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REGULAR ARTICLE

Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical and microbial properties in pine forests and shrubland

José A. Vega · Teresa Fontúrbel · Agustín Merino · Cristina Fernández · Andrea Ferreiro · Enrique Jiménez

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Abstract

Aims Areas affected by wildfire comprise spatially complex mosaics of burned patches in which a wide range of burn severities coexist. Rapid diagnosis of the different levels of soil burn severity and their extents is essential for designing emergency post-fire rehabilitation treatments. The main objective of this study was to determine whether visual signs of soil burn severity levels are related to changes in soil chemical and microbial properties immediately after fire.

Methods Eight areas affected by wildfires in NW Spain were selected immediately after fire, and soil chemical and biological properties (pH, extractable Ca, K, Mg and P, SOC, total N, $\delta^{13}C$, basal soil respiration, Cmic, phosphatase activity, extractable NH_4^+ and NO_3^-, ammonification and nitrification rates and potential N mineralization) were analysed in relation to five levels of soil burn severity (0: Unburned; 1: Oa layer partially or totally intact; 2: Oa layer totally charred; 3: Bare soil and soil structure unaffected; 4: Bare soil and soil structure affected; 5: Bare soil and surface soil structure and colour altered).

Results The five visually assessed levels of soil burn severity adequately reflected changes in SOC, pH, and phosphatase activity, which varied gradually with increasing soil burn severity. However, alterations in certain indicators related to the soil organic quality (C/N, Cmic/SOC, qCO_2, $\delta^{13}C$) were only detected in the most severely burned areas. Discriminant analysis revealed that the best combination of variables was acid phosphatase activity, SOC and pH, which correctly classified between 64 and 76 % of samples, depending on the levels of soil burn severity considered.

Conclusions The results showed that the proposed soil burn severity categories may be useful for indicating the degree of degradation of important soil chemical and microbiological properties in sites similar to the study area. This, in combination with other factors, will allow prioritization of areas for rehabilitation.

Keywords Wildfire · Soil burn severity · Post-fire rehabilitation criteria · pH · Soil nutrients · SOC · Acid phosphatase · Microbial biomass

Abbreviations

SOC	Soil organic carbon
BR	Basal respiration
Cmic	Microbial biomass C
qCO2	Metabolic quotient (Cmic/SOC)
ANOVA	Analysis of variance
SBS	Soil burn severity

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J. A. Vega (✉) · T. Fontúrbel · C. Fernández · E. Jiménez
Centro de Investigación Forestal. Lourizán,
Consellería do Medio Rural e do Mar. Xunta de Galicia,
P.O. Box 127, 36080 Pontevedra, Spain
e-mail: jose.antonio.vega.hidalgo@xunta.es

A. Merino · A. Ferreiro
Escuela Politécnica Superior,
University of Santiago de Compostela,
27002 Lugo, Spain

Introduction

Wildfires can significantly perturb soil properties, thus affecting plant growth which has important implication for ecosystem recovery (DeBano et al. 1998; Neary et al. 1999, 2005; Certini 2005; Cerdà and Mataix-Solera 2009). Such perturbations may enhance long-term soil degradation and consequently emergency stabilization and rehabilitation treatments are frequently required (Robichaud et al. 2000; Robichaud 2009). In this context, characterization of the level of soil perturbation in operationally useful terms is clearly essential for designing post-fire management strategies (Parsons et al. 2010). Furthermore, development of a fire severity index relevant to soil changes is considered a research priority (Shakesby and Doerr 2006). The term “soil burn severity” is often used to describe the level of alteration caused by fire in soil, although there is no single definition of the term (Keeley 2009).

Wildfires result in spatially complex mosaics of burned soil patches encompassing a wide range of soil burn severity, in which barely affected areas coexist with others highly perturbed areas. These differences are mainly attributed to the different temperatures reached in the soil and the duration of exposure (Hartford and Frandsen 1992; DeBano et al. 1998; Neary et al. 1999; Certini 2005). The spatial variability in soil burn severity is important because it may increase the diversity of post-fire processes, such as soil erosion, soil degradation, nutrient cycling, and plant regeneration. More specifically, soil burn severity is considered an essential component of any commonly used fire severity index (Ryan 2002; Neary et al. 2005; Key and Benson 2006; Jain and Graham 2007) because of its potential value as an indicator of the level of impact that fire has on the soil, and its influence on post-fire hydrological and erosive responses (Ice et al. 2004; Parsons 2003; Lewis et al. 2006). Therefore, evaluation of this parameter is a critical step in the decision making process for soil rehabilitation tasks (Jain et al. 2008; Parsons et al. 2010).

Several visual indicators of soil burn severity have been defined on the basis of the immediate changes (observed in the field) in the forest floor (level of consumption of organic layer) and mineral soil (changes in colour or structure) and the deposition of ash from the aboveground combustion of biomass after wildfire (Ryan and Noste 1985; Ulery and Graham 1993; Neary et al. 1999, 2005; Ketterings and Bingham 2000; Ryan 2002; Jain et al. 2008; Parsons et al. 2010). However, it is difficult to compare data from different environments, due to differences in vegetation type and soil properties. Jain et al. (2012) have recently reviewed the available literature and proposed an index including 12 classes for temperate forests.

Although there is abundant information about the effects of fire on the soil system, the relevant literature scarcely refers to soil burn severity, or only vague descriptions are given and based on different criteria. Moreover, the relationships between these descriptors and the associated quantitative changes in selected chemical and biological soil properties remain poorly explored.

Post-burn soil colour parameters have been used by Ketterings and Bingham (2000) to evaluate fire severity and to relate it to immediate changes in soil C, N and exchangeable elements. These authors concluded that field colour measurements are of limited usefulness for predicting soil fertility. Brais et al. (2000) used the percentage of mineral soil exposure and charred duff to evaluate the delayed effects of wildfire and salvage harvesting on several soil parameters. These authors found that slight-moderate combustion had little impact on site nutrient status, while severe combustion induced nutrient depletion.

There is broad agreement that severe fires reduce surface SOC content (e.g. Fernández et al. 1997; Mataix-Solera et al. 2002; Certini 2005; Neary et al. 2005). However, absence of any changes (Gimeno-García et al. 2000; Hatten and Zabowski 2010) or even increases (Ludwig et al. 1998) have also been reported after fires of moderate or low severity. The lack of uniformity in the response of the SOC content suggests that the relation between soil SOC consumption and soil burn severity has not been adequately defined. Decreases in C/N ratios after severe wildfire have been described (Fernández et al. 1999; Saito et al. 2007), although soil burn severity was not sufficiently characterized. Measurement of changes in the stable carbon isotope ^{13}C has also been used to explore the soil organic matter transformations caused by soil heating during wildfire (Aranibar et al. 2003; Saito et al. 2007; Certini et al. 2011) although the relationship with soil burn severity has not been addressed. Thus, changes in SOC content, C/N ratio and ^{13}C may potentially be of use as fire severity indicators, with respect to SOM degradation.

One of the most frequent fire effects reported in the literature is increased soil pH (see recent revisions by Neary et al. 2005; Certini 2005; Úbeda and Outeiro 2009). The increase was consistently higher for more pronounced soil heating (Giovannini et al. 1990; Giovannini 1994; Badía and Martí 2003). This suggests that pH may be sensitive to changes in soil burn severity.

Increases in available forms of Ca, Mg and K immediately after wildfires have been observed in many studies (e.g. Neary et al. 1999, 2005; Certini 2005), usually in relation to severe fires. No changes, or decreases, in concentration of these elements have been reported (Carreira and Niell 1992; Vose et al. 1999). Increased concentration in available P in burned soils have frequently been detected (DeBano and Klopatek 1988; Giovannini et al. 1990; Giovannini and Lucchesi 1997; Ketterings and Bingham 2000; Giardina et al. 2000; Kennard and Gholz 2001) although an absence of any changes in fires of low to moderate severity has been also observed (Saá et al. 1993). Therefore, it would be worthwhile exploring whether changes in these nutrients may provide useful information for characterizing soil burn severity.

With respect to soil microbiota, certain indicators, such as microbial C biomass (Cmic), microbial quotient (Cmic/SOC), metabolic quotient (qCO_2) and the activity of some soil enzymes also appear potentially useful, for characterizing the extent of soil perturbation in relation to fire severity (Mataix-Solera et al. 2009; Dooley and Treseder 2012). Large reductions in soil microbial respiration (Pietikäinen and Fritze 1995; D'Ascoli et al. 2005) and enzymatic activities (DeBano and Klopatek 1988; Saá et al. 1993, 1998; Serrasolsas and Khanna 1995; Boerner et al. 2000) have been reported in severely burned soils, although again different measurements of burn severity were used, making comparisons difficult. In general, the responses have not been simultaneously compared with those observed for other levels of burn severity. Moreover, after moderate or prescribed fires, variable responses have been reported, ranging from increases or no changes, to decreases in microbial populations or enzymatic activities (Andersson et al. 2004; D'Ascoli et al. 2005; De Marco et al. 2005; Mabuhay et al. 2006). Nevertheless, none of the former authors have specifically related visual signs of soil burn severity to changes in soil microbial properties.

Large increases in soil ammonium (NH_4^+) concentrations have generally been observed after severe wildfire or slash pile burning (Prieto-Fernández et al. 1993; Ellingson et al. 2000), whereas no clear pattern of response has been reported for changes in nitrate (NO_3^-) concentration. However, very few studies have related these immediate changes to soil burn severity indicators (Romanyà et al. 2001) or fire intensity (Weston and Attiwill 1990). Wan et al. (2001) summarized the available literature on the initial impact of fire on mineral forms of soil N, and concluded that in various terrestrial ecosystems soil $NH_4^+$and NO_3^- contents generally increased after burning, although specific information about the influence of burn severity was not considered. The immediate response of N mineralization following different types of fires is variable and there is not usually any clear pattern of response (see review by Smithwick et al. 2005), although again these studies did not specifically analyse the effect of fire severity.

In summary, the lack of a standard measurement of soil burn severity in previous studies makes it difficult to relate the changes in soil properties to fire severity. Moreover, some of the apparent divergent conclusions about the effects of fire on soil (e.g. Certini 2005; González-Pérez et al. 2004; Wan et al. 2001) may be due to the lack of appropriate characterization of soil burn severity during the soil sampling process. Therefore, exploration of the response of these properties to burn severity and the relationship between visual signs of burn severity and quantitative changes in selected properties is a research priority. If any such relationship exists, it would provide a very useful tool for land managers to help select and prioritize the most appropriate post-fire activities and to guide rehabilitation and restoration tasks.

In order to address the gaps in knowledge identified above, the main objective of the present study was to determine whether some proposed visual signs of soil burn severity, recognized in the field immediately after fire, are related to levels of changes in selected soil chemical and microbial properties.

Materials and methods

Study sites and sampling

The study was conducted in NW Spain, a region particularly affected by wildfires. In the period 2000–2011 approximately 10,000 wildfires occurred every year in the region, representing 47 % of all forest fires occurring annually in Spain (Ministerio de Medio Ambiente, Medio Rural y Marino 2011). Eight sites affected by five different wildfires between 2006 and 2009 were selected for study. Three wildfires (Santa María-Alba, Serra de Outes and Pardesoa) burned in areas representative of the Atlantic-climate zone of NW Spain and the other two (Ferreirós and Piñor) in a transition zone between Atlantic and Mediterranean climates. The soil humidity and temperature regimes are Udic (rainfall distributed regularly throughout the year with a 2 months period of partial drought) and Mesic (mean frost-free period, 10 months), respectively.

Four of the sites were *Pinus pinaster* stands (namely P1-P4), and the other four were shrublands (S1-S4) (Table 1).

The soils are developed from granitic rocks, schist and shale, and classified as Humic or Distric Cambisols and Alumi-humic Umbrisols (IUSS Working Group WRB 2006). The texture of all eight soils is loam or sandy loam and all are well drained.

All soils had high SOC contents (9–12 %), very low pH (3.8–4.4) and low amount of extractable base cations (0.5–1.5 $\mathrm{cmol_c/kg}$) and P (5–13 mg/kg). These values are characteristics of forest and shrubland soils developed on acid substrate of granite and schist bedrocks in Galicia.

Experimental design and measurements

Immediately after a wildfire event, a survey was conducted to confirm the availability of adjacent unburned areas. However, no similar unburned areas were found in the surrounding of two of the affected areas (P4 and S4). Between 1 and 3 days after the fires and before the first rainfall event, the approximate fire perimeter of the burned area was overlaid on a map of the area. For the wildfires affecting only shrubland vegetation (Pardesoa, Ferreirós and Piñor), a 200 m grid was overlaid on the map, and four or five randomly chosen intersection points in the grid were used to establish randomly oriented transects of length 150 m. For the large fire affecting Santa María and Alba (9,700 ha), the area covered by forest was previously delimited in an orthoimage; a grid of 1,000 m was overlaid on the map, and four or five randomly chosen intersection points in the grid were used to establish randomly oriented transects of length 150 m. Finally, for the Serra de Outes wildfire, the areas covered by shrubland, sapling and pole stands were previously delimited in an orthoimage and the same sampling scheme as above was applied. On each transect, the soil burn severity level was visually estimated, at 5 m intervals, following a modified version of Ryan and Noste's (1985) classification (Table 2), and a numerical value was assigned to each level of fire severity. Soil sampling was conducted 3–7 days after fire (Table 1) and before the first rainfall event in the area. A very short and similar interval of time between fire and sampling (with no rainfall) was selected to minimize possible changes in soil properties due to the time elapsed. The length of time between fire event and soil sampling may have a profound impact on the strength of correlation between visual assessment and underlying soil properties. At each sampling point, the type (litter, fermentation and humus), condition (unburned, charred) and the thickness of remaining soil organic layer, when present, were systematically evaluated or measured, in a 30×30 cm sampling quadrat, by two trained observers who independently classified each sampling point. The mean values for each transect and site were calculated. In the forest stands, crown length scorched and percentage of crown length scorched were obtained by measuring the corresponding distances, with a laser hypsometer, for each tree within five circles of radius 8 m. The centres of the circles were uniformly spaced along each transect and a mean value was again calculated for the site (Table 3). The percentage of bare soil was calculated from the number of samples of soil burn severity levels 3–5 relative to the total number of samples. The mean frequency of presence of the different levels of soil burn severity in each site is shown in Table 4. The levels of soil burn severity at each site were listed, and four to five surface mineral soil samples (0–5 cm) for each burn severity level were taken at random. Soil samples were selected to be analyzed at the laboratory only when observations from two independent observers agreed. In those cases where less than four soil samples per level of burn severity were available, a supplementary transect was established; the respective sampling points were classified by burn severity level, and further soil samples were collected. At each sampling point, the upper 0–5 cm of the surface mineral soil was collected in a 30×30 cm sampler. The samples were transported to the laboratory for analysis in cooler insulated containers.

Table 1 Main characteristics of the unburned study sites located in *Pinus pinaster* stands (P1 to P4) and in shrubland areas (S1 to S4)

	Santa María (P1)	Alba (P2)	Serra de Outes (Pole size stands) (P3)	Serra de Outes (Sapling size stands) (P4)	Pardesoa (S1)	Serra de Outes (S2)	Ferreirós (S3)	Piñor (S4)
Location	Pontevedra	Pontevedra	A Coruña	A Coruña	Pontevedra	A Coruña	Lugo	Ourense
	42° 27′ 50″ N	42° 29′ 16″ N	42° 50′ 57″ N	42° 50′ 7″ N	42° 30′ 23″ N	42° 50′ 34″ N	42° 36′ 36″ N	42° 31′ 25″ N
	8° 37′ 5″ W	8° 37′ 49″ W	8° 59′ 54″ W	9° 2′ 46″ W	8° 17′ 28″ W	8° 59′ 28″ W	7° 10′ 48″ W	8° 4′ 23″ W
Altitude (m a.s.l.)	175–190	125–135	124–350	240–257		252–429	753	815
Slope (%)	8–56	19–46	12–48	20–39	18–44	26–50	37–60	30–36
Aspect (° N)	NE, WSW	E, WNW	E, W	SE, SW	N	E, SE	NE	SW
Wildfire date[a]	08/4/06	08/5/06	09/14/07	09/14/07	08/8/06	09/14/07	08/24/08	09/28/09
Soil sampling date[a]	08/7–8/06	08/9–10/06	09/18–19/07	09/19–20/07	08/11–12/06	09/20–21/07	08/27–28/08	10/1–2/09
Burned area (ha)	9,700	9,700	600	600	1,040	600	66	350
Dominant vegetation	*P. pinaster*, *Ulex europaeus*, *Pteridium* sp., *Ulex minor*, *Erica umbellata*	*P. pinaster Ulex minor*, *Pteridium* sp., *Erica cinerea*, *E. umbellata*	*P. pinaster*, *Ulex europaeus*, *U. gallii*, *Erica umbellata*	*P. pinaster*, *Ulex europaeus*, *Calluna vulgaris*, *Erica umbellata*	*Ulex minor*, *Pterospartum tridentatum*, *Erica umbellata*, *Halymium alyssoides*	*Ulex europaeus*, *Ulex galli*, *Daboecia cantabrica*, *Calluna vulgaris*, *Erica umbellata*	*Erica arborea*, *Pterospartum tridentatum*, *Cytisus scoparius*, *Rubus* sp.	*Pterospartum tridentatum*, *Ulex europaeus*, *Halymium alyssoides*, *Erica umbellata*, *E.australis*
P. pinaster density (trees ha^{-1})	730	915	1,080 (314)	9,000[b] (420)				
P. pinaster diameter a.b.h. (cm)	19.6 (6.9)	15.3 (3.0)	25.2 (4.4)	3.3[b] (0.4)				
P. pinaster height (m)	13.0 (4.9)	11.0 (2.5)	14.4 (1.9)	2.7[b] (0.9)				
Shrub stratum height (cm)	28 (14)	87 (25)	158 (47)		78 (14)	122 (31)	158 (85)	
Soil organic cover depth (cm)	6.3 (0.7)	6.9 (0.7)	6.6 (0.6)		6.7 (0.8)	6.9 (0.3)	4.5 (0.4)	
Bedrock	granite	granite	granite and granodiorite	granite and granodiorite	schists	granite and granodiorite	schists	Schists

[a] Month/day/year; [b] Values of burned trees

Table 2 Soil burn severity (SBS) levels, including an unburned state, through the immediate post-fire soil and duff visual characteristics

SBS levels	Forest floor (Oi+Oe+Oa)	Mineral soil (Ah horizon)
0	No evidence of fire	No evidence of fire
1	Oa layer (lower duff) partially or totally intact.	Undisturbed
2	Oa layer totally charred and covering mineral soil. There may be ash.	Undisturbed
3	Forest floor completely consumed (bare soil). There may be ash.	Undisturbed. Soil structure unaffected. SOM not consumed. Surface fine roots not burned
4	Forest floor completely consumed (bare soil). There is no charred residue. Thick layer of ash.	Soil structure affected. SOM consumed in the upper layer. Surface soil colour altered (grey). Surface fine roots burned
5	Forest floor completely consumed (bare soil). There is no charred residue.	Soil structure affected. SOM consumed in the upper layer. Surface soil colour altered (reddish). Surface fine roots burned

Laboratory determinations

Soil samples were sieved (2 mm) immediately after arrival to the laboratory. Fresh soil samples were stored in polyethylene bags at 4 °C for no longer than 4–9 days for microbial determinations and 1–3 days for mineral N determinations. Air-dried soil samples were used for chemical analysis. In all cases, subsamples of soil were taken to determine moisture content gravimetrically (oven-dried for 24 h at 105 °C) and results were expressed on a dry soil basis. The pH value was determined in a suspension of soil in deionized water (1:2.5 *w*/*v*). Total C, N and S were analysed by dry combustion with a LECO Elemental Analyzer. Since the soil parent material at the study sites is non-calcareous, the total C corresponds to the total organic C.

Isotopic analyses were carried out at six of the eight sites, with an automated CN analyzer coupled to an isotope ratio mass spectrometer. Duplicate analyses were performed on all samples. The C isotopic composition was calculated relative to the Pee Dee Belemnite (V-PDB) standard. Stable isotope ratios of C are expressed as the ratio of heavy-to-light carbon ($^{13}C/^{12}C$), using conventional delta notation (δ^{13} C), in parts per thousand: $\delta^{13}C = 1,000\left[\left(R_{sample}/R_{standard}\right) - 1\right]$, where R_{sample} is the ratio $^{13}C/^{12}C$ in the sample and $R_{standard}$ is the ratio $^{13}C/^{12}C$ in the standard V-PDB.

Soil respiration was determined by estimation of the CO_2 emission from fresh soil samples incubated for 24 h at 22 °C in an automated impedance meter (BacTrac 4300, SY-LAB GmbH, Austria). The CO_2 output from the soil was determined by KOH absorption and subsequent changes in conductivity. Microbial biomass C (Cmic) was determined by the substrate-induced respiration (SIR) method, according to the criteria of Anderson and Domsch (1978). This technique involves the addition of glucose to a soil sample and measurement of the microbial respiratory response that occurs immediately prior to the onset of microbial growth. The initial respiratory response can be related to Cmic by the equation $y=40.04x+0.37$, where y is mg biomass C.100 g soil^{-1} and x is the substrate-induced respiration in mL CO_2.h^{-1}.100 g soil^{-1} (Anderson and Domsch 1978). This equation has been

Table 3 Mean values and standard deviations (in brackets) of soil burn severity (SBS) levels and post-fire soil organic layer depth, bare soil and characteristics of trees of the study sites for each column

	P1	P2	P3	P4	S1	S2	S3	S4
Average SBS level	2.9 (0.4)	3.4 (0.6)	2.3 (1.0)	2.7 (0.5)	4.2 (0.2)	3.2 (0.3)	2.0 (0.7)	4.0 (0.2)
Remaining organic layer depth (cm)	0.8 (0.6)	1.0 (1.0)	2.8 (1.6)	–	0.0 (0.0)	0.6 (0.1)	1.7 (0.9)	–
Percentage of bare soil (%)	72.6 (8.7)	71.8 (19.8)	38.7 (12.6)	54.9 (11.8)	87.6 (6.8)	67.6 (10.6)	28.8 (7.7)	87.44 (7.7)
Crown scorch height (cm)	11.1 (4.4)	8.5 (2.4)	13.4 (1.3)	2.5 (0.1)	–	–	–	–
Percentage of crown length scorched (%)	72 (11)	65 (20)	72 (14)	100 (0)	–	–	–	–

Table 4 Mean frequency of presence of the different soil burn severity (SBS) levels at each site

SBS level	P1	P2	P3	P4	S1	S2	S3	S4
1	10.5 (2.7)	9.7 (3.1)	32.3 (36.7)	8.1 (6.8)	6.3 (3.9)	10.0 (5.0)	53.8 (29.2)	6.3 (4.4)
2	16.9 (12.8)	18.5 (7.3)	29.0 (19.6)	37.1 (22.1)	6.3 (3.9)	22.5 (11.6)	17.5 (13.9)	6.3 (6.3)
3	47.6 (5.5)	26.6 (29.5)	16.1 (15.1)	35.5 (20.9)	6.3 (3.9)	30.0 (14.5)	12.5 (11.9)	9.4 (7.0)
4	20.2 (12.0)	19.4 (29.1)	15.3 (15.1)	12.1 (8.8)	15.0 (7.5)	18.8 (10.5)	8.8 (6.4)	35.9 (5.2)
5	4.8 (5.2)	25.8 (8.0)	7.3 (10.0)	7.3 (2.7)	66.3 (8.5)	18.8 (6.8)	7.5 (4.7)	42.1 (9.1)

successfully applied to a variety of highly organic forest soils (Anderson and Domsch 1993; Wardle 1993). Glucose was added to soil samples, to a final concentration of 5 mg glucose g^{-1} dry soil, and mixed thoroughly with the soil. The glucose concentration was determined in previous tests. The biomass specific respiration rate, also known as the metabolic quotient (qCO_2) (Anderson and Domsch 1993) was calculated by dividing the basal respiration (BR) by Cmic. The rate of microbial C biomass to SOC was also calculated.

Phosphatase activity was assayed by the method of Tabatabai (1982), modified by Trasar-Cepeda et al. (2003). The analysis involved the measurement of *p*-nitrophenol released during 30 min of incubation at 37 °C with *p*-nitrophenyl phosphate (14 mM) as substrate, buffered to sustain the reaction mixtures at pH 5.0 for the acidic soils under study (the optimum conditions were determined in preliminary tests). Acid phosphatase activity was measured as μg *p*-nitrophenol formed g^{-1} d.w.h^{-1}.

For the study of extractable soil mineral N concentrations and N mineralization rates, three study sites were considered, since logistic problems precluded conducting the respective analysis for all sites. The NH_4^+ and NO_3^- were extracted with 2 M KCl, according to Mulvaney (1996), and measured with a flux injection analyzer (FIAstar 5000, Foss Tecator, Denmark). To estimate the N aerobic mineralization capacity, duplicate soil sub-samples were adjusted to 80 % of water filled pore space and incubated at 25 °C for 10 days. The net ammonification and nitrification rates were calculated respectively as the difference between the values of NH_4^+ and NO_3^- present before and after incubation. The net mineralization rate was the sum of the ammonification and nitrification rates. To determine the N mineralization potential, the anaerobic incubation method of Waring and Bremner (1964) was used. Briefly, 5 g of soil and 12.5 ml of water were placed in a tube, sealed with a stopper, and incubated at 40 °C for 10 days. The concentrations of NH_4^+ and NO_3^- were then determined after extraction with 4 M KCl.

All results are expressed on an oven-dry soil basis.

Statistical analysis

A multifactorial ANOVA was used to test the effect on each soil parameter of two factors: soil burn severity and site. This revealed a significant qualitative interaction between these factors in most of cases. This precluded generalization of the results for all sites and severity levels. Consequently, a series of one way ANOVAs was performed for each soil parameter and for each site. Normality and homogeneity of variance assumptions were tested by the Shapiro-Wilk W-test and the Levene test, respectively. Kruskal-Wallis and Mann–Whitney U non-parametric tests were used in the event of failure of either of these tests. When the ANOVA indicated a significant difference, the Student-Newman-Keuls multiple range test was used to determine which of the means were significantly different.

The ordinary linear regression technique was used to examine the relationships between soil properties.

Discriminant analyses were performed to identify the most useful parameters for classifying burn severity classes. In the first approach, soil burn severity classes 1–5 were considered in relation to the following variables: pH, extractable K+Ca+Mg and P, SOC, N, SOC/N, basal respiration -BR-, microbial C biomass -Cmic-, Cmic/SOC, BR/Cmic and phosphatase activity. In a second version, microbial variables were excluded because they are not routinely determined in laboratory analyses. Thirdly, additional analyses were conducted (to include N mineralization data), with NO_3^- concentration and nitrification log-transformed data. In this case, the data set was reduced to 45 samples (because only three sites were studied).

Finally, another approach was used in which only three levels of soil burn severity were considered (low = 1+2, moderate = 3 and high = 4+5). Three levels may be more realistic from a practical point of view, as in the post-fire field evaluations many soil observations must be categorized and time saving is an important factor. Again, two variations were used in the analysis, one considering microbial and chemical variables and the other considering only chemical variables.

A stepwise procedure was used to retain the most significant variables for discrimination of the visual levels of soil burn severity. The Mahalanobis D^2 measure was applied to estimate the discriminant function. This procedure is based on a generalized squared Euclidean distance (which adjusts for unequal variances: Hair et al. 2005). This statistical analysis constructs a predictive model of group membership based on the observed characteristics of each sample. A cross-validation testing procedure was performed to assess the ability of the selected variables to predict soil burn severity (SBS) at the eight sites. Differences were tested with forward-entered variables using $F=3.84$ for entering and $F=2.71$ for removal. Differences were considered significant at $p=0.05$ (Hair et al. 2005). Tolerance values were examined to test for multicollinearity in the Discriminant analyses. When the values were below 0.30, the variable was excluded from the analysis.

All data were processed with SPSS v.13.0 software (SPSS 2004).

Results

Soil pH and available nutrients

At all sites, the pH increased with the level of soil burn severity (SBS) in the uppermost mineral layer (0–5 cm), (Fig. 1a). However, there were no changes in the pH of soils affected by fires of low and moderate intensity (SBS 1, 2 and 3). In the most severely burned soils (SBS 4 and 5), the pH increased by more than 1.5 units, so that the pH ranged between 5.3 and 6.3. The levels of extractable base cations (Fig. 1b) increased following the same trend as pH, with the greatest increases in the concentrations of Ca (data not shown). The extractable P generally increased with SBS (Fig. 1c), except at two sites where there was a relative decrease in P content at the highest level of soil burn severity. For the maximum burn severity (5), and coinciding with the highest pH values, the P contents of all eight soils were higher than 50 $\mathrm{mg\,kg^{-1}}$ (except P3, with values of 36 $\mathrm{mg\,kg^{-1}}$).

Soil organic C, N and C/N ratio and $\delta^{13}C$

In all eight soils the initial SOC was higher than 9 %. The SOC always decreased with fire severity (Fig. 2a). In the soils affected by moderate levels of SBS (levels 2 and 3) relative decreases of between 0 and 57 % were observed related to controls. In the most severely burned soils (level 5 of SBS), the soil lost between 54 and 86 % of the SOC, and contents as low as 2 % were recorded in some soils.

The changes in soil organic N with fire severity (Fig. 2b) followed a similar trend to SOC, although the N losses were lower for the highest level of SBS. Accordingly, the C/N ratio remained fairly constant in the soils affected by fires of low and moderate intensity. Some soils affected by moderate levels of SBS exhibited slightly higher C/N ratios. This parameter only decreased in the most severely burned soils (Fig. 2c). Thus, levels lower than 10 were recorded in 4 of the soils, reflecting the increased C loss with respect to N for high levels of burn severity.

Soil $\delta^{13}C$ values in the unburned soils varied within a narrow range of between −26.7‰ and −27.6‰ (Fig. 2d). Although the responses differed in the soils studied, a common pattern was observed. The $\delta^{13}C$ levels remained unchanged in the soils affected by low and moderate levels of SBS but increased (less negative values) in the two highest levels of fire severity (SBS 4 and 5). Nevertheless, the relative increases of between 1 and 13 %, corresponding to 0.3 and 4‰ of absolute increases, were much lower than the total SOC losses.

Soil biological properties (microbial biomass, soil respiration and acid phosphatase)

Soil basal respiration (BR) (Fig. 3a) and microbial biomass C (Cmic) (Fig. 3b) decreased greatly, and the effect was proportional to the SBS. In the most severely burned soils (level 5), the Cmic decreased by between 48 and 93 %. Soil respiration followed a similar trend, with decreases of between 39 and 83 %.

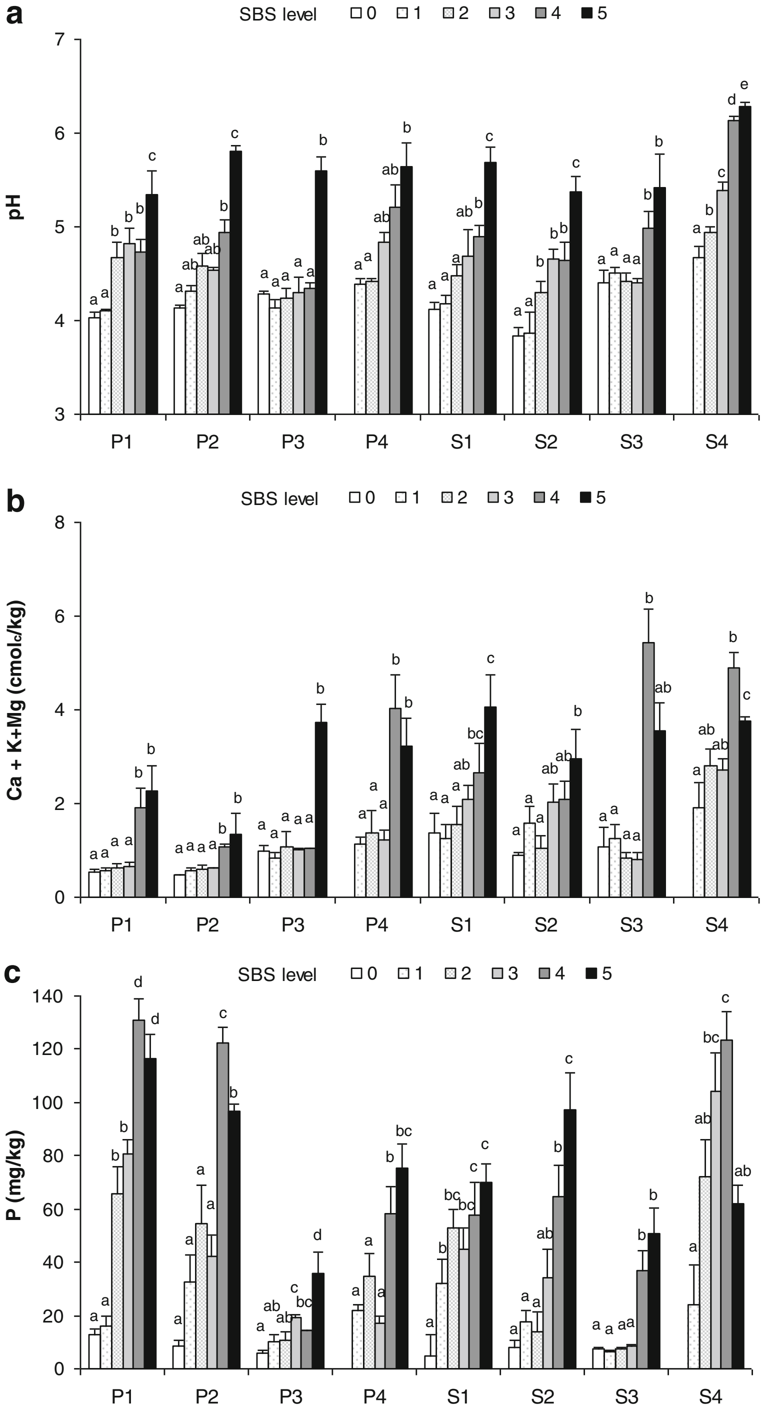

Fig. 1 **a** Soil pH, **b** extractable soil nutrients (sum of Ca, K, Mg; cmol$_c$/kg and **c** extractable P; mg/kg) for different soil burn severity (SBS) levels at each study site. *Bars* represent standard errors. *Different letters* indicate significant differences ($p<0.05$) among SBS level at each study site

However, the changes in Cmic/SOC (Fig. 3c) were rather different. For low-moderate levels of SBS (2 and 3), Cmic/SOC was not affected in any of the soils from the eight sites. Although the response was rather variable, large decreases were observed in soils affected by the highest SBS level, with relative decreases as high as 82 % for site S1.

The metabolic quotient (qCO_2) (Fig. 3d), followed a similar trend; it was rather constant for low and moderate burn severities, and in certain soils

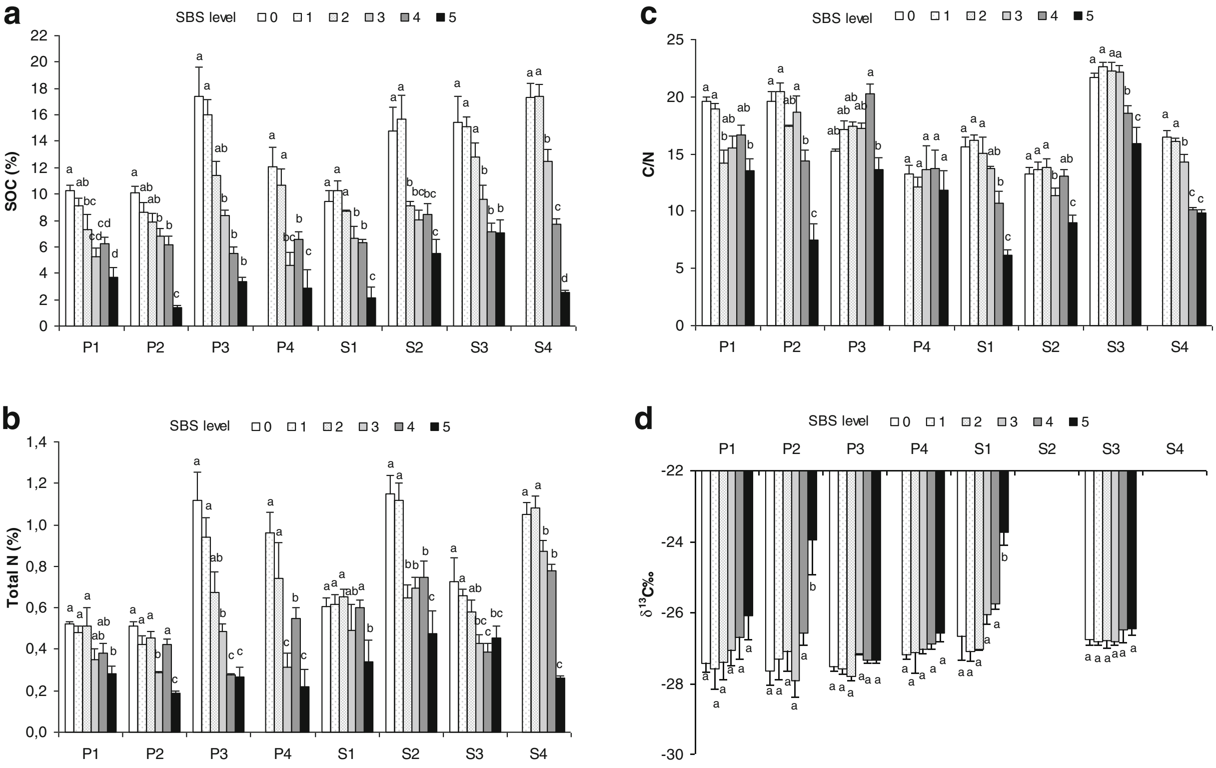

Fig. 2 **a** Soil organic Carbon (SOC), **b** total N, **c** C/N rate and **d** δ^{13} C values for different soil burn severity (SBS) levels at each study site. *Bars* represent standard errors. *Different letters* indicate significant differences ($p<0.05$) among SBS level at each study site

(coinciding with the lower Cmic/SOC) increased greatly (up to 5 times the values in the unburned soils) in soils affected by the highest level of SBS (5).

Unlike these parameters, phosphatase activity (Fig. 3e) decreased gradually from a moderate level of SBS (2) upwards. Decreases of between 67 and 99 % were recorded in the highest SBS level (5).

Mineral N and N-transformations

The concentration of NH_4^+ in soil increased with fire severity (Fig. 4a). NO_3^- (Fig. 4b), occurred at much lower concentrations than NH_4^+ and showed little response to fire severity. Coinciding with the increases in NH_4^+, the ammonification rates (Fig. 4c) decreased and reached negative values (immobilization) at the highest levels of burn severity. Nitrification rates (Fig. 4d) were low and the changes in relation to fire severity were not clear. The N mineralization rates (ammonification plus nitrification) also decreased with fire severity (Fig. 4e) and the greatest effect was observed for the three highest levels of burn severity, in which immobilization was detected. The potential mineralization (Fig. 4f) increased with fire severity in the three sites studied.

Stepwise discriminant analysis

The first discriminant analysis (Model 1), including the five burn severity classes and all microbial and chemical variables (with the exception of δ^{13}C and mineral N) showed that phosphatase activity, pH and SOC was the best combination of variables to discriminate the different levels of severity observed in the field. Three functions, which explained respectively 96 %, 3 % and 1 % of the total variability, were obtained. The standardized discriminant function coefficients (Table 5) indicate a slightly greater contribution of phosphatase activity in the model. The analysis correctly classified 64 % of the samples. The percentage of agreement ranged from 55 % for level 3 to 74 % for level 1 (Table 6). When the microbial variables were excluded (Model 2), two functions were obtained (Table 5). SOC and pH were the variables selected and

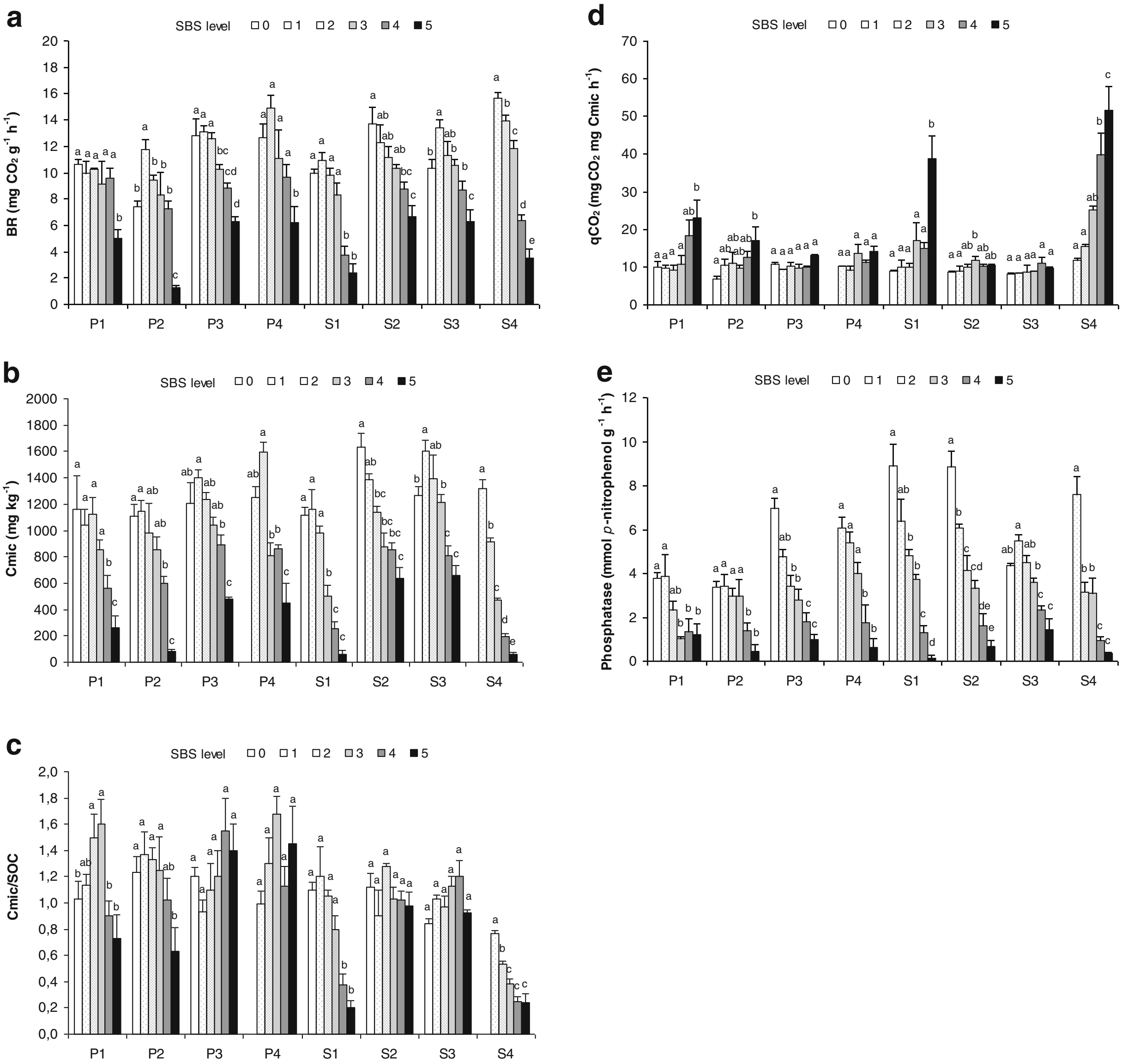

Fig. 3 **a** Basal respiration (BR), **b** microbial biomass C (Cmic), **c** Cmic/SOC rate, **d** metabolic quotient (qCO_2; BR/Cmic) and **e** acid phosphatase activity for different soil burn severity (SBS) levels at each study site. *Bars* represent standard errors. *Different letters* indicate significant differences ($p<0.05$) among SBS level at each study site

51 % of the samples were correctly classified. The analysis including N mineralization data did not improve the accuracy of these results.

When three levels of burn severity classes (1+2 = low, 3 = moderate and 4+5 = high) were taken into account in the discriminant analysis (Model 3) and microbial and chemical variables were considered (with the exception of $\delta^{13}C$ and mineral N), phosphatase activity, pH and SOC were again selected. Two functions, which explained respectively 97 and 3 % of the variance, were obtained. The standardized discriminant function coefficients (Table 5) showed similar values to those obtained in model 1. This analysis correctly classified 76 % of the samples. The highest percentage of misclassification occurred in relation to the highest level of burn severity (Table 7). The function obtained misclassified these samples (SBS 3) and included them in the moderate level of burn severity (SBS 2) in 26 % of instances. Finally, when the microbial variables were not included, SOC, pH and the sum of

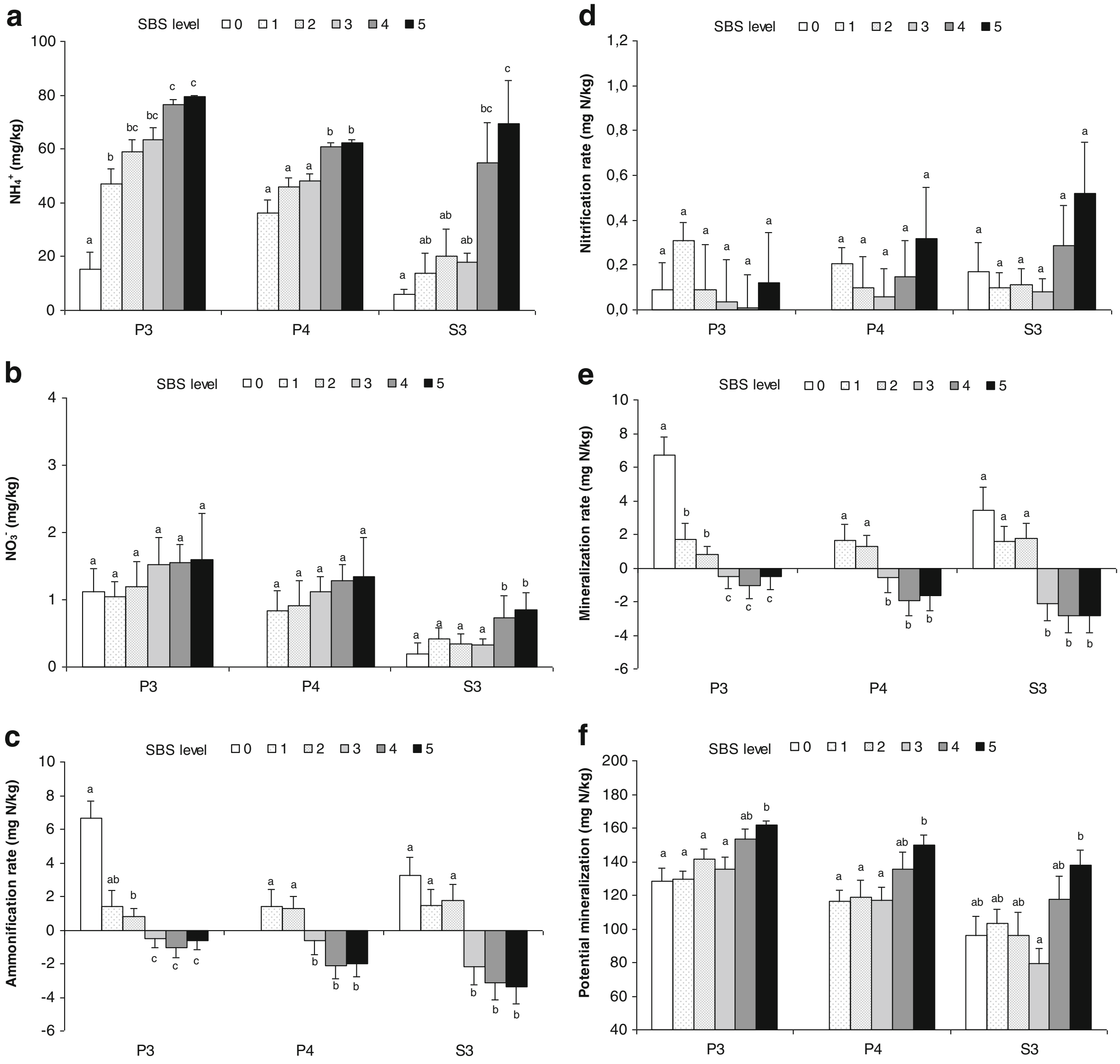

Fig. 4 **a** Concentration of ammonium (NH4+) and **b** nitrate (NO3−), **c** ammonification rate, **d** nitrification rate, **e** mineralization rate and **e** potential mineralization, for each soil burn severity (SBS) level at each study site. *Bars* represent standard errors. *Different letters* indicate significant differences ($p<0.05$) among SBS level at each study site

extractable Ca+K+Mg were selected by the discriminant analysis 70 % of the samples were correctly classified. In this case, the standardized discriminant function coefficients (Table 5) indicated a greater contribution of SOC in the model and 70 % of the samples were correctly classified. The highest rate of misclassified samples (33 %) was obtained for burn severity level 3.

Discussion

Soil chemical properties

The progressive increase in soil pH with soil burn severity appears consistent with the response to elevated soil temperatures frequently observed in laboratory experiments (Giovannini 1994; DeBano et al.

Table 5 Standardized discriminant function coefficients, resulting from a stepwise discriminant analysis performed on five (Model 1 and 2) and three (Model 3 and 4) levels of soil burn severity with both chemical and microbial variables (Model 1 and 3) and chemical variables only (Model 2 and 4)

	Model 1			Model 2		Model 3		Model 4	
	Function			Function		Function		Function	
	1	2	3	1	2	1	2	1	2
SOC	0.49	−0.41	0.82	0.73	0.69	0.45	0.70	−0.77	0.51
pH	−0.47	0.70	0.56	−0.70	0.72	−0.42	0.82	0.43	0.18
PHO[a]	0.57	0.84	−0.26			0.54	0.01		
CAT[b]								0.35	0.67

[a] PHO: acid phosphatase activity

[b] CAT: sum of extractable Ca, K, Mg

1998; Hatten and Zabowski 2010), and in the few field studies in which fire severity was measured (Kennard and Gholz 2001; Goforth et al. 2005).

The highest concentrations of cations were generally associated with the highest levels of burn severity, although the response was rather heterogeneous in the different soils. This was observed even though soil samples were collected immediately after the fire and before any rainfall, in order to minimize any possible effects of loss of ashes by wind and to avoid leaching of cations through rainfall. Other authors did not find any variations in soil extractable cations immediately after experimental fires (Johnston and Elliott 1998; Vose et al. 1999) or few months after (Marion et al. 1991) linked to fire severity. The mineral ash characteristics might influence the observed variability, because its composition may broadly vary between fires as a complex function of the initial composition of fuel, its consumption, temperature regime during burning, oxygen supply level and other still unknow factors (Khanna and Raison 1986; Úbeda et al. 2009; Pereira and Úbeda 2010; Pereira et al. 2012). The relative decrease in P content in relation to the highest SBS (level 5) in two of the soils (P2 and S4) may be due to the strong binding of P forms by chemisorption to Al, Fe and Mn oxides (Certini 2005) or to the formation of Ca phosphates (Giovannini et al. 1990). In fact, Saá et al. (1993) described an increase in the fractions of P bound to Fe and Al in severely burned soils in the region. Although P volatilization may also have occurred in some of these soils, this does not appear to be a major mechanism in the present study, given the relatively high volatilization temperature (700 °C) of this element (DeBano et al. 1998; Neary et al. 2005),

Soil organic C, N and C/N ratio and δ^{13} C

The gradual decrease in SOC with soil burn severity observed in this study may have been favoured by the relatively high SOC contents of the soils. This response contrasts with that frequently observed after wildfires in drier Mediterranean-type soils with lower initial SOC (Almendros et al. 1988, 1990; Gimeno-García et al. 2000). Decreases only for the most severe fires have been observed in field (Kutiel and Naveh 1987; Tomkins et al. 1991; Kennard and Gholz; 2001; Goforth et al. 2005) and

Table 6 Classification accuracies of the stepwise discriminant functions performed on five soil burn severity (SBS) levels including chemical and microbial variables. Values are the percentage classification

	SBS level	Predicted group membership				
		1	2	3	4	5
Original group	1	**74.3**	22.9	2.9	0	0
	2	14.3	**64.3**	17.9	3.6	0
	3	3.2	19.4	**54.8**	22.6	0
	4	0	2.8	16.7	**58.3**	22.2
	5	0	0	0	32.3	**67.7**

Values shown in **bold type** represent correct assignments

Table 7 Classification accuracies of the stepwise discriminant functions performed on three soil burn severity (SBS) levels, including chemical and microbial variables. Values are the percentage classification

		Predicted group membership		
	SBS level	1	2	3
Original group	1	**77.0**	23.0	0
	2	11.4	**80.0**	8.6
	3	0	26.2	**73.8**

Values shown in **bold type** represent correct assignments.

laboratory experiments (Hatten and Zabowski 2010: Fontúrbel et al. 2011).

The significant depletion in organic N with fire severity is consistent with that frequently observed in burned soils, especially after very severe fires (Ellingson et al. 2000; Certini 2005). The present results are also consistent with the results of meta-analysis, which did not reveal any changes in total N concentration after fires of low severity (Wan et al. 2001; Nave et al. 2011).

The decrease in C/N ratios observed only in the most severely burned soils agrees with the findings reported by Fernández et al. (1999) for similar types of soil affected by severe wildfires. This is also consistent with a higher rate of C loss with respect to N observed after wildfires (Johnson et al. 2004). The slight increases in C/N found in some soils subjected to moderate levels of SBS may reflect the accumulation of recalcitrant organic forms in charred material (Knicker et al. 2005).

The δ^{13}C values in the unburned soils are in accordance with those observed for forest soils in the region (−27.0‰±0.2‰; Fernández et al. 2004). The increases in δ^{13}C found only in the most severely burned soils might reflect the preferential volatilization of the lighter isotope at such high temperatures (Saito et al. 2007). An alternative explanation is that there is not discrimination at all due to burning and the level of organic C is not interfering the mass spectrometry analysis. Anyway, the response of stable isotope signature of SOM to fire is still a matter of debate (Certini et al. 2011). The absence of changes in δ^{13}C for low severity burned soils agrees with that observed in wildfires by Saito et al. (2007) and Certini et al. (2011) where not significant changes in SOC content were also detected. Therefore, our results suggest that δ^{13}C is unlikely that it would be an adequate indicator to discriminate soil burn severity levels.

Soil biological properties (microbial biomass, soil respiration and phosphatase activity)

The Cmic clearly responded to burn severity, in contrast to previous observations of no notable changes in soils affected by fires of low severity (Fontúrbel et al. 2012). Post-fire decreases in Cmic have been also observed after very severe fires by Prieto-Fernández et al. (1998) and Andersson et al. (2004) and attributed to direct heat-induced microbial mortality and lack of a C source (Choromanska and DeLuca 2001; Andersson et al. 2004; Hart et al. 2005; Díaz-Raviña et al. 2012). The slight increases in Cmic and BR, distinguished for low levels of burn severity, were consistent with other results observed in fires of low-moderate intensity (Andersson et al. 2004; D’Ascoli et al. 2005; Hatten and Zabowski 2010).

Interestingly, the decrease in Cmic/SOC and BR, and the increases in qCO_2, only found in the most severely burned soils, suggest that soil microbial growth was limited only at these levels of SBS. This may be due to the lack of the most labile C fractions and the macromolecular condensation of organic compounds conferring resistance to microbial attack (Almendros et al. 1988, 1990; González-Pérez et al. 2004). In addition, soil biota may also be negatively affected by certain organic pollutants (Kim et al. 2003) and heavy metals (Pereira and Úbeda 2010) produced by the combustion process.

The observed decrease in soil acid phosphatase activity in fires of moderate and high levels of SBS is consistent with results reported for severe wildfires (Saá et al. 1993; Hernández et al. 1997) and experimental soil heating (Serrasolsas and Khanna 1995), and which were attributed to thermal denaturalization, SOM alterations, microbial biomass losses and increased inorganic P (Saá et al. 1993; Hernández et al. 1997). Conversely, after low-severity prescribed fire in shrubland, the enzyme activity was only slightly reduced or not affected, which was attributed to a low level of soil heating (Saá et al. 1993; Boerner et al. 2000).

Mineral N and N-transformations

The increase in NH_4^+ with soil burn severity is consistent with that found immediately after severe fire (e.g. Andreu et al. 1996; Romanyà et al. 2001; Notario del Pino et al. 2008), and with the minor changes observed after low intensity fires in shrubland (Díaz-Fierros et al. 1990; Carreira and Niell 1995).

The lack of any immediate post-fire response in NO_3^- concentration to burn severity agrees with the findings of other field studies (e.g. Weston and Attiwill 1990; Knoepp and Swank 1993). Although other authors have reported increases in nitrate in relation to fire severity (Romanyà et al. 2001), such changes were more dependent on the type of vegetation than on fire severity.

The observed decrease in ammonification and N-mineralization rates with fire severity is consistent with that observed by Romanyà et al. (2001) in experimentally burned grasslands. Fernández et al. (2009) observed that fire severity had a negative effect on net N-mineralization after slash burning in similar types of soils. However, increases in N-mineralization have also been reported after severe fires in shrubland (Romanyà et al. 2001). The low but highly variable levels of nitrification measured in this study probably made it impossible to distinguish between levels of fire severity. Knoepp and Swank (1993) also did not find any response of nitrification to fire severity in field experiments.

The increase in anaerobic mineralization in relation to the highest levels of burn severity is consistent with that observed by Weston and Attiwill (1990), Choromanska and DeLuca (2001).

Statistical evaluation of soil burn severity classes

In the previous ANOVA, the three variables selected by the first (including 5 levels of SBS) and third (including 3 levels of SBS) discriminant models had already shown a response to soil burn severity, suggesting that these were more suitable that the other parameters as regards reflecting different levels of perturbation in soil, compared with the rest of parameters explored. The percentages of correctly classified samples obtained with these models are similar to those reported by Brais et al. (2000), who found that use of thickness of the L horizon and the pH of the forest floor correct classification of 87 % of cases. Note that these authors only considered two levels of burn severity (slight/moderate and severe), and for the highest level of burn severity, the forest floor was still partially present. This was different from the present study, in which bare soil was present in 52 % of samples. Lewis et al. (2006), who considered three levels of burn severity and used percentage of litter cover and exposed mineral soil for classifying variables, obtained an overall agreement of 56 %. The above findings suggest a tendency for the percentage of correctly classified soil samples to increase when the number of soil burn severity levels decreases. However, in the present study, although the overall agreement with the field classes was apparently higher when three levels of burn severity were considered, detailed scrutiny of the data revealed that 26 % of the most severely burned samples were classified by the discriminant analysis as moderately burned samples. This partly limits the applicability of this approach. In contrast, when five levels were considered, the percentage of misclassified samples, which changed from the highest (4 and 5) to moderate severity levels (2 and 3), was relatively low (19 %). Moreover, misclassifications between severity levels 4 and 5 are not problematic from a practical point of view, as this would not appreciably affect the selection of high priority areas for rehabilitation.

Another approach to fire severity evaluation, based only on the degree of consumption of plants (Notario del Pino et al. 2008), failed to classify moderately burned soil samples, characterized by the concentration of water-soluble nutrients, whereas very severe fires were consistent with high levels of changes in those chemical variables.

Usefulness of visual indicators of soil burn severity for management of burned areas

The availability of a relatively simple and rapid field tool for evaluating the degree of soil burn severity is critical for post-fire management decision making processes. Such information is particularly necessary in fire-prone environments under rainy climate and steep terrain, where the hydrological and erosive impact following fire is more pronounced and also where post-fire salvage logging effects may be magnified by soil burn severity.

The proposed visual classification system appears applicable to temperate climate areas in both forests and shublands. While the system based on three levels of severity is apparently more practical, it may result in more samples being misclassified (as regards the highest levels of burn severity) than with the system based on five levels. The latter system is currently used in Galicia, after by trained staff, as an operational tool for the assessment of the impact caused by wildfires and the selection of the priority areas for rehabilitation treatments.

Conclusions

The study demonstrated that the proposed soil burn severity categories, based on visual signs, are useful for inferring the degree of degradation of important soil chemical and microbiological properties, reflecting the changes in soil quality in burned soils. Furthermore, the results showed reasonably good agreement between those levels, based on visual signs, and those indicated by changes in relevant chemical and microbial properties. These findings may also help in the development of future better tools based on more refined indicators for evaluating soil burn severity. Further research should be addressed to test the suitability of soil burn severity indicators to reflect gradual changes in physical soil variables, given the critical role played by these variables in post-fire soil erosion susceptibility and in the selection of appropriate rehabilitation treatments.

The present study focused on soils in a humid temperate climate and in Atlantic-Mediterranean climate transitional zones. Although the relation between burn severity and soil properties found in the present study may be similar in other climates, specific characterization of the soil properties associated with visually recognizable soil burn severity classes should be carried out for different ecosystems.

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References

Almendros G, Martin F, González-Vila FJ (1988) Effects of fire on humic and lipid fractions in a dystric xerochrept in Spain. Geoderma 42:115–127

Almendros G, González-Vila FJ, Martin F (1990) Fire-induced transformation of soil organic matter from an oak forest: an experimental approach to the effects of fire on humic substances. Soil Sci 149:150–168

Anderson JPE, Domsch KH (1978) A physiological method for the quantitative measurement of microbial biomass in soil. Soil Biol Biochem 10:215–221

Anderson JPE, Domsch KH (1993) The metabolic quotient for CO_2 (qCO_2) as a specific activity parameter to assess the effects of environmental conditions, such as pH, on the microbial biomass of forest soils. Soil Biol Biochem 25:393–395

Andersson MA, Michelsen M, Jensen Kjoller A (2004) Tropical savannah woodland: effects of experimental fire on soil microorganisms and soil emissions of carbon dioxide. Soil Biol Biochem 36:849–858

Andreu V, Rubio JL, Corteza J, Cerni R (1996) Postfire effects on soil properties and nutrients losses. Int J Wildland Fire 6:53–58

Aranibar JN, Mack SA, Anderso IC, Potgieter ALF, Sowry R, Schugart HH (2003) Nutrient cycling responses to fire frequency in the Kruger National Park (South Africa) as indicated by stable isotope analysis. Isotopes Environ Health Stud 39:141–158

Badía D, Martí C (2003) Plant ash and heat intensity effects on chemical and physical properties of two contrasting soils. Arid Land Res Manag 17:23–41

Boerner REJ, Decker KLM, Sutherland EK (2000) Prescribed burning effects on soil enzyme activity in a southern Ohio hardwood forest: a landscape-scale analysis. Soil Biol Biochem 32:899–908

Brais S, Paré D, Ouimet R (2000) Impacts of wildfire severity and salvage harvesting on the nutrient balance of jack pine and black spruce boreal stands. For Ecol Manag 137:231–243

Carreira JA, Niell FX (1992) Plant nutrient changes in a semiarid Mediterranean shrubland after fire. J Veget Sci 3:457–466

Carreira JA, Niell FX (1995) Mobilization of nutrients by fire in a semiarid gorse-shrubland ecosystem of Southern Spain. Arid Soil Res Rehabil 9:73–89

Cerdà A, Mataix-Solera J (2009) Efectos de los incendios forestales sobre los suelos en España. El estado de la cuestión visto por los científicos españoles. Càtedra de Divulgació de la Ciència. Universitat de Valencia

Certini G (2005) Effects of fire on properties of forest soil: a review. Oecologia 143:1–10

Certini G, Nocentini C, Knicker H, Arfaioli P, Rumpel C (2011) Wildfire effects on soil organic matter quantity and quality in two fire-prone Mediterranean pine forests. Geoderma 167–168:148–155

Choromanska U, DeLuca TH (2001) Prescribed fire alters the impact of wildfire on soil biochemical properties in a Ponderosa pine forest. Soil Sci Soc Am J 65:232–238

D'Ascoli R, Rutigliano FA, DePascuale RA, Gentile A, Virzo De Santo A (2005) Functional diversity of the microbial community in Mediterranean maquis soils as affected by fires. Int J Wildland Fire 14:355–363

DeBano LF, Klopatek JM (1988) Phosphorus dynamics of pinyon-juniper soils following simulated burning. Soil Sci Soc Am J 52: 271–277. USDA For Serv Gen Tech Rep RM-149, pp 157–160

DeBano LF, Neary DG, Ffolliott PF (1998) Fire's effects on ecosystems. Wiley, New York, 333 p

De Marco A, Gentile AE, Arena C, De Santo AV (2005) Organic matter, nutrient content and biological activity in burned and unburned soils of a Mediterranean maquis area of southern Italy. Int J Wildland Fire 14:365–377

Díaz-Fierros F, Benito E, Vega JA, Castelao A, Soto B, Pérez R, Taboada T (1990) Solute loss and soil erosion in burnt soils from Galicia (NW Spain). In: Goldammer JG, Jenkins MJ (eds) Fire and ecosystem dynamics. SPB Academic Publishing, The Hague, pp 103–116

Díaz-Raviña M, Martín A, Barreiro A, Lombao A, Iglesias L, Díaz-Fierros F, Carballas T (2012) Mulching and seeding treatments for post-fire stabilisation in N.W. Spain: short-term effects and effectiveness. Geoderma 191:31–39

Dooley SR, Treseder KK (2012) The effect of fire on microbial biomass: a meta-analysis of field studies. Biogeochem 109:49–61

Ellingson LJ, Kauffman JB, Cummings DL (2000) Soil N dynamics associated with deforestation, biomass, burning, and pasture conversion in a Mexican tropical dry forest. For Ecol Manag 137:41–51

Fernández I, Cabaneiro A, Carballas T (1997) Organic matter changes immediately after a wildfire in an Atlantic forest soil and comparison with laboratory soil heating. Soil Biol Biochem 29:1–11

Fernández I, Cabaneiro A, Carballas T (1999) Carbon mineralization dynamics in soils after wildfires in two Galician forests. Soil Biol Biochem 31:1853–1865

Fernández I, Pérez-Ventura L, González-Prieto S, Cabaneiro A (2004) Soil δ13 C and δ15 N as a good indicator for predicting the site index of Galician pine forests (Pinus pinaster Ait and Pinus sylvestris L). Invest Agrar: Sist Recur For 15:3–13

Fernández C, Vega JA, Bará S, Beloso C, Alonso M, Fonturbel T (2009) Nitrogen mineralization after clearcutting and residue managementin a second rotation *Eucalyptus globulus* Labill. stand in Galicia (NW Spain). Ann For Sci 66:807

Fontúrbel MT, Vega JA, Pérez-Gorostiaga P, Fernández C, Alonso M, Cuiñas P, Jiménez E (2011) Effects of soil burn severity on germination and initial establishment of maritime pine seedlings, under greenhouse conditions, in two contrasting experimentally burned soils. Int J Wildland Fire 20:209–222

Fontúrbel MT, Barreiro A, Vega JA, Martín A, Jiménez E, Carballas T, Fernández C, Díaz-Raviña M (2012) Effects of an experimental fire and post-fire stabilisation treatments on soil microbial communities. Geoderma 191:51–60

Giardina CP, Sanford RL Jr, Dockersmith IC (2000) Changes in soil P and N during slash-and-burn clearing of a dry tropical forest. Soil Sci Soc Am J 64:399–405

Gimeno-García E, Andreu V, Rubio JL (2000) Changes in organic matter, nitrogen, phosphorus and cations as a result of fire and water erosion in a Mediterranean landscape. Eur J Soil Sci 51:201–210

Giovannini G (1994) The effect of fire on soil quality. In: Sala M, Rubio JL (eds) Soil erosion and degradation as a consequence of forest fires. Geoforma Ediciones, Logroño, pp 15–27

Giovannini G, Lucchesi S (1997) Modificatons induced in soil physico-chemical parameters by experimental fires at different intensities. Soil Sci 162:479–486

Giovannini G, Lucchesi S, Giachetti M (1990) Effects of heating on chemical parameters related to soil fertility and plant growth. Soil Sci 149:344–350

Goforth BR, Graham RC, Hubbert KR, Zanner CW, Minnich RA (2005) Spatial distribution and properties of ash and thermally altered soils after high-severity forest fire, Southern California. Int J Wildland Fire 14:343–354

González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter: a review. Environ Internat 30:855–870

Hair JF, William CB, Barry B, Ralph EA, Ronald LT (2005) Multivariate data analysis, 6th edn. Prentice Hall, Upper Saddle River

Hart SC, Deluca TH, Newman GS, Mackenzie DM, Boyle SI (2005) Post-fire vegetative dynamics as drivers of microbial community structure and function in forest soils. For Ecol Manag 220:166–184

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). Int J Wildland Fire 2:139–144

Hatten JA, Zabowski D (2010) Fire severity effects on soil organic matter from a ponderosa pine forest: a laboratory study. Int J Wildland Fire 19:613–623

Hernández T, García C, Reinhardt I (1997) Short-term effect of wildfire on the chemical, biochemical, and microbiological properties of Mediterranean pine forest soils. Biol Fert Soils 25:109–116

Ice GG, Neary DG, Adams PW (2004) Effects of wildfire on soils and watershed processes. J Forest 102:6–20

IUSS Working Group WRB (2006) World reference base for soil resources (2006) World Soil Resources Reports No 103 FAO, Rome

Jain TB, Graham RT (2007) The relation between tree burn severity and forest structure in the Rocky Mountains. In: Powers RF (technical editor). Restoring fire-adapted ecosystems: proceedings of the 2005 National Silviculture Workshop. pp 213–250. General Technical Report PSWGTR-203. USDA Forest Service, Albany, California, USA

Jain TB, Gould WA, Graham RT, Pilliod DS, Lentile LB, González G (2008) A soil burn severity index for understanding soil-fire relations in tropical forests. Ambio: J Hum Environ 37:563–568

Jain TB, Pilliod DS, Graham RT, Lentile LB, Sandquist JE (2012) Index for characterizing post-fire soil environments in temperate coniferous forests. Forests 3:445–466. doi:10.3390/f3030445

Johnson DW, Susfalk RB, Caldwell TG, Murphy JD, Miller WW, Walker RF (2004) Fire effects on carbon and nitrogen budgets in forests. Water Air Soil Pollut Focus 4:263–275

Johnston M, Elliott J (1998) The effect of fire severity on ash, and plant and soil nutrient levels following experimental burning in a boreal mixedwood stand. Can J Soil Sci 78:35–44

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

Kennard DK, Gholz HL (2001) Effects of high- and low-intensity fires on soil properties and plant growth in a Bolivian dry forest. Plant Soil 234:119–129

Ketterings QM, Bingham JM (2000) Soil color as an indicator of slash-and-burn severity and soil fertility in Sumatra, Indonesia. Soil Sci Soc Am J 64:1826–1833

Key CH, Benson NC (2006) Landscape Assessment: Ground measure of severity, the Composite Burn Index, and Remote sensing of severity, the Normalized Burn Ratio FIREMON: Fire Effects Monitoring and Inventory System. In: Lutes DC, Keane RE, Caratti JF et al (eds) Ogden, UT, USDA For. Serv., Rocky Mountain Research Station, Gen Tech Rep RMRS-GTR-164

Khanna PK, Raison RJ (1986) Effect of fire intensity on solution chemistry of surface soil under a *Eucalyptus pauciflora* forest. Aust J Soil Res 24:423–434

Kim EJ, Oh JE, Chang YS (2003) Effects of forest fire on the level and distribution of PCDD/Fs and PAHs in soil. Sci Total Environ 311(1–3):177–189

Knicker H, González-Vila FJ, Polvillo O, González JA, Almendros G (2005) Fire-induced transformation of C- and N forms in different organic soil fractions from a dystric cambisol under a Mediterranean pine forest (*Pinus pinaster*). Soil Biol Biochem 37:701–718

Knoepp JD, Swank WT (1993) Site preparation burning to improve southern Appalachian pine-hardwood stands: N responses in soil, soil water, and streams. Can J For Res 23:2263–2270

Kutiel P, Naveh Z (1987) Effect of fire on nutrients in a pine forest soil. Plant Soil 104:269–274

Lewis SA, Wu JQ, Robichaud PR (2006) Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. Hydrol Proced 20:1–16

Ludwig B, Khanna PK, Raison RI, Iacobsen KL (1998) Modelling cation composition of soil extracts under ashbeds following an intense slashfire in a eucalypt forest. For Ecol Manag 103:9–20

Mabuhay JA, Nakagoshi N, Isagi Y (2006) Soil microbial biomass, abundance, and diversity in a Japanese red pine forest: first year after fire. J For Res 11:165–173

Marion GM, Moreno JM, Oechel WC (1991) Fire severity, ash deposition and cliping effects on soil nutrients in chaparral. Soil Sci Soc Am J 55:235–240

Mataix-Solera J, Gómez I, Navarro-Pedreño J, Guerrero C, Moral R (2002) Soil organic matter and aggregates affected by wildfire in a *Pinus halepensis* forest in a Mediterranean environment. Int J Wildland Fire 11:107–114

Mataix-Solera J, Guerrero C, García-Orenes F, Bárcenas G, Torres P (2009) Forest fire effects on soil microbiology In: Fire effects on soils and restoration strategies enfield. New Hampshire, Estados Unidos Science Publisher pp 133–175

Ministerio de Medio Ambiente, Medio Rural y Marino (2011) Los incendios forestales en España: Decenio 2001–2010 (Madrid, Spain)

Mulvaney RL (1996) Nitrogen-inorganic forms. In: Sparks DL (ed) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America, Madison, p 1390

Nave LE, Vance ED, Swanston CW, Curtis PS (2011) Fire effects on temperate forest soil C and N storage. Ecol Appl 21:1189–1201

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. For Ecol Manag 122:51–71

Neary DG, Ryan KC, DeBano LF (2005) Wildland fire in ecosystems Effects of fire on soil and water. USDA Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-42-vol 4, Ogden, UT

Notario del Pino J, Dorta Almenar I, Rodríguez Rodríguez A, Arbelo Rodríguez C, Navarro Rivero FJ, Mora Hernández JL, Armas Herrera CM, Guerra García JA (2008) Analysis of the 1:5 soil:water extract in burnt soils to evaluate fire severity. Catena 74:246–255

Parsons A (2003) Burned Area Emergency Rehabilitation (BAER) soil burn severity definitions and mapping guidelines Draft. USDA Forest Service, Rocky Mountain Research Station, Missoula

Parsons A, Robichaud P, Lewis S, Napper C, Clark J (2010) Field guide for mapping post-fire soil burn severity. USDA For Serv Gen Tech Rep RMRS-GTR-243

Pereira P, Úbeda X (2010) Spatial distribution of heavy metals released from ashes after a wildfire. J Environ Eng Landsc Manag 18:13–22

Pereira P, Úbeda X, Martin D (2012) Fire severity effects on ash chemical composition and water-extractable elements. Geoderma 191:105–114

Pietikäinen J, Fritze H (1995) Clear-cutting and prescribed burning in coniferous forests: comparison of effects on soil fungal and total microbial biomass, respiration and nitrification. Soil Biol Biochem 27:229–240

Prieto-Fernández A, Villar MC, Carballas M, Carballas T (1993) Short-term effects of a wildfire in the nitrogen status and its mineralization kinetics in an Atlantic forest soil. Soil Biol Biochem 25:1657–1664

Prieto-Fernández A, Acea MJ, Carballas T (1998) Soil microbial and extractable C and N after wildfire. Biol Fert Soils 27:132–142

Robichaud PR (2009) Post-fire stabilization and rehabilitation. In: Cerdá A, Robichaud PR (eds) Fire effects on soils and restoration strategies. Science Publishers, Enfield, pp 299–320

Robichaud PR, Beyers JL, Neary DG (2000) Evaluating the effectiveness of postfire rehabilitation treatments. USDA For Serv Gen Tech Rep RMRS-GTR-63

Romanyà J, Casals P, Vallejo VR (2001) Short-term effects of fire on soil nitrogen availability in Mediterranean grasslands and shrublands growing in old fields. For Ecol Manag 147:39–53

Ryan KC (2002) Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Sylva Fenn 36:13–39

Ryan KC, Noste NV (1985) Evaluating prescribed fires In: Lotan JE, Kilgore BM, Fischer WC Mutch RW (Tech Coord). Workshop of Wilderness Fire. USDA Forest Service Res Sta, Proc Gen Tech Rep INT-182, pp 230–238

Saá A, Trasar-Cepeda C, Gil-Sotres F, Carballas T (1993) Changes in soil phosphorus and acid phosphatase activity immediately following forest fires. Soil Biol Biochem 25:1223–1230

Saá A, Trasar-Cepeda C, Carballas T (1998) Soil P status and phosphomonoesterase activity of recently burned and unburned soil following laboratory incubation. Soil Biol Biochem 30:419–428

Saito LS, Miller WW, Johnson DW, Qualls RG, Provencher L, Carroll E, Szameitat P (2007) Fire effects on stable isotopes in a Sierran forested watershed. J Environ Qual 36:91–100

Serrasolsas I, Khanna PK (1995) Changes in heated and autoclaves forest soils of S.E. Australia. II Phosphorus and phosphatase activity. Biogeochemistry 29:25–41

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. Earth Sci Rev 74:269–307

Smithwick EAH, Turner MG, Mack MC, Chapin FS III (2005) Post-fire soil N cycling in northern conifer forests affected by severe, stand-replacing wildfires. Ecosystems 8:163–181

SPSS (2004) Statistical Program User's Manual. Ireland

Tabatabai AM (1982) Soil enzymes. In: Methods of soil analysis. Part 2 Chemical and microbiological properties. Agronomy Monograph 2ª ed ASA-SSSA

Tomkins IB, Kellas JD, Tolhurst KG, Oswin DA (1991) Effects of fire intensity on soil chemistry in a eucalypt forest. Aust J Soil Res 29:25–47

Trasar-Cepeda C, Gil F, Leirós MC (2003) Determinación de la actividad fosfatasa del suelo. In: García C, Gil F, Hernández T, Trasar-Cepeda C (eds) Técnicas de Análisis de Parámetros Bioquímicos en Suelos: Medidas de Actividades Enzimáticas y Biomasa Microbiana. Ediciones Mundi-Prensa, Madrid, pp 51–76

Úbeda X, Outeiro L (2009) Physical and chemical effects of fire on soil. In: Cerdà A, Robichaud PR (eds) Fire effects on soils and restoration strategies. Science Pub Inc, pp 105–132

Úbeda X, Pereira P, Outeiro L, Martin DA (2009) Effects of fire temperature on the physical and chemical characteristics of the ash from two plots of cork oak (*Quercus suber*). Land Degrad Develop 20:589–608

Ulery AL, Graham RC (1993) Forest fire effects on soil color and texture. Soil Sci Soc Am J 57:135–140

Vose JM, Swank WT, Clinton BD, Knoepp JD, Swift LW (1999) Using stand replacement fires to restore southern Appalachian pine-hardwood ecosystems: effects on mass, carbon, and nutrient pools. For Ecol Manag 114:215–226

Wan S, Hui D, Luo Y (2001) Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. Ecol Appl 11:1349–1365

Wardle DA (1993) Changes in the microbial biomass and metabolic quotient during leaf litter succession in some New Zealand forest and scrubland ecosystem. Funct Ecol 7:346–355

Waring SA, Bremner JM (1964) Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. Nature (London) 201:951–952

Weston CJ, Attiwill PM (1990) Effects of fire and harvesting on N transformations and mobility in soils of Eucalyptus regnans forests of southeastern Australia. Oecologia 83:20–26