and control areas are shown in fig. 3. It is visible that in some points the second measurement ash was thicker than in the first. We did not identify any measured point without ash cover 4 and 16 days after the fire. Only 34 and 45 days after the fire some points were bare (17.50% and 40% respectively). The coefficient of variation (CV%) was of 37.05% in the control, 40.60% 4 days after the fire, 46.30% 16 days after the fire, 86.97% 34 days after the fire, and 113.48% 45 days after the fire.

## Slope area

In the slope transect we identified ash with four colours: black (40.94%), followed by dark grey (29.03%), white (16.13%) and light grey (12.90%). 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). Among ash colours, differences were registered in the first two ash thickness measurements, 4 (K-W =51.27, p<0.001) and 16 days after the fire (K-W =29.20, p<0.001). Between 34 (K-W =3.38, p >0.05)and 45 days (K-W =3.11, p>0.05) no differences were identified (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 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, 11.47% of the measured points were already uncovered from ash, increasing to 52.45% after 34 days and up to 67.21% after 45 days. The CV% was of 33.42% in the control, 57.52% 4 days after the fire, 69.73% 16 days after the fire, 133.04% 34 days after the fire, and 167.01% 45 days after the fire.

The comparison between sites showed significant differences between days (F=246699.20, p<0.001), place (F=13272.23, p<0.001)and the interaction between days x place (F=12.94, 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. After this period no significant differences were observed in ash thickness in time and between the flat and slope transects (Fig. 6).

## Grid area

In the grid area we identified black (57.50%) and dark grey ash (42.50%). The results of the ANOVA test showed significant differences in ash thickness among ash colour (F=5.80, p<0.05), days (F=328.80, p<0.001) and ash colour and days (F= 6.31 p<0.05). The greatest reduction of ash thickness was observed between 16 and 34 days after the fire and in the last two measurements no significant differences were observed (Fig. 7). As in the flat transect, all measured points 4 and 16 days after the fire were covered by ash. Only 34 and 45 days after the fire some points were bare (17.50% and 40% respectively). The CV% was 34.39% 4 days after the fire, 37.19% 16 days after the fire, 75.86% 34 days after the fire, and 99.10% 45 days after the fire. The temporal and spatial evolution of vegetation recovery in the grid 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 is the best fit for the experimental variogram calculated for ash thickness measured 4 days after the fire (Fig. 9a) and presents a nugget effect of 13.35 and a slope of 1.42 (Table 3). Sixteen and 45 days after the fire, the linear model also fitted with the calculated experimental variograms (Fig. 9b and d) and shows a nugget effect of 7.31 and 0.80 and a slope of 0.60 and 0.49, respectively (Table 3). The spherical model fits perfectly with the experimental variogram calculated with the data collected 34 days after the fire and shows a nugget effect of 0.80, a sill of 6.90 along a range of 7.22 m. The nug/sill ratio (0.11) showed that the variable has 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 ln 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, 4.323) and the least precise was TPS (RMSE, 6.394) (Table 4a), 16 after the fire, the most precise technique was SK (RMSE 0.3464) and the least accurate was the LP2 (RMSE 0.4700) (Table 4b), 34 days most accurate was IMTQ (RMSE 1.802) and the least precise was IDW1 (RMSE, 2.144) (Table 4c) and 45 days the most accurate method was CRS (RMSE, 0.6706) and the least precise was IDW1 (RMSE, 0.8686) (Table 4D). The methods tests 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).

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 north-eastern and central parts of the plot, and the ash was less thick in the eastern and south-eastern 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 south-eastern, western and north-western 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 north-eastern and south-western portions of the plot.

# 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 were done on this topic on boreal grassland ecosystems.

Overall, the studied fire had low severity, nevertheless, induced a significant reduction on ground cover. Ash colour is a key variable to understand 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 confirm previous research developed on 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 leaves a greater amount of organic material remaining in the black 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 a reduction of ash thickness in all studied areas. 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. 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.

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 rain splash compacted the ash (Onda et al. 2008) and wind promoted transport, (re)distribution and incorporation into the 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 incorporate 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. 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. Ants also contribute with their nests to remove or covert 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 after 34 days after the fire may be also evidence of this process.

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. Between 36 and 45 days after the fire, the reduction of ash thickness might be a result of ash compaction and soil infiltration, since vegetation recuperation (probably a result of the timing of the fire during the growing season and to the incorporation of ash nutrients into the soil profile), reduced wind impact (Fig. 10C and D). Among all plots the ash depletion happened quickly on the sloping area.

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) which suggests that ash thickness was controlled by intrinsic factors (e.g. soil properties and ash texture), which facilitated ash infiltration. The vegetation recuperation in this period might reduce the impact of wind and rain on ash dynamic and favoured ash infiltration into the soil porous media. 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.

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. The interpolation with this method gives us indirect evidence of the probable fire line progression from northeast to south-west and the attendant fire severity. Litter consumption is a tracer of fire severity and temperature as identified elsewhere (Úbeda et al. 2009). It is also widely recognized that fire temperature rises with the distance covered by the fire line (Marcelli et al. 2002; Gimeno-Garcia et al. 2004), 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 have impact also 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 the time this variability increases especially in the sloping area where surface wash and wind erosion is more efficient. The ash thickness reduction and the increase of spatial variability will induce a heterogeneous soil protection pattern over time, and 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 have also important implications on the type and amount of nutrients availability for plant growth (Pereira et al. 2012a).

# Conclusion

The study of the spatio-temporal evolution of ash thickness is relevant in order to assess the degree of soil protection after fire and the major factors affecting this evolution. The studied fire was of low severity, yet it produced a significant reduction in vegetation cover, especially in the sloping area, owing to lower fuel amounts previous to the fire and/or higher fire severity such as the ash colour shown.

Vegetation recovered very fast 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 north-east to south-west 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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References

Bodi, M., Mataix-Solera, J., Doerr, S., and Cerdà, A.: The wettability of ash from burned vegetation and its relationship to Mediterranean plant species type, burn severity and total organic carbon content, Geoderma, 160, 599–607, 2011.

[Box, G.E.P.](http://en.wikipedia.org/wiki/George_E._P._Box), and [Cox, D.R.](http://en.wikipedia.org/wiki/David_Cox_(statistician)): An analysis of transformations. [J. R. Stat. So](http://en.wikipedia.org/wiki/Journal_of_the_Royal_Statistical_Society)c., Series B, 26, 211–252, 1964.

Bukantis, A.: Lietuvos klimatas. Vilniaus Universitetas, leidykla. Vilniaus, 1994.

Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Turco, R.F., and Konopka, A.E.: Field scale variability of soil properties in central Iowa soils, Soil Sci. Soc. Am. J., 58, 1501-1511, 1994.

Cerdà, A.: Postfire dynamics of erosional processes under mediterranean climatic conditions. Z. Geomorphol., 42 (3) 373-398. 1998a.

Cerdà, A.: Changes in overland flow and infiltration after a rangeland fire in a Mediterranean scrubland, Hydrol. Process., 12, 1031–1042, 1998b.

Cerdà, A., and Doerr, S.H.: The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period, Catena, 74, 256–263, 2008.

Cerdà, A., and Doerr, S. H.: The effect of ant mounds on overland flow and soil erodibility following a wildfire in eastern Spain, Ecohydrology, 3, 392–401, 2010.

Chaplot, V., Darboux, F., Bourennane, H., Leguédois, S., Silvera, N., and Phachomphon, K. Accurancy of interpolation techniques for derivation of digital elevation models in relation to landform types and data density, Geomorphology, 77, 126–476, 2006.

Chien, Y.L., Lee, D.Y., Guo, H.Y., and Houng, K.H.: Geostatistical analysis of soil properties of mid-west Taiwan soils, Soil Sci., 162, 291–298, 1997.

Conover, W. J.: Practical nonparametric statistics. Wiley, New York, 1980.

Diodato, N., and Ceccarelli, M.: Interpolation processes using multivariate geostatistics for mapping of climatological precipitation mean in the Sannio mountains (Southern Italy), Earth Surf. Proc. Land., 30, 259–268, 2005.

Erdogan, S.: A comparison of interpolation methods producing digital elevation models at field scale, Earth Surf. Proc. Land., 34, 366–376, 2009.

Erxleben, J., Elder, K., and Davies, R.: Comparison of spatial interpolation methods for estimating snow distribution in the Colorado Rocky Mountains, Hydrol. Process., 16, 3627–3649, 2002.

Gabet, E.J., and Sternberg, P.: The effects of vegetative ash on infiltration capacity sediment transport and generation of progressively bulked debris flows. Geomorphology, 101, 666–673, 2008. 

Gimeno-Garcia, E., Andreu,V., and Rubio, J.L.: Spatial patterns of soil temperatures during experimental fires, Geoderma, 118, 17–38 2004.

Goforth, B.R., Graham, R.C., Hubbert, K.R., Zanner, C.W., and Minnich, R.A.: 2005. Spatial distribution and properties of ash and thermally altered soil properties after high-severity forest fire, Int. J. Wildland Fire, 14, 343–354, 2005.

Goovaerts, P. 1999. Geostatistics in soil science: state of art and perspectives, Geoderma, 89, 1–45.

Isaaks, E.H., and Srivastava, R.M.; 1989. An Introduction to Applied Geostatistics, Oxford University Press, 1989.

Kadunas, V., Budavicius, R., Gregorauskiene, V., Katinas, V., Kliaugiene, E., Radzevicius, A., and Taraskevicius, R.: Geochemical Atlas of Lithuania, Lithuanian Geological Survey, 1999.

Keeley, J.E.: 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage, Int. J. Wildland Fire, 18, 116 – 126, 2009.

Knapp, E.E., and Keeley, J.E.: Heterogeneity in fire severity within early season and late season prescribed burns in a mixed-conifer forest, Int. J. Wildland Fire, 15, 37–45, 2006.

Larsen, I., MacDonald, L.H., Brown, E., Rough, D., Welsh, M. J., Pietraszek, J.H., Libohava, Z., Benavides-Solorio, J. D., and Schaffrath, K.: Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing?, Soil Sci. Soc. Am. J., 73, 1393–1407, 2009.

Leighton-Boyce, G., Doerr, S.H., Shakesby, R.A., and Walsh, R.P.D.: Quantifying the impact of soil water repellency on overland flow generation and erosion: a new approach using rainfall simulation and wetting agent on in situ soil, Hydrol. Process., 21, 2337–2435, 2007.

Liodakis, S., Tsoukala, M., and Katsigiannis, G.: Laboratory study of leaching properties of Mediterranean forest species. Water Air Soil Poll., 203, 99–107, 2009.

Maingi, J.K., and Henry, M.C.: Factors influencing wildfire occurrence and distribution in eastern Kentucky. USA, Int. J. Wildland Fire, 16, 23–33, 2007.

Mallik, A.U., Gimingham, C.H., and Rahman, A.A.: Ecological effects of heather burning. I. Water infiltration, moisture retention and porosity surface soil, J. Ecol. 72, 787–776, 1984.

Marcelli, T., Santoni, P. A., Simeoni, A., Leoni, E., and Porterie, B.: Fire spread across pine needle fuel beds: characterization of temperature and velocity distributions within the fire plume, Int. J. Wildland Fire, 13, 37–48, 2002.

Mardikis, M.G., Kalivas, D. P., and Kollias, V.J.: Comparison of interpolation methods for the prediction of reference evapotranspiration – An application in Greece, Int. Ser. Prog. Wat. Res., 19, 251–278, 2005.

Moral, F.J.: Comparison of different geostatistical approaches to map climate variables: application to precipitation, Int. J. Climatol., 30, 620–631, 2010.

Neary, D.G., Klopatek, C.C., DeBano, L., and Ffolliott, P.F.: Fire effects on bellow ground sustainability: a review and synthesis, Forest Ecol. Manag., 122, 51–71, 1999.

Onda, Y., Dietrich W. E., and Booker, F.: Evolution of overland flow after severe forest fire, Point Reyes, California, Catena, 72, 13–20, 2008. 

# Jerome, O., and Andersen, A.N.: Fire and biodiversity: responses of grass-layer beetles to experimental fire regimes in an Australian tropical savana. J. of Appl. Ecol., 38, 49–62, 2001.

Palmer, D.J., Höck, B.K., Kimberley, M.O., Watt, M.S., Lowe, D.J. and Payn, T.W.,: Comparison of spatial prediction for developing Pinus radiata productivity surfaces across New Zealand, Forest Ecol. Manag., 258, 2046–2055, 2009.

Pereira, P., Ubeda, X., Martin, D.A.: Fire severity effects on ash chemical composition and extractable elements, Geoderma, 191, 105 – 114, 2012.

Pereira, P., Cerdà, A., Úbeda, X., Mataix-Solera, J., Arcenegui, V., Zavala, L.: Modelling the impacts of wildfire on ash thickness in a short-term period, Land Degrad. Dev., 2013 (DOI: 10.1002/ldr.2195)

Pereira, P., Bodi, M., Úbeda, X., Cerdà, A., Mataix-Solera, J., Balfour, V. and Woods, S.: Las cenizas y el ecosistema suelo, in: Cerdà, A., Jordan, A. (Eds.), Actualización en métodos y técnicas de estudio de los suelos afectados por incendios forestales. Càtedra de Divulgació de la Ciència, pp. 345–398, 2010.

Pereira, P., Cerdà, A., Úbeda, X., Mataix-Solera, J., and Martin, D.: 2011. High severity wildfire effects in ash-thickness and short-term evolution in a Portuguese forest, EGU General Assembly 2011**,** Geophysical Research Abstracts, 13, **EGU 2011 - 30 Vienna, 2011.**

Pereira, P., and Úbeda, X.: Spatial distribution of heavy metals released from ashes after a wildfire, Journal of Environment Engineering and Landscape Management, 18, 13–22, 2010.

Pereira, P., Úbeda, X., Outeiro, L. and Martin, D.: Factor analysis applied to fire temperature effects on water quality, in: Gomez, E., Alvarez, K. (Eds.), Forest Fires: Detection, Suppression and Prevention. Series Natural Disaster Research, Prediction and Mitigation. Nova Science Publishers. New York, pp. 273–285, 2009.

Robinson, T.P., and Metternicht, G.: Testing the performance of spatial interpolation techniques for mapping soil properties, Comp. Electron. Agr., 50, 97–108, 2006.

Schloeder, C.A., Zimmerman, N.E., and Jacobs, M.J., 2001. Comparison of methods for interpolating soil properties using limited data, Soil Sci. Soc. Am. J., 65, 470–479, 2001.

Shapiro, S., and Wilk, M.: An analysis of variance test for normality, Biometrika, 52, 591–611, 2001, 1965.

Simbahan, G.C., Dobermann, A., Goovaerts, P., Ping, J., and Haddix, M.L.: Fine-resolution mapping of soil organic carbon based on multivariate secondary data, Geoderma, 132, 471–489, 2006.

Smith, A.M.S., and Hudak, A.T.: Estimating combustion of large downed woody debris from residual white ash. Int. J. Wildland Fire, 14, 245–248, 2005.

Smith, M.J., Goodchild, M.F., and Longley, P.A.: Geospatial Analysis. A comprehensive guide to principles techniques and software tools. Troubador Publishing. Leicister, 2009.

Smith, M.P., Zhu, A.X., Burt, J.E., and Stiles, C.: The effects of DEM resolution and neighborhood size on soil digital survey, Geoderma, 137, 58–69, 2006.

Sokal, R. R., and Rohlf, F.J.: Biometry: the principles and practice of statistics in biological research, 3rd ed. Freeman, San Francisco, 1995.

Sun, Y., Kang, S., Li, F., and Zhang, Lu.: Comparison of interpolation methods for depth to groundwater and its temporal and spatial variations in the Minqin oasis of Northwest of China, Environ. Modell. Softw., 24, 1163–1170, 2009.

Úbeda, X., Pereira, P., Outeiro, L., and Martin, D.: Effects of fire temperature on the physical and chemical characteristics of the ash from two plots of cork oak (Quercus suber). Land Degrad. Dev., 20, 589–609, 2009.

Ulery, A., Graham, R.C., and Amrhein, C.: Wood ash composition and soil pH following intense burning, Soil Sci., 156, 358–364, 1993.

Webster, R., and Oliver, M.A.: Geostatistics for environmen-tal scientists. Wiley Interscience. 2nd ed. London, 2007.

Wikars, L.O., and Schimmel, J.: 2001. Immediate effects of fire-severityon soil invertebrates in cut and uncut pine forests. Forest Ecol. Manag., 141, 189–200, 2001.

Woods, S.W., and Balfour, V.N. 2008. The effect of ash on runoff and erosion after a severe forest wildfire, Int. J. Wildland Fire, 17, 535–548, 2008.

Woods, S.W., Balfour, V.N.: The effects of soil texture and ash thickness on the post-fire hydrological response from ash-covered soils, J. Hydrol., 393, 274–286, 2010.

Xie, Y., Chen, T-B., Lei, M., Yang, J., Guo, Q-J., Song, Bo., and Zhou, X-Y.: Spatial distribution of soil heavy metal estimated by different interpolation methods; Accurancy and uncertainty analysis, Chemosphere, 82, 468–476, 2011.

Yilmaz, H.M.: The effect of interpolation methods in surface definition: an experimental study, Earth Surf. Proc. Land., 32, 1346–1361, 2007.

Zavala, L.M., Jordán A., Gil, J., Bellinfante, N. and Pain, C.: 2009. Intact ash and charred litter reduces susceptibility to rain splash erosion post-fire. Earth Surf. Proc. Land., 34, 1522–1532, 2009