

2014

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Paulo Pereira

*Mykolas Romeris University, pereiraub@gmail.com*

Xavier Ubeda

*University of Barcelona*

Deborah Martin

USGS

Jorge Mataix-Solera

*Miguel Hernández University*

Artemi Cerda

*University of Valencia*

*See next page for additional authors*

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Pereira, Paulo; Ubeda, Xavier; Martin, Deborah; Mataix-Solera, Jorge; Cerda, Artemi; and Burguet, Maria, "Wildfire effects on extractable elements in ash from a *Pinus pinaster* forest in Portugal" (2014). *USGS Staff -- Published Research*. 839. <http://digitalcommons.unl.edu/usgsstaffpub/839>

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**Authors**

Paulo Pereira, Xavier Ubeda, Deborah Martin, Jorge Mataix-Solera, Artemi Cerda, and Maria Burguet

# Wildfire effects on extractable elements in ash from a *Pinus pinaster* forest in Portugal

Paulo Pereira,<sup>1\*</sup> Xavier Úbeda,<sup>2</sup> Deborah Martin,<sup>3</sup> Jorge Mataix-Solera,<sup>4</sup> Artemi Cerdà<sup>5</sup>  
and Maria Burguet<sup>6</sup>

<sup>1</sup> Environmental Management Center, Mykolas Romeris University, Ateities g. 20, LT-08303 Vilnius, Lithuania

<sup>2</sup> GRAM (Mediterranean Environmental Research Group), Department of Physical Geography and Regional Geographic Analysis, University of Barcelona, Montalegre 6, 08001 Barcelona, Spain

<sup>3</sup> USGS, 3215 Marine Street, Boulder, CO, USA

<sup>4</sup> Environmental Soil Science Group, Department of Agrochemistry and Environment, Miguel Hernández University, Avda. de la Universidad s/n, Elche, Alicante, Spain

<sup>5</sup> Department of Geography, University of Valencia, Blasco Ibañez 28, 46010 Valencia, Spain

<sup>6</sup> Institute for Sustainable Agriculture (IAS-CSIC), Department of Agronomy, University of Córdoba, Av. Menéndez Pidal s/n Campus Alameda del Obispo, Apartado 4084, 14080 Córdoba, Spain

## Abstract:

The aim of this work is to study the effects of a wildfire on water-extractable elements in ash from a *Pinus pinaster* forest located in Portugal. The pH, electrical conductivity (EC), calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), sodium (Na<sup>+</sup>), potassium (K<sup>+</sup>), sodium and potassium adsorption ratio (SPAR), aluminium (Al<sup>3+</sup>), manganese (Mn<sup>2+</sup>), iron (Fe<sup>2+</sup>), zinc (Zn<sup>2+</sup>), sulphur (S), silica (Si) and phosphorous (P) were analysed in ash sampled from a sloped area burned in a wildfire and from litter from a contiguous unburned area, with similar morphological conditions. The results showed that ash leachates had higher pH and EC, and were significantly richer in water-extractable Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup>, SPAR, S and Si and significantly poorer in water-extractable Al<sup>3+</sup>, Fe<sup>2+</sup>, Mn<sup>2+</sup> and Zn<sup>2+</sup> than litter solutions. No significant differences were observed in water-extractable P. The fire changed the ash solute chemistry compared with the unburned litter and increased the sample variability of nutrient distribution with potential implications for plant recovery. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS wildfire; water-extractable elements; SPAR; ash; litter; sample variability

Received 4 January 2013; Accepted 3 May 2013

## INTRODUCTION

Wildland fires are a common disturbance in many ecosystems. In the Mediterranean environment, fires are frequent in the summer season, especially in dry years (Pausas, 2004; Pereira *et al.*, 2005). Several studies have pointed out that the frequency and severity of summer wildland fires in the Mediterranean region will tend to increase in the future as a result of climate change (Carvalho *et al.*, 2010) and as a consequence of human activities such as land-use changes (e.g. rural abandonment) and fire suppression (Lavorel *et al.*, 2006).

After a wildfire, the most common sight is the ash deposited on the soil surface. The plant species burned by the fire, the combustion temperature and the time of exposure to elevated temperatures influence the physical and chemical characteristics of ash and its leachates. Ash

has an important role in the recovery of burned areas, because it contains a large reservoir of the available nutrients for plant growth (Úbeda *et al.*, 2009; Bodí *et al.*, 2011; Pereira *et al.*, 2011a, b; Dlapa *et al.*, 2013; Pereira *et al.*, 2012a). In addition, the ash layer has an influence on soil erosion vulnerability and water retention (Khanna and Raison, 1986; Cerdà, 1998a, b; Gabet and Sternberg, 2008; Onda *et al.*, 2008; Larsen *et al.*, 2009; Stoof *et al.*, 2010; Bodí *et al.*, 2011; Pereira *et al.*, 2012a, c; Ebel *et al.*, 2012; Bodí *et al.*, 2011). Ash cover after the fire provides protection against rainsplash impact, retains water, reduces erosion and run-off (Cerdà and Doerr, 2008), and has the potential to seal the soil surface and thus promote run-off and erosion (Gabet and Sternberg, 2008; Onda *et al.*, 2008). These effects depend on the degree of fire impacts on soil hydrophobicity (Mataix-Solera and Doerr, 2004) and the type of ash produced. The ash produced at low temperatures is hydrophobic, and that produced at high combustion temperatures is hydrophilic (Bodí *et al.*, 2011; Pereira *et al.*, 2012b) and can temporarily change soil hydrologic properties. Dlapa

\*Correspondence to: Paulo Pereira, Environmental Management Center, Mykolas Romeris University, Ateities g. 20, LT-08303 Vilnius, Lithuania.  
E-mail: pereiraub@gmail.com

*et al.* (2013) observed that the organic matter combustion, which increases with fire temperature and severity, increases ash wettability due to the consumption of organic substances with hydrophobic surfaces. The calcium carbonate produced at high temperatures has hydrophilic surfaces, increasing the water retention. This suggests that ash chemistry has direct effects on the hydrological properties of ash.

Ash beds may protect the soil against erosion in the immediate period after the fire (Cerdà and Doerr, 2008; Woods and Balfour, 2008; Zavala *et al.*, 2009; Woods and Balfour, 2010; Pereira *et al.*, 2010a), which is especially important in the European Mediterranean environment where intense rainfall is common after the fire season (e.g. September, October and November) (Pereira *et al.*, 2010b). Ash is alkaline and rich in base elements such as calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), sodium ( $\text{Na}^+$ ) and potassium ( $\text{K}^+$ ) and also is rich in other elements such as phosphorous (P), sulphur (S) and the microelements such as aluminium ( $\text{Al}^{3+}$ ), manganese ( $\text{Mn}^{2+}$ ), iron ( $\text{Fe}^{2+}$ ) and zinc ( $\text{Zn}^{2+}$ ) (Etiégni and Campbell, 1991; Demeyer *et al.*, 2001; Plumlee *et al.*, 2007; Pandey and Singh, 2010; Gabet and Bookter, 2011). These elements are leached into run-off and into the soil profile and may have impacts on surface water chemistry. In this work, we study the water-extractable ash nutrients. After wildfires, ash and the suspended sediments transported into surface water can increase the amount of nutrients above the recommended limits, including trace elements, P and water turbidity, with impacts on drinking water resources. Despite the limited impact overtime (less than 1 year), sediment and ash transport in burned catchments can lead to important water consumption restrictions from surface water bodies and impacts on groundwater reserves (Lewis, 1974; Scott, 1993; Smith *et al.*, 2011a).

Normally, sodium adsorption ratio (SAR) is used to measure the effects of salts on clay dispersion. However, very frequently, solutions are rich in other salts such as  $\text{K}^+$ . Thus, it is necessary to define a new ratio that can measure the dispersive effects of a solution of  $\text{Na}^+$  and  $\text{K}^+$  on clay and aggregate stability. It is widely known that  $\text{K}^+$  has a strong capacity to disperse clay fractions and reduce soil aggregate stability (Levy and Torrento, 1995; Rengasamy and Marchuk, 2011). Sarah (2004) suggested the usage of a new ratio that considers  $\text{K}^+$  and  $\text{Na}^+$ . This ratio, called the sodium potassium adsorption ratio (SPAR), compares the amount of these monovalent cations with bivalent elements ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ). According to the author, the ratio is especially useful for solutions rich in  $\text{K}^+$  that normally are not considered or considered separately from  $\text{Na}^+$  when examining clay dispersion. Ash extracts are rich in  $\text{K}^+$  (Soto and Diaz-Fierros, 1993; Blank and Zamudio, 1998; Badía and Martí, 2003; Ûbeda *et al.*, 2009; Pereira

*et al.*, 2011a; Pereira *et al.*, 2012a). Thus in this paper, we used this index to evaluate the potential of ash extracts to induce clay dispersion/flocculation.

Few research efforts have focused on the chemistry of ash produced in wildfires in the Mediterranean environment (Goforth *et al.*, 2005; Pereira *et al.*, 2011a, b; Pereira *et al.*, 2012a). Until recently, most studies were conducted on ash from vegetation in temperate and cold environments (Ulery *et al.*, 1993; Blank and Zamudio, 1998; Khanna *et al.*, 1994; Santín *et al.*, 2012). Some measurements of the chemical composition of ash have been conducted on samples from controlled laboratory experiments using Mediterranean (Ûbeda *et al.*, 2009; Pereira *et al.*, 2009; Liodakis *et al.*, 2009) and non-Mediterranean species (Gray and Dighton, 2006; Qian *et al.*, 2009; Hogue and Inglett, 2012). However, most reports are published about wood ash chemistry produced in boilers (Misra *et al.*, 1993; Demeyer *et al.*, 2001; Pöykiö *et al.*, 2009) that differs from ash produced following wildfire, due to the different combustion conditions, material and temperature reached during the experiment (Pereira *et al.*, 2010a). Despite the advances in the research on the effects of wildfire ash on soil physical and hydrological properties, little is known about the effects of wildfires on the type and amount of water-extractable elements in ash and how the concentration of these elements differs from those in unburned litter. To our knowledge, no research has been conducted on the effects of wildfire on the SPAR values of ash extracts. This comparison allows us to understand the impacts of organic matter combustion on water-extractable elements and the degree of change imposed by fire on leachable elements in a real situation.

To address this research gap, this work aims to study the effects of a wildfire on water-extractable elements in ash in relation to unburned samples, specifically, pH, electrical conductivity (EC),  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ , SPAR,  $\text{Al}^{3+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Zn}^{2+}$ , S, Si and P.

## METHODS AND MATERIALS

### *Study site*

The study area is located in Portugal, near Lisbon (Figure 1) at 38°33'N and 09°03'W at 55 metres above sea level. The parent material is composed of Plio-Pleistocene dunes with low cementation, and soils are classified as *podzols* (Food and Agriculture Organization, 2006) with a high content of sand and low values of organic matter, pH, EC and cation exchange capacity (Pereira *et al.*, 2012a). The mean annual temperature is 14.8 °C, and the mean annual rainfall is 639.2 mm. The vegetation is mainly composed of *Pinus pinaster* with some patches of *Quercus suber*. This forest was exploited for industrial purposes (cork, wood and resin) until the 1990s.

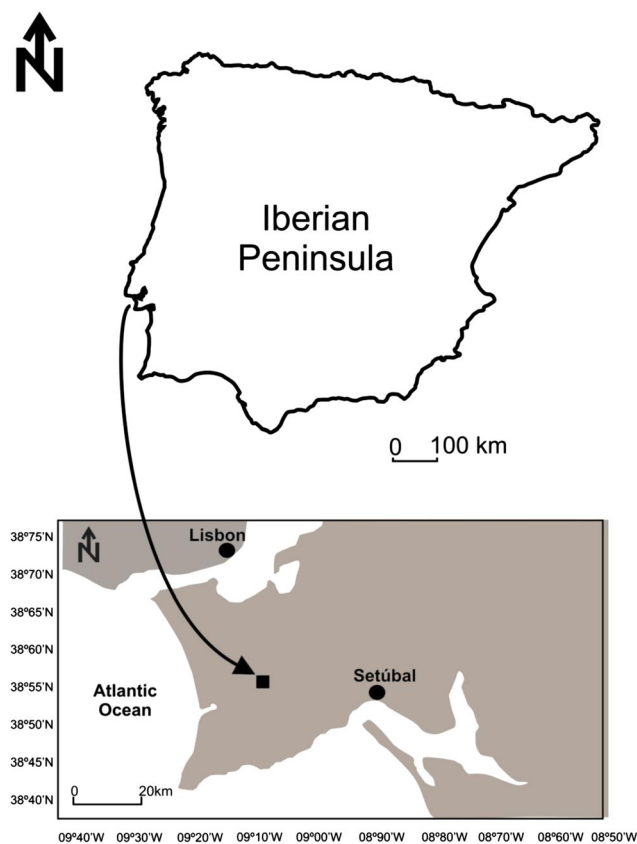


Figure 1. Study area

Afterwards, the land was abandoned leading to a great accumulation of biomass, which increased the wildfire risk. The wildfire occurred on 30 July 2008 near an urban site and affected an area of  $\pm 40$  ha. Three days after the fire, we collected 40 random ash samples (in an area of approximately of  $\pm 900$  m<sup>2</sup>) from the soil surface on a west-facing 15% slope under *P. pinaster* trees. Samples were collected carefully with a brush and a spoon to avoid mixing soil particulates into the samples. Following this step, samples were stored in plastic bags and taken to the laboratory for ash colour and chemical analysis. In a neighbouring unburned area with similar morphological conditions, we sampled 25 *P. pinaster* litter samples, in order to observe the effects of wildfire on the analysed parameters.

#### Sample preparation and physical and chemical analyses

The litter sampled in the unburned plot was cleaned with deionised water in the laboratory to remove all impurities and thereafter air-dried for 24 h (Pereira *et al.*, 2011a). Ash colour was analysed by pulverizing 1 g of ash in the Frich Pulverizate 23 for about 2 min in order to homogenize the sample. To determine the ash colour, the Munsell colour chart was used (Munsell, 1975).

For the pH determination of ash and litter samples, a slurry was created by mixing 6 g of sample with 36 ml of

deionised water, which was mixed for 2 h on a Thermo Scientific Variomag Poly inductive-drive stirrer. The solutions were filtered through a 4.7 cm diameter Whatman QMA 0.45- $\mu$ m pore size quartz fibre filter, using a Millipore 220/240 V, 50-Hz pump. After this step, the pH was measured with a Crison GLP 22 pH metre and the EC with a Hanna Instruments HI 8820 (Ùbeda *et al.*, 2009). Ions were determined by producing a slurry 1:40 (1 g of litter or ash and 40 ml of deionised water), which was mixed for 24 h and then filtered through a Whatman QMA 0.45- $\mu$ m pore size quartz fibre filter. The solution was analysed by inductively coupled plasma mass spectrometry with a PerkinElmer, model Elan 6000 spectrometer and by optical emission spectrometry with the PerkinElmer Optima 3200 RL spectrometer (Pereira *et al.*, 2010a). The data presented in this study for all elements represent the mean of three replicates. SPAR was calculated according to the formula suggested by Sarah (2004)  $(\text{Na}^+ + \text{K}^+)/(\text{Ca}^{2+} + \text{Mg}^{2+})^{1/2}$ .

#### Statistical analyses

We calculated the mean (m), median (M), standard deviation (SD), minimum (min), maximum (max) and coefficient of variation (CV%) of water-extractable elements from litter and ash. Prior to comparing litter and ash water-extractable elements, we tested the data for normality by using the Shapiro–Wilk test (Shapiro and Wilk, 1965). Data were considered normal at a  $p > 0.05$ . The majority of the distributions were not normal. Thus we carried out a neperian logarithmic (Ln) transformation as used previously in other studies (Martin-Garcia *et al.*, 2012; Pereira *et al.*, 2013a). After the Ln transformation, if some variable did not follow the Gaussian distribution, a Box–Cox data transformation was carried out (Box and Cox, 1964). The results presented here, however, consider the untransformed values. One-way analysis of variance was used to test whether litter and ash water-extractable elements were significantly different. When normality was not achieved after these transformations, the comparisons between treatments were carried out with the Mann–Whitney *U* nonparametric test. Differences were considered significant at a  $p < 0.05$ . Multivariate analysis was carried out with principal component analysis (PCA) based on the correlation matrix (with Box–Cox transformed data, because they had the distributions closest to normality) to identify relations among water-extractable elements from litter and ash.

## RESULTS

Ash colour was mainly dark grey (10YR 4/1), in 52.5% of the samples, followed by light grey (10YR 6/1 and 10YR 7/1), in 20%, very dark grey (10YR 3/1), in 17.5%, and black (10YR 2/1), in 10% of samples.

*pH, electrical conductivity, major elements and sodium and potassium adsorption ratio*

The ash pH and EC values were significantly higher than those observed in litter solutions. The sample variability (assessed by the CV%, as in the following cases) of pH was low in the burned plot, in contrast to EC (Table I). The amounts of water-extractable Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup> and SPAR were significantly higher in ash slurries than in the litter solutions. For all nutrients, with exception of SPAR, the sample variability was higher in the ash slurries (Table I).

*Microelements and other extractable elements*

The concentration of water-extractable Al<sup>3+</sup>, Mn<sup>2+</sup>, Fe<sup>2+</sup> and Zn<sup>2+</sup> was significantly lower in the ash slurries than in litter solutions. The sample variability (CV%) of all elements was higher in ash slurries (Table I). The water-extractable S, Si and P had higher concentrations in ash slurries. However, only the results for the first two elements were statistically significant. The sample variability of these elements was also high in the ash solutions (Table I).

*Multivariate analysis*

The first two factors extracted from the PCA explained the greatest part of the variance (68.97%). The PCA identified three groups: (i) one with higher amounts in litter extracts than in ash slurries (Al<sup>3+</sup>, Mn<sup>2+</sup>, Fe<sup>2+</sup> and Zn<sup>2+</sup>); (ii) one with a concentration slightly higher in ash extracts (K<sup>+</sup> and P); and (iii) one with significantly higher concentrations in ash solutions (pH, EC, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, SPAR, S and Si). The first factor presented high negative scores in the first group and high positive scores in the third group, showing that they have a negative correlation. The second group had high positive scores in factor 2 that explains the variance of these variables (Figure 2a). The elements extracted from ash had a higher variability. In ash slurries, we identified some samples with high values of some nutrients. For the points numbered with 1, high values of pH and water-extractable S were identified, and the points numbered with 2 had high concentrations of extractable Al<sup>3+</sup>, Fe<sup>2+</sup> and Zn<sup>2+</sup> (Figure 2b).

Table I. Descriptive statistics of water-extractable elements from litter and ash.

		Mean	Median	SD	min	max	CV%	<i>p</i>
pH	Litter	5.29	5.32	0.37	4.58	5.89	6.99	0.0001 <sup>(1)</sup>
	Ash	7.95	7.96	0.22	7.52	8.64	2.76	
EC	Litter	0.40	0.40	0.07	0.28	0.55	17.5	0.0001 <sup>(2)</sup>
	Ash	1.30	1.22	0.45	0.63	2.76	34.62	
Ca <sup>2+</sup>	Litter	450.93	390.54	180.23	214.54	838.94	39.96	0.0001 <sup>(2)</sup>
	Ash	4371.01	3458.52	2362.39	1813.05	12695.04	54.04	
Mg <sup>2+</sup>	Litter	382.61	348.43	141	185.30	712.48	36.85	0.0001 <sup>(2)</sup>
	Ash	1196.01	1087.79	626.18	468.12	4036.32	52.35	
Na <sup>+</sup>	Litter	789.06	784.33	160.94	517.34	1041.68	20.39	0.0001 <sup>(2)</sup>
	Ash	1737.42	1753.49	686.58	286.72	3071.12	39.51	
K <sup>+</sup>	Litter	2009.50	1995.56	664.82	1134.65	3456.32	33.08	0.01 <sup>(3)</sup>
	Ash	3469.29	2876.53	2457.41	1246.97	13 355	70.83	
SPAR	Litter	0.30	0.26	0.11	0.16	0.57	36.66	0.0001 <sup>(1)</sup>
	Ash	0.62	0.64	0.13	0.15	0.80	20.96	
Al <sup>3+</sup>	Litter	22.48	22.31	2.20	18.37	26.95	9.78	0.001 <sup>(1)</sup>
	Ash	12.51	12.80	7.01	0.61	31.24	56.03	
Mn <sup>2+</sup>	Litter	8.85	9.34	3.75	1.94	15.43	42.37	0.001 <sup>(1)</sup>
	Ash	4.52	4.14	1.76	0.39	10.12	42.51	
Fe <sup>2+</sup>	Litter	13.42	12.46	4.71	7.72	24.58	37.80	0.001 <sup>(2)</sup>
	Ash	9.38	6.35	9.43	1.63	53.55	100.53	
Zn <sup>2+</sup>	Litter	13.77	12.46	4.71	7.72	24.58	34.20	0.001 <sup>(2)</sup>
	Ash	1.25	1.07	1.10	0.08	5.33	88	
S	Litter	229.91	245.30	35.52	170.74	282.70	14.48	0.001 <sup>(1)</sup>
	Ash	1690.27	1707.94	468.72	702.72	2573.78	27.73	
Si	Litter	136.27	143.65	26.03	81.53	174.71	19.10	0.001 <sup>(1)</sup>
	Ash	1050.56	1032.95	384.25	224.76	1890.11	36.57	
P	Litter	67.70	65.41	18.68	44.77	112.89	27.59	n.s <sup>(1)</sup>
	Ash	92.42	59.88	77.34	4.68	314	83.68	

Comparisons made with untransformed data (1), and Ln transformed data (2), and with Mann–Whitney *U* test due to lack of normality after Ln and Box–Cox data transformations (3). n.s means that differences are not significant at *p* < 0.05, electrical conductivity is in mS/cm and extractable elements are in mg/l.

SD, standard deviation; min, minimum; max, maximum; CV%, coefficient of variation; SPAR, sodium and potassium adsorption ratio.

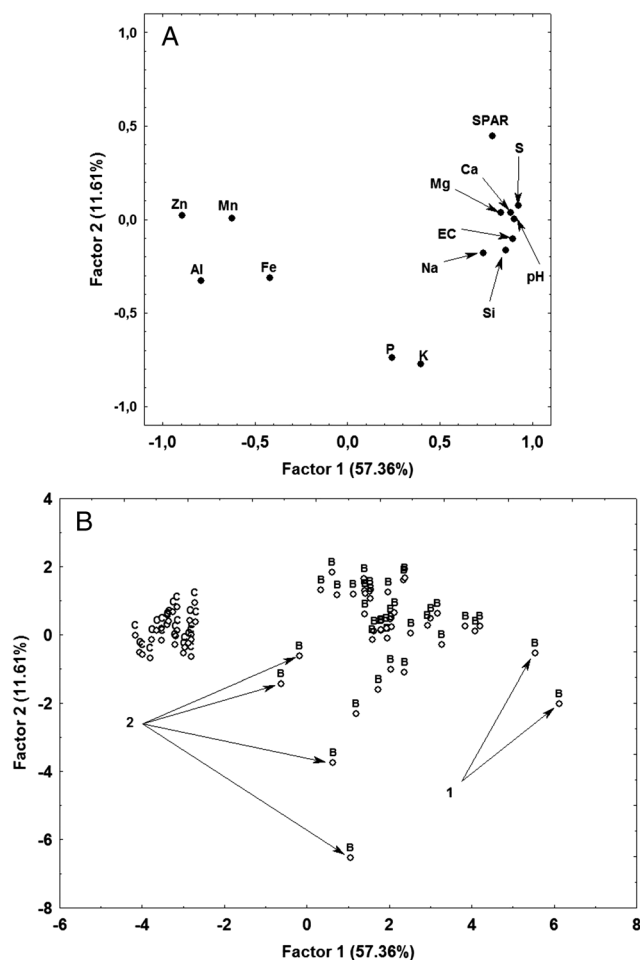


Figure 2. Relation between factor 1 and factor 2: (a) variables and (b) cases. C, control plot, B, burned plot

## DISCUSSION

The ash collected was produced at medium to high fire severity based on the predominance of dark grey and light grey colour ash, an indication that organic matter was extensively consumed (Goforth *et al.*, 2005). Fire has a mineralization effect on organic matter, increasing the amount of carbonates, oxides, hydroxides and base cations available for leaching (Ulery *et al.*, 1993; Soto and Diaz-Fierros, 1993), and explains the increase of the pH and EC in ash slurries. Our results agree with previous studies carried out by Blank and Zamudio (1998) and Johnston and Elliott (1998), who also observed that pH was significantly higher in ash extracts than in unburned litter. Lewis (1974) identified a higher concentration of salts in ash slurry solutions compared with unburned litter. Values for pH and EC increased significantly in relation to unburned litter. Pereira *et al.* (2011a) also found this response for ash from a prescribed fire carried out in a Mediterranean ecosystem. In laboratory fire experiments, Ûbeda *et al.* (2009) observed that pH and

EC were higher in ash slurries than slurries of the unburned litter. The same findings were observed by Qian *et al.* (2009) for pH. In ash sampled in wildfires, Ulery *et al.* (1993), Henig-Sever *et al.* (2001), Goforth *et al.* (2005) and Pereira *et al.* (2012a) identified that ash pH increases with fire severity.

The solubility of the nutrients from wood ash is complex because the diverse chemical forms found in ash, such as oxides, hydroxides and carbonates, dissolve at different rates in solution (Meiwes, 1995). This has implications for the type and amount of leached elements in solution. In our work, we observed that all water-extractable base cations, SPAR, S and Si were significantly higher in ash extracts compared with litter solutions. In contrast, the water-extractable heavy metals were significantly higher in litter solutions in relation to ash extracts. Pereira *et al.* (2011a) also observed higher concentrations of  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ , S and Si in ash slurries than in litter solutions, and the inverse situation for water-extractable  $\text{Mn}^{2+}$ ,  $\text{Fe}^{2+}$  and  $\text{Zn}^{2+}$ . The increase of extractable  $\text{Al}^{3+}$  found by Pereira *et al.* (2011a) was not observed in this study, and this can be attributed to differences in pH in the solutions. We found that the pH in ash slurries reached lower values (5.99) in the study carried out by Pereira *et al.* (2011a) than the ones measured in this work (pH = 7.52), which explains the higher values of  $\text{Al}^{3+}$  in solution in the earlier study. Aluminium is more soluble under acidic conditions (Sposito, 2000). In this work, the litter and ash collected was only from *P. pinaster*. However, in previous studies, a comparison among different plant species was carried out, and differences in extractable components were observed. Laboratory fire simulations carried out by Pereira *et al.* (2011b) demonstrated that at low fire temperatures, extractable  $\text{Al}^{3+}$  was higher in ash extracts compared with unburned litter solutions, mainly in *Q. suber* extracts. An identical experiment was carried out with *P. pinaster* litter collected in the same ecosystem, and the extractable  $\text{Al}^{3+}$  was always lower in the ash extracts than in the unburned sample solution (Pereira, 2010).

The degree of element solubilisation depends on the pH of the ash slurry. Liodakis *et al.*, (2009) observed in laboratory studies that the leaching of  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$  and  $\text{Zn}^{2+}$  from ash was favoured at pH 6 compared with pH 1. In our study, the pH values ranged from 4.58 to 5.89 in the litter extracts and from 7.52 to 8.64 in the ash slurries. Compared with water extracts of litter, slurries of ash produce neutral to alkaline pH conditions that favour the solubility of some elements and reduce the solubility of others. The pH values observed in ash slurries are in the range of optimal dissolution of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , pH 7–8 (Holden, 2005),  $\text{Na}^+$  and  $\text{K}^+$ , around pH 7.5, but especially at pH 8.5 (Throeh and Thompson,

2005; Nieminen *et al.*, 2005), S between pH 6–8 (Throeh and Thompson, 2005), and Si pH > 7 (Steenari and Lindqvist, 1997). For P, the optimal pH range is 6.5–7.5, and only the ash slurries with low pH were inside the optimal value for P extraction. This explains the nonsignificant increase of water-extractable P in ash slurries compared with litter solutions. In addition, at low pH, P precipitates with  $\text{Al}^{3+}$ ,  $\text{Mn}^{2+}$  and  $\text{Fe}^{2+}$  and at high pH precipitates with  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  (Carreira and Lajtha, 1997).

The optimal pH to extract  $\text{Al}^{3+}$  and  $\text{Mn}^{2+}$  is <5, and these elements show a reduced solubility between pH 5 and 8 (Kabata-Pendias and Pendias, 2000; Sposito, 2000; Lee *et al.*, 2002). Iron in solution is reduced at pH > 4 (Lee *et al.*, 2002) and precipitates strongly in the presence of other elements such as  $\text{Ca}^{2+}$ ,  $\text{K}^+$  and  $\text{Mn}^{2+}$  (Varenes, 2003; Das *et al.*, 2007). Zinc is very sensitive to pH changes (Chirenge *et al.*, 2006), and it is only present in important quantities in solution at pH < 5 (Lee *et al.*, 2002). At pH > 7–7.5,  $\text{Zn}^{2+}$  is retained dramatically in organic and mineral particulates (Harter, 1983).

Fire transforms organic matter on the soil surface to ash, and any water that percolates through the ash into the underlying soil has a dramatically altered solution chemistry compared with unburned litter. Water percolating through the ash deposited on the soil surface will leach large quantities of base cations into the soil profile that will change the soil nutrient status and pH. The increase of pH has implications for nutrient availability, soil respiration, microbial activity, mineralization rates and plant germination. High pH and high amounts of  $\text{Na}^+$  and  $\text{K}^+$  may induce clay dispersion and decrease aggregate stability (Durgin, 1980; Durgin and Vogelsang, 1984; Botelho, 1999; Endo *et al.*, 2002). In our study, SPAR increased significantly, and this showed that the ash extracts have a higher potential to induce clay dispersion and aggregate stability than the unburned litter extracts. However, the increase of EC can also counteract the effects of SPAR. Previous studies observed that hydraulic conductivity reduction and clay dispersion are favoured in soil solutions with high SAR and low EC (Mace and Amrhein, 2001; Bhardwaj *et al.*, 2008). In the studied area, soils are sandy with low clay content, and thus, ash extracts can increase the dispersion of small particulates and the vulnerability to erosion. However, these results have to be considered with care, due to the potential effects of EC and the fact that  $\text{K}^+$  is a less effective dispersion agent as compared with  $\text{Na}^+$  (Rengasamy and Marchuk, 2011). To our knowledge, no previous studies have identified fire impacts on SPAR. However earlier research has shown that SAR increases in ash extracts with fire severity (Pereira and Úbeda, 2010). This suggests that solutions produced by ash combusted at high temperatures might have a great potential to promote clay dispersion and reduce aggregate

stability, contributing to a high erosion vulnerability in the affected areas. The studies on fire impacts on soil SAR showed an increase in the immediate period after the fire and the tendency to produce soil crusting (Dormar and Schaber, 1985; Mills and Fey, 2004) that can be attributed to ash extracts.

The high pH and large input of  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$  may inhibit the availability of other ions in solution, such as  $\text{Mn}^{2+}$ ,  $\text{Fe}^{2+}$  and  $\text{Zn}^{2+}$  (Varenes, 2003). These changes depend on the ash amount, chemical composition and soil buffering capacity (Raison and McGarity, 1980a; Raison and McGarity, 1980b; Henig-Sever *et al.*, 1996). Immediately after the fire, changes in the soil are due to temperature effects. In the post-fire period, the modifications in soil protection and properties are dominated by ash. These effects depend strongly on the type of ash produced, the exposure and morphology of the burned area and meteorological conditions post-fire (Pereira *et al.*, 2010b).

Fire increases the sample variability of all nutrients whose availability influences plant regrowth. This suggests that for the studied slope, the presence of ash will probably change the type and amount of nutrients in soil solution for an unknown period, with effects on soil physical and chemical properties (Badía and Martí, 2003; Stoff *et al.*, 2011; Bodí *et al.*, 2011). In our study, we observed with PCA analysis that some ash samples had different concentrations in the amount of the elements studied (Figure 2b). Ash slurries from black ash were richer in water-extractable  $\text{Al}^{3+}$  and transition metals and had low pH and extractable S. This confirms that fire severity has implications for the type and amount of elements present in ash extracts, as observed in previous studies by Johnston and Elliott (1998) and Pereira *et al.* (2012a).

However, ash is a very mobile material, especially after severe wildfires, because it is composed of small-sized granulates that can be easily transported and have effects outside of the burned area (Blank and Zamudio, 1998; Pereira *et al.*, 2013a). In addition, leaching rates are different according to the pH attained in the ash slurries. After several leachings, the pH decreases (Soto and Diaz-Fierros, 1993; Steenari and Lindqvist, 1997), favouring the solubility of elements that previously were inhibited, such as transition metals (Lioudakis *et al.*, 2009), that could act as contaminants. This suggests that the leaching of elements from ash in space and time is a very complex process.

This research confirms that fires produce ash that can contribute to larger amounts of cations to the soil. These cations are available for plant regrowth and can contribute to a potential enrichment of nutrients in overland flow. It is extensively reported in the literature that after the fire, soil pH, EC and water-extractable cations increase, and this has been attributed to the effect of ash (Raison and



McGarity, 1980a; Ludwig *et al.*, 1998; Ûbeda *et al.*, 2005). Other studies also observed that the addition of ash to heated soils changes their hydrological properties and nutrient availability (Badía and Martí, 2003). However, little information is available about the chemistry of ash extracts of  $Al^{3+}$  and transition metals, and the effects of the soluble components on the mineral soil. The previous studies are mainly focused on the major cations (Lewis, 1974; Thomas *et al.*, 2000), and few works have considered  $Al^{3+}$  and transition metals. In addition, previous studies showed that the same temperatures had different impacts in the same species located in different environments (Ûbeda *et al.*, 2009). Thus different impacts are expected on soil properties and overland flow. This will make the evaluation of the impacts of ash more complex. Also, different species have different flammability, as is common in wildland environments and reported elsewhere (Nunez-Regueira *et al.*, 1997; Dimitrakopoulos and Papaioannou, 2011; Dimitrakopoulos and Panov, 2001), and this has implications for ash chemistry.

The impact of fires on litter and on soil at the same point is not equal, because of the different material properties (Hartford and Frandsen, 1992). The amount of nutrients is normally higher in ash extracts than in soil solutions (Thomas *et al.*, 2000; Ponder *et al.*, 2009) that can be attributed to the different degree of mineralization. This will have implications in the type and amount of extractable elements. Litter is less resistant to flames than the organic matter in soil (Neary *et al.*, 1999). Thus, in the same fire, it is very likely that litter and soil organic matter will burn differently, and as expected, the impacts are diverse. More research is needed to accurately characterize these differences. Normally within a few weeks after the fire, ash is transported, compacts or infiltrates into the soil, especially the fine particulates produced by high severity fire, and these fine particulates are the ones to have the primary impact (Woods and Balfour, 2008, 2010; Pereira *et al.*, 2013b). Ash and heated soil are mixed, and the hydrological effects of fire on soil will be a product of this interaction. Under field conditions, it is complex to evaluate the separate impacts of ash and heated soil on the hydrology of the burned area.

Our findings fit with the results of the researchers working on soil erosion that usually document that after fire, the chemical properties of run-off are characterized by a high content of cations that will decrease with time (Soto *et al.*, 1997; Thomas *et al.*, 2000; Cerdà and Lasanta, 2005; Lasanta and Cerdà, 2005). The flux of cations from burned landscapes can increase as a consequence of the increase in the run-off rates that are typically much higher after fires (Cerdà and Doerr, 2005), thus changing the sediment flux into water bodies and

their chemistry and biology in the immediate period after the fire (Minshall *et al.*, 2001; Smith *et al.*, 2011b). Moreover, erosion rates can increase as a result of the increased run-off and because of effects of ash and heat on clay and aggregate stability (Durgin and Vogelsang, 1984; Durgin, 1980; Pierson *et al.*, 2001; Cerdà and Doerr, 2005; Lasanta and Cerdà, 2005; Mataix-Solera *et al.*, 2011). The flux of elements is reduced by vegetation recovery, and during this post-fire evolution period, the amount of material being transported is related to the total run-off, which is controlled by the type of vegetation that regrows (Cerdà and Doerr, 2007).

## CONCLUSIONS

Forest fires create ash that interacts with water to favour the extraction of some base cations, SPAR, S and Si. Heavy metals decrease in the slurry of ash from a fire in *P. pinaster* forest relative to unburned litter. Extractable P did not change significantly. The sample variability of the studied elements was higher in ash slurries, suggesting that the distribution will be uneven, affecting the nutrients available for plant recovery.

## ACKNOWLEDGEMENTS

This study was supported by the Spanish Ministry of Science and Technology, project CGL2006-11107-C02-02/BOS 'Evaluation of the quality of Mediterranean soils affected by fire in a middle and large term' and the European Regional Development Fund (FEDER). We are also thankful to Serveis Científico-Tècnics from the University of Barcelona. The authors would also like to acknowledge FuegoRed (Fire Effects on Soil Properties Network) for financing the projects CGL2007-28764-E/BTE CGL2008-01632-E/BTE y CGL2009-06861-E/BTE, the Lithuanian Research Council for financing the project LITFIRE, Fire effects on Lithuanian soils and ecosystems (MIP-48/2011), the HYDFIRE project (CGL2010-21670-C02-01) and the *Comissionat per a Universitats i Recerca del DIUE de la Generalitat de Catalunya*. The authors appreciate the comments of two anonymous reviewers that improved substantially the quality of the manuscript.

## REFERENCES

- Badía D, Martí C. 2003. Plant ash and heat intensive effects on chemical and physical properties of two contrasting soils. *Arid Land Research Management* **17**: 23–41 DOI: 10.1080/15324980390169046.
- Bhardwaj AK, Mandal UK, Bar-Tal A, Gilboa A, Levy GJ. 2008. Replacing saline-sodic irrigation water with treated wastewater: effects on saturated hydraulic conductivity, slaking and swelling. *Irrigation Science* **26**: 139–146 DOI 10.1007/s00271-007-0080-1.

- Blank RR, Zamudio DC. 1998 The influence of wildfire on aqueous-extractable soil solutes in forested and wet meadow ecosystems along Eastern front of the Sierra-Nevada range, California. *International Journal of Wildland Fire* **8**: 79–85 DOI: 10.1071/WF9980079.
- Bodí M, Mataix-Solera J, Doerr S, Cerdà A. 2011. The wettability of ash from burned vegetation and its relationship to Mediterranean plant species type, burn severity and total organic content. *Geoderma* **160**: 599–607 DOI: 10.1016/j.geoderma.2010.11.009.
- Botelho JM. 1999. Caracterizacáo e constituicáo do solo, Fundacáo Calouste Gulbenkian: 6th Ed. Lisboa; 528.
- Box GEP, Cox DR. 1964. An analysis of transformations. *Journal of the Royal Statistical Society Series B* **26**: 211–246.
- Carreira JA, Lajtha K. 1997. Factors affecting phosphate sorption along a Mediterranean, dolomitic soil and vegetation chronosequence. *European Journal of Soil Science* **48**: 139–149 DOI: 10.1111/j.1365-2389.1997.tb00193.x.
- Carvalho A, Flannigan MD, Logan KA, Gowman LM, Miranda AI, Borrego C. 2010. The impact of spatial resolution on area burned and fire occurrence projections in Portugal under climate change. *Climatic Change* **98**: 177–197 DOI: 10.1007/s10584-009-9667-2.
- Cerdà A. 1998a. Changes in overland flow and infiltration after a rangeland fire in a Mediterranean scrubland. *Hydrological Process* **12**: 1031–1042 DOI: 10.1002/(SICI)1099-1085(19980615)12:7<1031::AID-HYP636>3.0.CO;2-V
- Cerdà A, Doerr S. 2008. The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *Catena* **74**: 256–263 DOI: 10.1016/j.catena.2008.03.010.
- Cerdà A. 1998b. Postfire dynamics of erosional processes under Mediterranean climatic conditions. *Zeitschrift für Geomorphologie* **42**: 373–398.
- Cerdà A, Doerr S. 2005. The influence of vegetation recovery on soil hydrology and erodibility following fire: an eleven-year research. *International Journal of Wildland Fire* **14**: 423–427 DOI: 10.1071/WF05044.
- Cerdà A, Lasanta A. 2005. Long-term erosional responses after fire in the Central Spanish Pyrenees: 1. Water and sediment yield. *Catena* **60**: 59–80 DOI: 10.1016/j.catena.2004.09.006.
- Cerdà A, Doerr SH. 2007. Soil wettability, runoff and erodibility of major dry-Mediterranean land use types on calcareous soils. *Hydrological Processes* **21**: 2325–2336 DOI: 10.1002/hyp.6755.
- Das B, Hazarika P, Saikia G, Kalita H, Goswami DC, Das HB, Dube SN, Dutta RK. 2007. Removal of iron from groundwater by ash: a systematic study of traditional method. *Journal of Hazardous Materials* **141**: 834–841 DOI: 10.1016/j.jhazmat.2006.07.052.
- Demeyer A, Vuondi Nkana JC, Verloo MG. 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. *Bioresource Technology* **77**: 287–295 DOI: 10.1016/S0960-8524(00)00043-2.
- Dimitrakopoulos AP, Papaioannou KK. 2011. Flammability assessment of Mediterranean forest fuels. *Fire Technology* **34**: 143–152.
- Dimitrakopoulos AP, Panov PI. 2001. Pyric properties of some dominant Mediterranean vegetation species. *International Journal of Wildland Fire* **10**: 23–27 DOI: 10.1071/WF01003.
- Dlapa P, Bodí M, Mataix-Solera J, Cerdà A. 2013. FT-IR spectroscopy reveals that ash water repellency is highly dependent on ash chemical composition. *Catena* **108**: 35–43. DOI: 10.1016/j.catena.2012.02.011.
- Dormar JF, Schaber BD. 1985. Chemical properties of soil as affected by a single burn of alfalfa stubble to control insects. *Canadian Journal of Soil Science* **65**: 357–361.
- Durgin PB. 1980. The influence of ash leachate on forest erosion. Abstracts with Programs, 76th Annual Meeting of the Geological Society of America, Boulder, CO, United States; 104.
- Durgin PB, Vogelsang PJ. 1984. Dispersion of kaolinite by water extracts of Douglas-fir ash. *Canada Journal of Soil Science* **64**: 439–443.
- Ebel BA, Moody JA, Martin DA. 2012. Hydrologic conditions controlling runoff generation immediately after wildfire. *Water Resources Research* **48**: W03529 DOI: 10.1029/2011WR011470.
- Endo T, Yamamoto S, Honna T, Eneija AE. 2002. Sodium–calcium exchange selectivity as influenced by clay minerals and composition. *Soil Science* **167**: 117–125.
- Etiégni L, Campbell AG. 1991. Physical and chemical characteristics of wood ash. *Bioresource Technology* **37**: 173–178 DOI: 10.1016/0960-8524(91)90207-Z.
- Gabet EJ, Bookter A. 2011. Physical, chemical and hydrological properties of Ponderosa pine ash. *International Journal of Wildland Fire* **20**: 443–452 DOI: 10.1071/WF09105.
- Gabet EJ, Sternberg P. 2008. The effects of vegetative ash on infiltration capacity sediment transport and generation of progressively bulked debris flows. *Geomorphology* **101**: 666–673 DOI: 10.1016/j.geomorph.2008.03.005.
- Goforth BR, Graham RC, Hubbert KR, Zanner CW, Minnich RA. 2005. Spatial distribution of ash and thermally altered soils after high severity forest fire, Southern California. *International Journal of Wildland Fire* **14**: 343–354 DOI: 10.1071/WF05038.
- Gray DM, Dighton J. 2006. Mineralization of forest litter nutrients by heat and combustion. *Soil Biology and Biogeochemistry* **38**: 1469–1477 DOI: 10.1016/j.soilbio.2005.11.003.
- Harter RD. 1983. Effect of soil pH on adsorption of lead, copper, zinc, and nickel. *Soil Science Society of America Journal* **47**: 47–51.
- Hartford RA, Frandsen WH. 1992. When it's hot, it's hot...or maybe it's not! (surface flaming may not portend extensive soil heating). *International Journal of Wildland Fire* **2**: 139–144 DOI: 10.1071/WF9920139.
- Henig-Sever N, Eshel A, Ne'eman G. 1996. pH and osmotic potential of pine ash as post fire germination inhibitors. *Physiologia Plantarum* **96**: 71–76 DOI: 10.1111/j.1399-3054.1996.tb00185.x.
- Henig-Sever N, Poliakov D, Broza M. 2001. A novel method for estimation of wild fire intensity based on ash pH and soil microarthropod community. *Pedobiologia* **45**: 98–106.
- Hogue BA, Inglett PW. 2012. Nutrient release from combustion residues from two contrasting herbaceous vegetation types. *Science of the Total Environment* **431**: 9–19 DOI: 10.1016/j.scitotenv.2012.04.074.
- Holden J. 2005. *An Introduction to Physical Geography and the Environment*, Pearson Education Limited: Essex; 665.
- Johnston M, Elliott J. 1998. The effects of fire severity on ash, and plant and soil nutrient levels following experimental burning in a boreal mixedwood stand. *Canadian Journal of Soil Science* **78**: 35–44.
- Kabata-Pendias A, Pendias H. 2000. *Trace Elements in Soils and Plants*, 3rd Ed., CRC Press: Florida; 413.
- Khanna PK, Raison RJ. 1986. Effect of fire intensity on solution chemistry of surface soil under *Eucalyptus pauciflora*. *Australian Journal of Soil Research* **24**: 423–434 DOI: 10.1071/SR9860423.
- Khanna PK, Raison RJ, Falkiner RA. 1994. Chemical properties of ash derived from *Eucalyptus* litter and its effects on forest soils. *Forest Ecology and Management* **66**: 107–125 DOI: 10.1016/0378-1127(94)90151-1.
- Larsen I, MacDonald LH, Brown E, Rough D, Welsh MJ, Pietraszek JH, Libohava Z, Benavides-Solorio JD, Schaffrath K. 2009. Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing? *Soil Science Society of America Journal* **73**: 1393–1407 DOI: 10.2136/sssaj2007.0432.
- Lasanta A, Cerdà A. 2005. Long-term erosional responses after fire in the Central Spanish Pyrenees: 2. Solute release. *Catena* **60**: 80–101 DOI: 10.1016/j.catena.2004.09.005.
- Lavorel S, Flannigan MD, Lambin EF, Scholes MC. 2006. Vulnerability of land systems to fire: interactions among humans, climate, the atmosphere, and ecosystems. *Mitigation and Adaptation Strategies for Global Change* **12**: 33–53 DOI: 10.1007/s11027-006-9046-5.
- Lee G, Bigham JM, Faure G. 2002. Removal of trace metals by coprecipitation with Fe, Al and Mn from natural contaminated waters with acid mine drainage in the Ducktown mining district, Tennessee. *Applied Geochemistry* **17**: 569–581 DOI: 10.1016/S0883-2927(01)00125-1.
- Levy GJ, Torrento JR. 1995. Clay dispersion and macroaggregate stability as affected by exchangeable potassium and sodium. *Soil Science* **5**: 352–358 DOI: 10.1097/00010694-199511000-00004.
- Lewis Jr WM. 1974. Effects of fire on nutrient movement in a South Carolina pine forest. *Ecology* **55**: 1120–1127.
- Liodakis S, Tsoukala M, Katsigiannis G. 2009. Laboratory study of leaching properties of Mediterranean forest species ashes. *Water, Air, and Soil Pollution* **203**: 99–107 DOI: 10.1007/s11270-009-9994-y.
- Ludwig B, Khanna PK, Raison RJ, Jacobsen KL. 1998. Modelling cation composition of soil extracts under ashbeds following an intense slashfire in a eucalypt forest. *Forest Ecology and Management* **103**: 9–20 [http://dx.doi.org/10.1016/S0378-1127\(97\)00173-4](http://dx.doi.org/10.1016/S0378-1127(97)00173-4).

- Mace JE, Amrhein C. 2001. Leaching and reclamation of a soil irrigated with moderate SAR waters. *Soil Science Society of America Journal* **65**: 199–204 DOI: 10.2136/sssaj2001.651199x.
- Mataix-Solera J, Cerdà A, Arcenegui V, Jordán A, Zavala LM. 2011. Fire effects on soil aggregation: a review. *Earth-Science Reviews* **109**: 44–60 DOI: 10.1016/j.earscirev.2011.08.002.
- Mataix-Solera J, Doerr S. 2004. Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forests in southeastern Spain. *Geoderma* **118**: 77–88.
- Martin-García J, Merino A, Diez J. 2012. Relating visual crown conditions to nutritional status and site quality in monoclonal poplar plantations (*Populus x euroamericana*). *European Journal of Forest Research* **131**: 1185–1198 DOI: 10.1007/s10342-011-0590-5.
- Meiwes KJ. 1995. Application of lime and wood ash to decrease acidification of forest soils. *Water, Air, and Soil Pollution* **85**: 143–152.
- Mills AJ, Fey MV. 2004. Frequent fires intensify soil crusting: physiochemical feedback in the pedoderm of long-term burn experiments in South Africa. *Geoderma* **121**: 45–64.
- Minshall GW, Brock JT, Andrews DA, Robinson CT. 2001. Water quality, substratum and biotic responses of five central Idaho (USA) streams during the first year following the Mortar Creek fire. *International Journal of Wildland Fire* **10**: 185–199 DOI: 10.1071/WF01017.
- Misra MK, Ragland KW, Baker AJ. 1993. Wood ash composition as a function of furnace temperature. *Biomass and Bioenergy* **4**: 103–116 DOI: 10.1016/0961-9534(93)90032-Y.
- Munsell. 1975. *Soil Color Chart. Handbook, 58*, U.S. Department of Agriculture: Baltimore.
- Nearly DG, Klopatek CC, DeBano LF, Ffolliot PF. 1999. Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**: 51–71 [http://dx.doi.org/10.1016/S0378-1127\(99\)00032-8](http://dx.doi.org/10.1016/S0378-1127(99)00032-8).
- Nieminen M, Piirainen S, Moilanen M. 2005. Release of mineral and heavy metals from wood and peat ash fertilizers: field studies in Finnish forest soils. *Scandinavian Journal of Forest Research* **20**: 146–153 DOI: 10.1080/02827580510008293.
- Nunez-Regueira L, Rodriguez-Anon JA, Proupin CJ. 1997. Calorific values and flammability of forest species in Galicia, continental high mountains and humid Atlantic zones. *Bioresource Technology* **61**: 111–119.
- Onda Y, Dietrich WE, and Booker, F. 2008. Evolution of overland flow after severe forest fire, Point Reyes, California. *Catena* **72**: 13–20 DOI:10.1016/j.catena.2007.02.003.
- Pandey VC, Singh N. 2010. Impact of fly ash incorporation in soil systems. *Agriculture, Ecosystems and Environment* **136**: 16–27 DOI: 10.1016/j.agee.2009.11.013.
- Pausas JG. 2004. Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean Basin). *Climatic Change* **63**: 337–350 DOI: 10.1023/B:CLIM.0000018508.94901.9c.
- Pereira MG, Trigo RM, Câmara CC, Pereira JMC, Leite SM. 2005. Synoptic patterns associated with large summer forest fires in Portugal. *Agricultural and Forest Meteorology* **129**: 11–25 DOI: 10.1016/j.agrformet.2004.12.007.
- Pereira P, Bodí M, Úbeda X, Cerdà A, Mataix-Solera J, Balfour V, Woods S. 2010a. Las cenizas en el ecosistema suelo. In *Actualización en métodos y técnicas para el estudio de los suelos afectados por incendios forestales*, Cerdà A, Jordan A (eds) Càtedra de Divulgació de la Ciència: Universitat de València; 345–398.
- Pereira P, Úbeda X, Martin D. 2011a. Heavy metals released from leaf litter exposed to different fire temperatures. A laboratory experiment. *Darnus Vystymosi Strategia ir Pratica* **1**: 137–154.
- Pereira P, Cepanko V, Vaitkute D, Pundyte N, Pranskevicius M, Zuokaite E, Úbeda X, Mataix-Solera J, Cerdà A. 2012a. Grassland fire effects on ash properties and vegetation restoration in Lithuania (North-Eastern Europe). *Flamma* **3**: 3–8.
- Pereira P, Cerdà A, Úbeda X, Mataix-Solera J, Arcenegui V, Zavala L. 2013a. Modelling the impacts of wildfire on ash thickness in a short-term period. *Land Degradation and Development* DOI: 10.1002/ldr.2195.
- Pereira P, Cerdà A, Úbeda X, Mataix-Solera J, Jordan A, Burguet M. 2013b. Spatial models for monitoring the spatio-temporal evolution of ashes after fire—a case study of a burnt grassland in Lithuania. *Solid Earth*, **4**: 153–165 DOI: 10.5194/se-4-153-2013.
- Pereira P, Mataix-Solera J, Úbeda X, Cerdà A, Cepanko V, Vaitkute D, Pundyte N, Pranskevicius M, Zuokaite E. 2012b. *Spring Grassland Fire Effects on Soil Organic Matter, Soil Moisture and Soil Water Repellency in Lithuania (North-Eastern Europe)*, First results. 4th International Congress Eurosoil 2012: Bari, Italy; 1127.
- Pereira P, Oliva M, Baltreñaite E. 2010b. Modelling extreme precipitation in mountain hazard areas. A contribution to landscape planning and environmental management. *Journal of Environmental Engineering and Landscape Management* **18**: 329–342 DOI: 10.3846/jeelm.2010.38.
- Pereira P. 2010. Efeitos da intensidade de fogo nas características físico-químicas das cinzas das espécies vegetais Mediterrâneas e o seu impacto na qualidade da água. PhD thesis, University of Barcelona.
- Pereira P, Úbeda X, Martin D. 2012c. Fire severity effects on ash chemical composition and extractable elements. *Geoderma* **191**: 105–114 DOI: 10.1016/j.geoderma.2012.02.005.
- Pereira P, Úbeda X, Martin DA, Mataix-Solera J, Guerrero C. 2011b. Effects of a low prescribed fire in ash water soluble elements in a Cork Oak (*Quercus suber*) forest located in northeast of Iberian Peninsula. *Environmental Research* **111**: 237–247 DOI: 10.1016/j.envres.2010.09.002.
- Pereira P, Úbeda X, Outeiro L, Martin DA. 2009. Factor analysis applied to fire temperature effects on water quality. In *Forest Fires: Detection, Suppression and Prevention, Series Natural Disaster Research, Prediction and Mitigation*, Gomez E, Alvarez K. (eds) Chapter 9, Nova Science Publishers: New York; 273–285.
- Pereira P, Úbeda X. 2010. Efectos del fuego en la razón de adsorción de sodio (SAR) de la solución liberada por las cenizas y sus potenciales efectos en la erosión del suelo. Estudio a la escala de la microparcela. In *Advances in Spanish Geomorphology 2008–2010*, Úbeda X, Vericat D, Batalla RJ. (eds), Barcelona; 255–285.
- Pierson FB, Robichaud PR, Spaeth KE. 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrological Processes* **15**: 2905–2916.
- Plumlee GS, Martin DA, Hoefen T, Kokaly R, Hageman P, Eckberg A, Meeker GP, Adams M, Anthony M, Lamothe PJ. 2007. Preliminary analytical results for ash and burned soils from the October 2007 southern California wildfires: U.S. Geological Survey Open-File Report 2007–1407; 13.
- Ponder Jr F, Tadros M, Loewenstein EF. 2009. Microbial properties and litter and soil nutrients after two prescribed fires in developing savanas in an upland Missouri Ozark Forest. *Forest Ecology and Management* **257**: 755–763. <http://dx.doi.org/10.1016/j.foreco.2008.10.009>.
- Pöykiö R, Rönkkömäki H, Nurmesniemi H, Perämäki P, Popov K, Välimäki I, Tuomi T. 2009. Chemical and physical properties of cyclone fly ash from the grate-fired boiler incinerating forest residues at a small municipal district heating plant (6 MW). *Journal of Hazardous Materials* **162**: 1059–1064 DOI: 10.1016/j.jhazmat.2008.05.140.
- Qian Y, Miao SL, Gu B, Li YC. 2009. Estimation of postfire nutrient loss in the Florida Everglades. *Journal of Environmental Quality* **38**: 1812–1820 DOI: 10.2134/jeq2008.0391.
- Raison RJ, McGarity JW. 1980a. Effects of ash, heat and the ash-heat interaction on biological activities in two contrasting soils. *Plant and Soil* **55**: 363–379 DOI: 10.1007/BF02182697.
- Raison RJ, McGarity JW. 1980b. Some effects of plant ash on the chemical properties of soils and aqueous suspensions. *Plant and Soil* **55**: 339–352 DOI: 10.1007/BF02182695.
- Rengasamy P, Marchuk A. 2011. Cation ratio of structural stability (CROSS). *Soil Research* **49**: 280–285 <http://dx.doi.org/10.1071/SR10105>.
- Santín C, Doerr SH, Shakesby RA, Bryant R, Sheridan GJ, Lane PNJ, Smith HG, Bell TL. 2012. Carbon loads, forms and sequestration potential within ash deposits produced by wildfire: new insights from the 2009 ‘Black Saturday’ fires, Australia. *European Journal of Forest Research* **131**: 1245–1253 DOI: 10.1007/s10342-012-0595-8.
- Sarah P. 2004. Soil sodium and potassium adsorption ratio along a Mediterranean–arid transect. *Journal of Arid Environments* **59**: 731–741 DOI: 10.1016/j.jaridenv.2004.02.007.
- Scott DF. 1993. The hydrological effects of fire in South African mountain catchments. *Journal of Hydrology* **150**: 409–432 [http://dx.doi.org/10.1016/0022-1694\(93\)90119-T](http://dx.doi.org/10.1016/0022-1694(93)90119-T).
- Shapiro S, Wilk M. 1965. An analysis of variance test for normality. *Biometrika* **52**: 591–611.
- Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Haydon S. 2011a. Wildfire effects on water quality in forest catchments: a review with implications

- for water supply. *Journal of Hydrology* **396**: 170–192 DOI: 10.1016/j.jhydrol.2010.10.043.
- Smith HG, Sheridan GJ, Lane PNJ, Noske PJ, Heijnis H. 2011b. Changes to sediment sources following wildfire in a forested upland catchment, southeastern Australia. *Hydrological Processes* **25**: 2878–2889 DOI: 10.1002/hyp.8050.
- Soto B, Diaz-Fierros F. 1993. Interactions between ash leachates and soil. *International Journal of Wildland Fire* **3**: 207–216. DOI: 10.1071/WF9930207.
- Soto B, Basanta R, Diaz-Fierros F. 1997. Effects of burning on nutrient balance in a gorse (*Ulex europaeus*) scrub. *The Science of the Total Environment* **204**: 271–281. [http://dx.doi.org/10.1016/S0048-9697\(97\)00185-X](http://dx.doi.org/10.1016/S0048-9697(97)00185-X).
- Sposito G. 2000. The environmental chemistry of aluminium, 2nd ed. Lewis Publishers, Boca Raton; 331.
- Steenari BM, Lindqvist O. 1997. Stabilisation of biofuel ashes for recycling to forest soil. *Biomass and Bioenergy* **13**: 39–50.
- Stoof CR, Wesseling JG, Risema CJ. 2010. Effects of fire and ash on soil water retention. *Geoderma* **159**: 276–285 DOI: 10.1016/j.geoderma.2010.08.002.
- Thomas AD, Walsh RPD, Shakesby RA. 2000. Solutes in overland flow following fire in eucalyptus and pine forests, northern Portugal. *Hydrological Processes* **14**: 971–985 DOI: 10.1002/(SICI)1099-1085(20000415)14:5<971::AID-HYP4>3.0.CO;2-J.
- Throeh FR, Thompson LM. 2005. *Soils and Soil Fertility*, 6th ed., Blackwell Publishing: New York; 489.
- Ùbeda X, Pereira P, Outeiro L, Martin D. 2009. Effects of fire temperature on the physical and chemical characteristics of the ash from two plots of cork oak (*Quercus suber*). *Land Degradation and Development* **20**: 589–608 DOI: 10.1002/ldr.930.
- Ùbeda X, Lorca M, Outeiro LR, Bernia S, Castellnou M. 2005. Effects of prescribed fire on soil quality in Mediterranean grassland (Prades Mountains, north-east Spain). *International Journal of Wildland Fire* **14**: 379–384 <http://dx.doi.org/10.1071/WF05040>.
- Ulery AL, Graham RC, Amrhein C. 1993. Wood ash composition and soil pH following intense burning. *Soil Science* **156**: 358–364.
- Varenes A 2003. *Produtividade dos solos e Ambiente*. Escolar Editora, Lisboa
- Woods S, Balfour VN. 2008. The effect of ash on runoff and erosion after a severe forest wildfire, Montana, USA. *International Journal of Wildland Fire* **17**: 535–548 DOI: 10.1071/WF07040.
- Woods SW, Balfour VN. 2010. The effects of soil texture and ash thickness on the post-fire hydrological response from ash covered soils. *Journal of Hydrology* **393**: 274–286 DOI: 10.1016/j.jhydrol.2010.08.025.
- Zavala LM, Jordán A, Gil J, Bellifante N, Pain C. 2009. Intact ash and charred litter reduces susceptibility to rain splash erosion post-wildfire. *Earth Surface Processes and Landforms* **34**: 1522–1532 DOI: 10.1002/esp.1837.