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Influence of straw mulch application on the properties of a soil affected by a forest wildfire

Influencia de la aplicación de paja sobre las propiedades de un suelo afectado por un incendio forestal
Influência da aplicação de "mulch" de palha nas propriedades de um solo afetado por um incêndio florestal

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ABSTRACT

Mulching treatment is often recommended in order to reduce post-fire erosion and sediment yields, but information concerning their effects on soil properties and hence on soil quality is scarce. In the present investigation, the influence of straw application on soil quality was evaluated on hillslope shrubland in Saviñao (Lugo, NW Spain) that is susceptible to post-fire erosion (38% slope). In this area, which was affected by a medium-high severity wildfire in September 2012, different treatments with wheat straw were applied to the burnt soil in mulch strips (0.8 and 1 Mg ha^{-1}) using quadruplicate 10 m x 40 m plots and compared with the corresponding burnt untreated control. Soil samples were collected from the A horizon (0-2.5 cm depth) at different sampling times for 12 months after the wildfire, and a wide range of physicochemical, chemical and biochemical soil properties (water retention, pH, electric conductivity, total C, ^{13}C, extractable C, water soluble C, soluble carbohydrates, total N, ^{15}N, microbial biomass C, soil respiration, bacterial activity, β-glucosidase, urease and phosphatase activities) were analyzed. The results showed that the application of straw mulch had a minor influence on the post-fire soil quality but, in contrast, the sampling time showed a significant influence attributed to short- and medium term changes in soil properties induced by both fire and climatic conditions.

RESUMEN

Entre las técnicas para reducir la erosión post-incendio se recomienda la aplicación de un acolchado de paja al suelo quemado; sin embargo, es escasa la información disponible acerca de sus efectos sobre la calidad del suelo. En esta investigación se evaluó la influencia de la aplicación de paja sobre la calidad del suelo en un matorral afectado por un incendio no controlado de media-alta severidad en el año 2012, localizado en Saviñao (Lugo, NO España) y situado en una ladera susceptible de sufrir erosión post-incendio (pendiente 38%). En esta área quemada se instalaron parcelas grandes (10 m de ancho x 40 m de largo) con diferentes tratamientos de paja de trigo aplicado en franjas (0, 0,8 y 1 Mg ha^{-1}, 4 repeticiones por tratamiento). Se recogieron muestras de suelo del horizonte superficial (0-2,5 cm) de los diferentes tratamientos y a diferentes períodos de tiempo durante 1 año y se analizaron diversas propiedades físico-químicas, químicas y bioquímicas del suelo (retención de agua, pH, conductividad eléctrica, C total, ^{13}C, C extraíble, C soluble, hidratos de C solubles, N total, ^{15}N, biomasa microbiana, respiración, actividad bacteriana y las actividades enzimáticas glucosidasa, ureasa y fosfatasa). Los resultados demostraron que la adición de paja no produjo ningún efecto sobre la calidad del suelo quemado mientras que, por el contrario, la época de muestreo ejerció una marcada influencia sobre la misma que se atribuye a cambios en las propiedades del suelo inducidos por el fuego y a las condiciones climáticas a corto y medio plazo.

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RESUMO

Uma das técnicas para reduzir a erosão após incêndios florestais é a aplicação ao solo queimado de um "mulch" de palha; contudo, a informação disponível relativamente aos efeitos desta técnica na qualidade do solo é muito escassa. O objetivo desta pesquisa foi avaliar a influência da aplicação de palha na qualidade do solo de um matagal localizado no Saviñao (Lugo, NO da Espanha) e sito numa encosta sob influência da erosão pós incêndio (declive 38%). Nesta área, afectada em setembro do 2012 por um fogo não controlado de média-alta intensidade, aplicou-se ao solo queimado diferentes tratamentos em faixas de palha de trigo (0.8 e 1 Mg ha^{-1}) , em quatro parcelas de 10 m de largura x 40 m de comprimento, e compararam-se com o correspondente solo controlo sem nenhum tratamento. Retiraram-se amostras da camada superficial do solo (0-2.5 cm) dos diferentes tratamentos em distintos tempos ao longo de um ano e após incêndio. Determinaram-se as propriedades físico-químicas, químicas e bioquímicas do solo (retenção de água, pH, condutividade elétrica, carbono (C) total, ^{13}C, C extraível, C solúvel, hidratos de C solúveis, nitrogênio (N) total, ^{15}N, biomassa microbiana, respiração basal, actividade bacteriana e as actividades enzimáticas da glucosidase, ureasea e fosfatase. Os resultados mostraram que a adição da palha teve um efeito reduzido na qualidade do solo queimado, enquanto pelo contrário se observou um forte efeito da época da amostragem atribuído à mudança nas propriedades do solo sob influencia do fogo e das condições climáticas a curto e médio prazo.

KEY WORDS
Post-fire erosion treatments, burnt soil, chemical and biochemical properties, soil quality

PALABRAS CLAVE
Tratamientos de control de la erosión post-incendio, suelo quemado, propiedades químicas y bioquímicas, calidad del suelo

PALAVRAS-CHAVE
Tratamentos de controlo da erosão após incêndio, solo queimado, propriedades químicas e bioquímicas, qualidade do solo

1. Introduction

The frequency and extent of wildfires has increased dramatically in the European Mediterranean region since the 1960s, aided by a general warming and drying trend, but driven primarily by socioeconomic changes including rural depopulation, land abandonment and afforestation with flammable species (Shakesby 2011). Globally, forest fires are one of the most widespread factors of forest destruction and are a strong soil desertification factor, causing the acceleration of soil degradation processes and nutrient losses through volatilization, leaching and erosion (Chandler et al. 1983). Most soil physical, chemical and biochemical properties are more or less affected by fires, leading to a reduction in soil quality; fire can cause partial or complete combustion of organic matter, deterioration of soil structure, alteration of aggregate stability and water repellence, depletion of nutrients through volatilization and leaching, together with marked modifications in the number, activity and composition of soil microbial communities (Neary et al. 1999; Certini 2005; Almendros and González-Vila 2012). As a consequence of these fire induced changes in soil properties and vegetation cover, the soil is more susceptible to soil erosion processes, particularly during the first year after the fire when the soil is bare and intense rainfall events are frequent (Andreu et al. 2001; Cerdá and Doerr 2008; Díaz-Raviña et al. 2010a). Therefore, efforts must be made to minimize wildfire risk and to mitigate post-fire soil erosion by the implementation of post-fire stabilisation and rehabilitation treatments (Badía and Martí 2000; Prats et al. 2012).

Wildfires are often the cause of large landscape changes within and downstream of the burned area in the N.W. of the Iberian Peninsula. In fact, Galicia and the North of Portugal are the areas of Europe most affected by forest wildfires, and worldwide they are amongst the areas with the greatest number of fires per hectare and inhabitant (Carballas et al. 2009). Despite being a temperate-humid region, in Galicia from 1991 to 2010 more than 510.000 ha (almost one fifth of region's area) was burned by more than 175.000 wildfires (Ministerio de Agricultura y Medio Ambiente 2012), causing huge economic and ecological damages that probably will become worse given the predicted scenario of climate change. Most of the wildfires occur in forest and shrubland areas, which are often located on sloping terrain, in soils with moderate erodibility due to their inherent soil properties (Benito et al. 2010; Varela et al. 2010). All these factors and post-fire meteorological conditions (abundant high-intensity rainfall events in the autumn period immediately after wildfires) tend to increase runoff and erosion processes in the surface soil horizon (Díaz-Fierros et al. 1990; Vega et al. 2005; Fernández et al. 2008). The Forest Service has recently initiated a post-fire stabilisation programme in Galicia in order to reduce the potential increases in runoff and erosion. This has increased the research on the implementation and effectiveness of different post-fire erosion mitigation techniques in this zone (Fernández et al. 2011, 2012; Díaz-Raviña et al. 2012; Vega et al. 2013a). The results of these studies have shown that: a) in the short-term, the recovery of the soil-plant system was slightly altered by different post-fire stabilisation treatments; b) all treatments reduced the runoff and erosion rates but the effectiveness varied depending on the technique (seeding, mulching and erosion barriers), the material (hydromulch, straw, wood strands, wood chips) and the site conditions; and c) the straw mulch applied uniformly by hand at a rate of 2.5 Mg ha^{-1} was the most adequate treatment due to its immediate effectiveness after installation, greater reduction of sediment yields (70-90% reduction) and lower impact on forest ecosystem.

Given the elevated potential of mulching as an emergency rehabilitation treatment in the temperate humid zone, quantitative studies concerning its effectiveness in minimizing risks and mitigating post-fire erosion and its effects on the recovery of the soil-plant system under different sceneries are required to plan post-fire actions at regional level (Vega et al. 2013a). An important disadvantage of the straw mulch is its elevated cost, which can vary depending on the application rate and technique (e.g. helicopter or hand-spreading, uniformly or in strips). An altered vegetation recovery has also been reported for some burnt areas under specific site conditions since mulch layers can obstruct emerging natural and seeded vegetation (sunlight interception) and be a source of non-native vegetation (seeds) (Bautista et al. 2009; Robichaud et al. 2013), which in turn can also affect soil properties. Therefore, before using mulching as the primary treatment in large post-fire rehabilitation efforts, there is an urgent need to optimize the technique towards an acceptable cost-effectiveness ratio and minimizing adverse effects on soil-plant system. The working hypothesis of the present study is that post-fire emergency stabilisation treatments can affect the soil characteristics that determine the soil quality. The overall aim of the present research was to study the short- and medium-term effects of an erosion-mitigation technique (straw mulch applied in strips at low doses (0.8-1 Mg ha^{-1})) on soil properties in a shrubland ecosystem highly susceptible to post-fire erosion processes under field conditions in the NW Spain (Galicia).

2. Materials and Methods

2.1. Site description

The study was carried out in an ecosystem located in Saviñao (Lugo, NW Spain) that was affected by a wildfire in September 2012 (85 ha of surface burned). The region is highly susceptible to soil erosion due to the steep relief and the high erosivity of the rainfall. The mean annual temperature was 12.7 ºC (Tmin 8.2 ºC, Tmax 17.3 ºC) and the annual precipitation was 904 mm, around 39% of the rainfall occurred in winter. A hillslope area of approximately 1.3 ha was selected for the study because of its homogeneity in terms of fire severity, vegetation and slope (UTM 29T 06133-47247, 530 m above sea level and 33-38% slope oriented S-SW). The soil was a *Haplic Leptosol* (humic, dystric) (IUSS Working Group 2006) developed over slates. Prior the wildfire, the dominant vegetation was shrubland (*Erica arborea, Ulex europaeus* y *Pterospartum tridentatum*) mixed with dispersed *Quercus pyrenaica* (short- and medium sized trees). The prevalence of black and white ashes and the total consumption of the ground plant communities (vegetation and litter layers) suggested that fire severity had been moderate to high in the study area (Vega et al. 2013b).

Twelve experimental plots (10 m × 40 m each) were established in a randomized block design 1 week after the wildfire. In order to study the effect of the mulching treatment, three treatments were applied in quadruplicate: burnt control soil (B), burnt soil with wheat straw in a 20 m wide strip mulch in the upper half plot alternating with a 20 m wide bare strip soil in the lower half plot (B+M1; 1 straw strip per plot, 1 Mg ha^{-1} global rate per plot) and burnt soil with wheat straw in a 8 m wide strip mulch alternating with a 8 m wide bare strip in both upper and lower half plot (B+M2; 2 straw strips per plot, 0.8 Mg ha^{-1} global rate per plot). Wheat straw was selected because it was considered to be the most effective hillslope treatment to reduce surface runoff and keep post-wildfire soil in place (Vega et al. 2013a), and was spread manually without water irrigation. A general view of the experimental area is showed in **Figure 1**. Soil sampling was performed immediately (0) and 3, 6, 9 and 12 months after the wildfire in all treatments. The soil with straw strip (s) and the soil with bare strips (b) was considered separately; therefore, a total of five soil treatments were analyzed: B; B+M1s; B+M1b; B+M2s; B+M2b. From each plot and treatment, twelve soil subsamples were taken from the top layer (0–2.5 cm) without removing the ashes and the straw; they were mixed to form one representative composite soil sample (3-5 kg), sieved (< 2 mm) and homogenized. Physicochemical and chemical properties were analyzed using air-dried soil whereas biochemical properties were measured in samples refrigerated (4 ºC) no longer than one month.

Figure 1. View of the macro-plots in the area affected by the wildfire (12 experimental plots, 10 × 40 m each) and detail of straw mulch application. Treatments: B, burned soil (2, 5, 9, 12); B+M1s, treatment with 1 straw strip per plot, soil with straw mulching; B+M1b, treatment with 1 straw strip per plot, bare soil (1, 4, 8, 11); B+M2s, treatment with 2 straw strips per plot, soil with straw mulching; B+M2b, treatment with 2 straw strips per plot, bare soil (3, 6, 7, 10).

The following soil properties were monitored in the < 2 mm fraction: moisture content and water retention capacity, pH (in water and KCl), electrical conductivity, total N, $\delta^{15}N$, total C, $\delta^{13}C$, extractable C, soluble C, soluble carbohydrates, microbial biomass, soil respiration, bacterial activity and soil enzymes related with the C, N and P cycles. Fire induced changes in soil physical properties such as texture, aggregate stability and water repellence were of minor importance for microbial communities as compared with the modifications in the rest of soil parameters analyzed (Díaz-Raviña et al. 2012); therefore, these properties were not included in the present evaluation of the wildfire on overall soil quality.

2.2. Physicochemical and chemical properties

The methods described by Guitián-Ojea and Carballas (1976) were utilized to determine the following properties: moisture content by oven-drying soil samples at 105 ºC for 6-7 h; water retention capacity using Richard´s pressure plates apparatus (pF = 2); pH in H_2O and KCl in a soil:solution ratio of 1:2.5; electrical conductivity in a soil/water extract of 1:5; total C, total N, $\delta^{13}C$ and $\delta^{15}N$ were measured on finely ground soil samples (< 100 µm) with an elemental analyzer (Carlo Erba CNS 1508) coupled on-line with an isotopic ratio mass spectrometer (Finnigan Mat, delta C, Bremen, Germany). The labile fractions of the soil organic matter, soluble C and carbohydrates were analyzed on fresh field samples using a modification of method described by Ghani et al. (2003). The water soluble C (WSC) was determined after extraction with distilled water (1:5 w/v) at 20 ºC for 2 h; and hot water extractable C (HWC) after extraction with distilled water (1:5 w/v) at 80 ºC for 24 h). The soluble total C in the extracts was measured by oxidation with dichromate in an acidic medium. The total carbohydrate content (WSCH, HWCH) was determined in the same soil-water extracts by the anthrone method, with glucose as the standard (Doutre et al. 1978).

2.3. Biochemical properties

The microbial biomass C was determined using the fumigation extraction method with some modifications (Díaz-Raviña et al. 1992). After soil fumigation with $CHCl_3$ for 24 h, the organic C was extracted from the unfumigated and fumigated samples with 0.05 M K_2SO_4 using a 1:4 soil-extract ratio. The microbial biomass C values were calculated from the equation: biomass C = 2.64 EC, where EC is the extractable C flush (difference between the extractable organic C from the fumigated and unfumigated samples). The extractable C from the unfumigated samples was used as a measurement of the available C (soil solution).

The soil respiration, an overall index of activity of heterotrophic microorganisms, and the measurement of three specific enzyme activities related with the C (ß-glucosidase), N (urease) and P (phosphatase) cycles were used as indicators of the soil microbial activity. The soil respiration was determined by incubation of fresh soil samples (75% of field capacity) at 22 ºC during a 10 day period, measuring the CO_2 trapped in a NaOH solution, which was then titrated with HCl (Díaz-Raviña et al. 1993a).

The ß-glucosidase activity was measured following the procedure of Eivazi and Tabatabai (1988), which determines the released *p*-nitrophenol after soil incubation with a *p*-nitrophenyl glucosidase solution for 3 h at 37 ºC. The urease activity was estimated by incubating the soil samples with an aqueous urea solution and extracting the NH_4^+ with 1 M KCl and 0.01 M HCl followed by the colorimetric NH_4^+ determination by a modified indophenol reaction (Kandeler and Gerber 1988). The phosphatase activity was assessed following the method described by Trasar-Cepeda et al. (1985), which determines the *p*-nitrophenol released after soil incubation with *p*-nitrophenyl phosphate during 30 minutes at 37 ºC. The bacterial activity was also determined by means of the incorporation of labelled leucine into bacteria extracted obtained from fresh soil after homogenization-centrifugation (Bååth et al. 2001).

All the results were obtained by triplicate determinations and expressed on the basis of oven-dry (105 ºC, 24 h) weight of soil (d.w.).

2.4. Statistical analysis

In order to evaluate the effect of the post-fire stabilisation treatment, the values of four plots with the same treatment were averaged (mean ± SE). The data were analyzed by a two way analysis of variance (ANOVA 2) to determine the percentage of variation attributable to the factors soil treatment (B, B+M1s, B+M1b, B+M2s, B+M2b) and sampling time (0, 3, 6, 9 and 12 months). For each sampling time, the data were also analyzed by a standard analysis of variance (ANOVA1) and, in the cases of significant F statistics, the Tukey´s minimum significant difference test was used to separate the means. A principal component analysis (PCA) was also carried out on physicochemical, chemical and biochemical data for the evaluation of the soil status. All statistical analyses were made using the SPSS 15.0 statistical package.

3. Results and Discussion

The data showed that immediately after the fire (t0) there were no significant differences among the plots assigned to the different treatments for the soil physicochemical, chemical and biochemical properties analyzed, which indicated an acceptable spatial homogeneity of the study area. Thus, in order to facilitate the comparison of the different parameters with the time, the average value of the burnt soil was used as reference value (Bt0).

3.1. Physicochemical and chemical properties

The main physicochemical characteristics of the soil samples from the *Haplic Leptosol* in the different soils treatments, collected in the different sampling times, are showed in **Figures 2** and **3**. Immediately after the fire the soil showed an acid pH (4.5), elevated content of organic matter (151 g C kg^{-1}; 10.7 g N kg^{-1}), a high associated water retention capacity (595 g water kg^{-1}) and low electrical conductivity (80 µS cm^{-1}). These values were higher than those reported for burned soils in the Mediterranean region (Caon et al. 2014) but within the reported range given for forest soils developed over acid rocks located in the temperate humid zone and affected by wildfire of different severity (Villar et al. 2004; Varela et al. 2005; Santín et al. 2008; Carballas et al. 2009; Martín et al. 2012; Lombao et al. 2014). The two-way ANOVA showed that sampling time explained 56-91% of the variation of pH, moisture and water retention; and only a 17% of the variance for electrical conductivity data, while the emergence stabilisation treatments did not have a significant influence. A different evolution during the study period (one year) was observed depending on the soil property considered. The pH increased by 0.5 units within the first three months and then decreased, reaching values similar to those exhibited immediately after the fire (Bt0). The moisture content exhibited values higher than those of the recently burned soils (Bt0) and displayed marked fluctuations with time. Total N, δ^{15}N and water retention showed a similar trend, with values similar to or lower than the reference values (Bt0), although the time influence was only significant for the latter. Only small fluctuations were detected in the electrical conductivity in the whole study, most values being similar to the reference burnt soil.

Immediately after the fire, the water soluble C was 288 mg kg^{-1} (0.5% of total C) and the hot-water extractable C was 2383 mg kg^{-1} (1.7% of total C), with the carbohydrates representing 26-28% of these fractions (**Figure 3**). In contrast to the total C content, the δ^{13}C values were significantly affected by both sampling time (18% of variance explained) and mulching treatment (14% of variance explained). The ANOVA 2 showed a significant effect of the sampling time on the labile fractions of C (WSC, HWC, WSCH, HWCH), explaining between 20-85% of the data

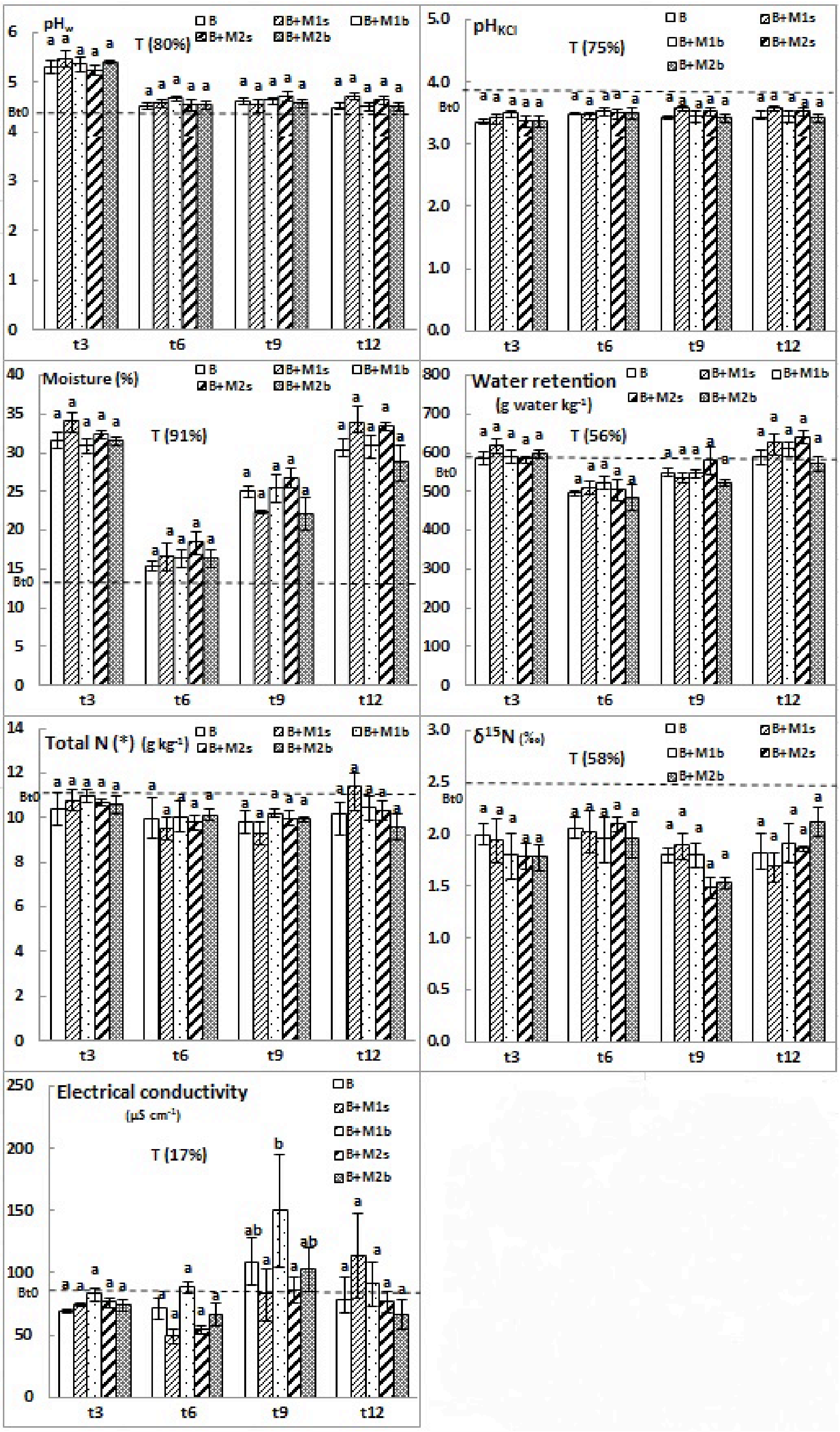

Figure 2. Soil physicochemical and chemical properties in the different soil treatments (mean ± SE; n = 4 field plots) at different sampling times (3, 6, 9 and 12 months after fire). The reference values in the burnt soil immediately after the wildfire (Bt0) are indicated by horizontal lines. For each sampling time, different letters show significant differences (ANOVA 1, $p < 0.05$ level). For each parameter an ANOVA 2 (T, time; M, mulching) was performed, but only the percentage of the variance explained by significant factors ($p < 0.05$ level) is indicated. Treatments: B, burned soil; B+M1s, treatment with 1 straw strip per plot, soil with straw mulching; B+M1b, treatment with 1 straw strip per plot, bare soil; B+M2s, treatment with 2 straw strips per plot, soil with straw mulching; B+M2b, treatment with 2 straw strips per plot, bare soil. *Data taken from Vieites Blanco (2014).

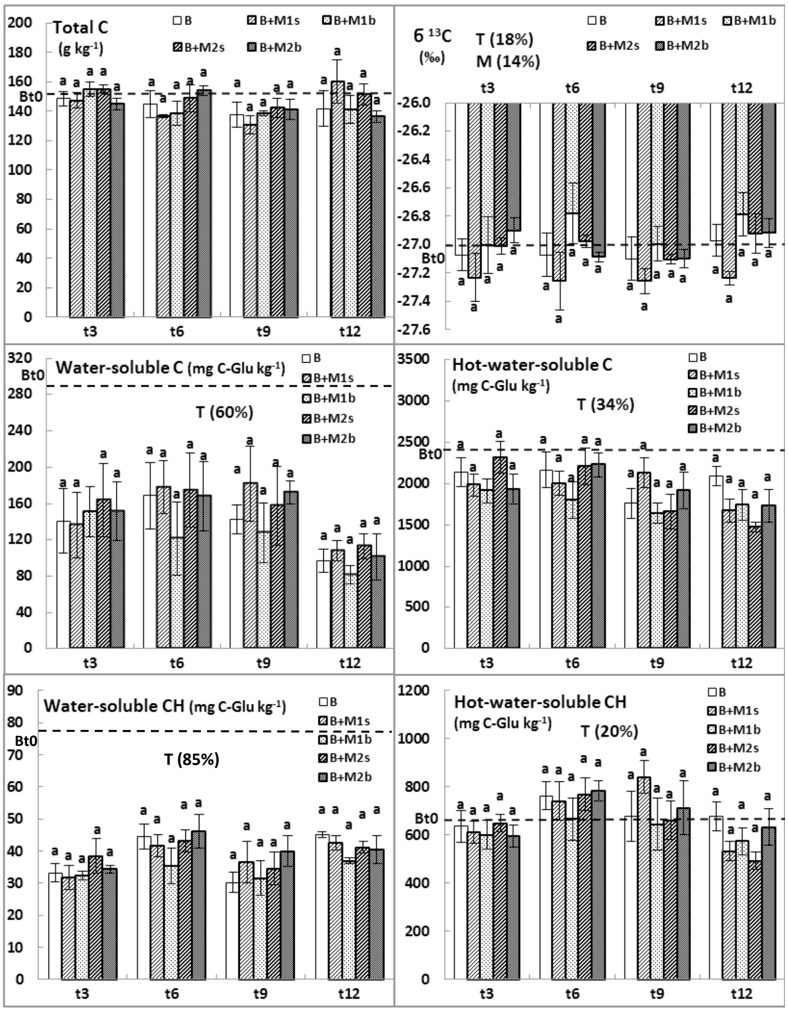

Figure 3. Total C, δ^{13}C and labile fractions (C, carbon; CH, carbohydrates) of soil organic matter in the different soil treatments (mean ± SE; n = 4 field plots) at different sampling times (3, 6, 9 and 12 months after fire). The reference values in the burnt soil immediately after the wildfire (Bt0) are indicated by horizontal lines. For each sampling time, different letters show significant differences (ANOVA 1, $p < 0.05$ level). For each parameter an ANOVA 2 (T, time; M, mulching) was performed, but only the percentage of the variance explained by significant factors ($p < 0.05$ level) is indicated. Treatments: B, burned soil; B+M1s, treatment with 1 straw strip per plot, soil with straw mulching; B+M1b, treatment with 1 straw strip per plot, bare soil; B+M2s, treatment with 2 straw strips per plot, soil with straw mulching; B+M2b, treatment with 2 straw strips per plot, bare soil.

variance. The results also indicated that, as compared with the reference values (Bt0), water extractable C (WSC, HWC) values decreased during the first 3 months by a factor of 2, and thereafter they remained rather constant during the rest of the study period. For the carbohydrate content, there were less pronounced variations with time, showing even similar or slightly higher HWCH values than those in the reference burnt control (Bt0). This is consistent with previous studies, which showed that the size and composition of the carbohydrate pool (Martín et al. 2009, 2011; Almendros and González-Vila 2012; Rovira et al. 2012) as well as the extractable C fraction (Díaz-Raviña et al. 1992, 1995, 2010b; Prieto-Fernández et al. 1998) varied with the season and was dramatically affected following wildfire. The labile pools of soil organic matter are especially important because they control the ecosystem productivity in the short-term, and could be most affected by soil perturbations such as wildfire or prescribed fires (Martín et al. 2011; Rovira et al. 2012; Wang et al. 2012). The labile C pools extracted by the hot and cold water (WSC, HWC, WCH, HWCH) were considered to degrade rapidly and may be immediate energy sources for microorganisms; however, our data seem to indicate that the cold water fractions are more adequate for examining the effects of sampling time and post-fire stabilisation treatments (higher percentages of variance explained in the ANOVA).

3.2. Biochemical properties

The biochemical properties are shown in **Figure 4**. The amount of C extractable with SO_4K_2 was always lower than the water extractable C (about 7-14 times) and the soluble carbohydrates (2-3 times). Immediately after the fire the soil microbial biomass was 346 mg C kg^{-1} and represented 0.23% of total C, the soil respiration 74 µg CO_2 g^{-1} day^{-1} and the bacterial activity 3.9 x 10^{-15} mol Leu g^{-1} h^{-1}. The values for the enzyme activities were 48 µg *p*-nitrophenol g^{-1} h^{-1} for glucosidase, 33 µg NH_4^+ g^{-1} h^{-1} for urease and 129 µg *p*-nitrophenol g^{-1} h^{-1} for phosphatase. These values of microbial biomass and activity are within the reported range given for Galician forest soils affected by wildfires of medium and high intensity (Prieto-Fernández et al. 1998; Villar et al. 2004; Díaz-Raviña et al. 2010b, 2012; Carballas et al. 2009; Lombao et al. 2014). The post-fire stabilisation treatments scarcely affected these variables (5% of variance of respiration and 9% of variance of bacterial activity values), whereas the sampling time, explaining 15-71% of the variance, had a pronounced and significant influence on the biochemical properties.

Generally the parameters measured changed with the sampling time but a different pattern was observed depending on the variable considered. The microbial C showed a marked and not consistent variation with time (62% of variance) with a transient increase 9 months after the fire. The bacterial activity and respiration values also varied significantly among sampling data (53-71% of variance explained) but they exhibited a different pattern (increase for bacterial activity, particularly after 3 months, and reduction for respiration) when compared to those obtained immediately after the fire (Bt0). The glucosidase activity was strongly influenced by the sampling data (65% of variance explained), with a clear increase within the first 3 months and a significant reduction during the rest of the sampling times (6-12 months). The phosphatase and urease also varied without a clear trend over the studied period (15-38% of variance explained), higher values being detected 3 and 6 months after the fire for urease and phosphatase, respectively. This behaviour can be explained on the basis of the different information obtained from the microbial indices (overall microbial biomass, overall metabolic activity, specific enzyme activity), and also the different sensitivity of the parameters analyzed to detect the impact of fire (Certini 2005; Mataix-Solera et al. 2009; Díaz-Raviña et al. 1996, 2010b). Likewise, the data are consistent with studies showing marked fluctuations in several indices of mass and activity of soil microorganisms following wildfires or prescribed fires, which can be attributed to seasonal changes as well as variations in several physicochemical and chemical properties induced in the short- and medium-term by the fire (Hernández et al. 1997; Basanta et al. 2004; Barreiro et al. 2010; Bárcenas et al. 2011; Díaz-Raviña et al. 2012; Fontúrbel et al. 2012; Lombao et al. 2014).

3.3. Combined interpretation of the soil properties analyzed

The individual analysis of the variables clearly indicated that most soil properties were not affected by the post-fire stabilisation treatments; however, they have experienced modifications in a different way and extent depending of the sampling times. Nevertheless, in order to evaluate the global impact of these factors (sampling time, mulching treatments) and hence

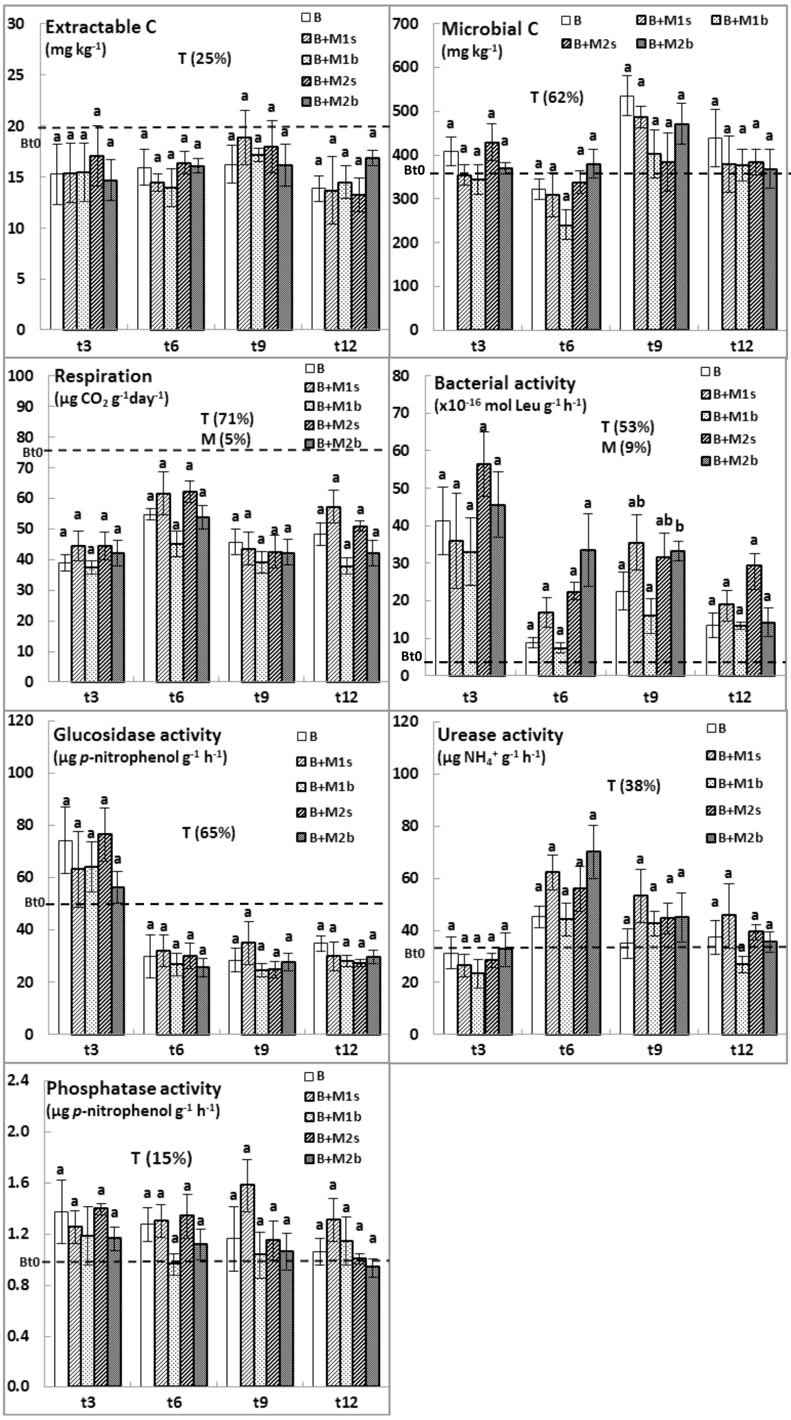

Figure 4. Soil biochemical properties in the different soil treatments (mean ± SE; n = 4 field plots) at different sampling times (3, 6, 9 and 12 months after fire). The reference values in the burnt soil immediately after the wildfire (Bt0) are indicated by horizontal lines. For each sampling times, different letters show significant differences (ANOVA 1, $p < 0.05$ level). For each parameter an ANOVA 2 (T, time; M, mulching) was performed, but only the percentage of the variance explained by significant factors ($p < 0.05$ level) is indicated. Treatments: B, burned soil; B+M1s, treatment with 1 straw strip per plot, soil with straw mulching; B+M1b, treatment with 1 straw strip per plot, bare soil; B+M2s, treatment with 2 straw strips per plot, soil with straw mulching; B+M2b, treatment with 2 straw strips per plot, bare soil.

to compare the soil quality in the burnt soil samples, all the physicochemical, chemical and biochemical properties should be considered together. The PCA is an adequate statistical technique for soil status evaluation and examining relationships among variables as well as for identifying the main factors influencing the quality of burnt soils with different post-fire stabilisation treatments. Thus, the PCA was used to analyse the whole data matrix including 21 variables monitored for 12 months. The two main factors identified accounted for 38% of the total variance (**Figure 5**). Factor I, which accounted for 21% of the variance, is defined in its positive extreme by all variables related with the labile pool of the soil organic matter (soluble C and carbohydrates fractions, soil respiration and extractable C) and at its negative extreme by $\delta^{13}C$. Factor II, which accounted for 17% of the variance, exhibited positive correlations with pH, glucosidase, bacterial activity and moisture content and negative correlation with $\delta^{15}N$.

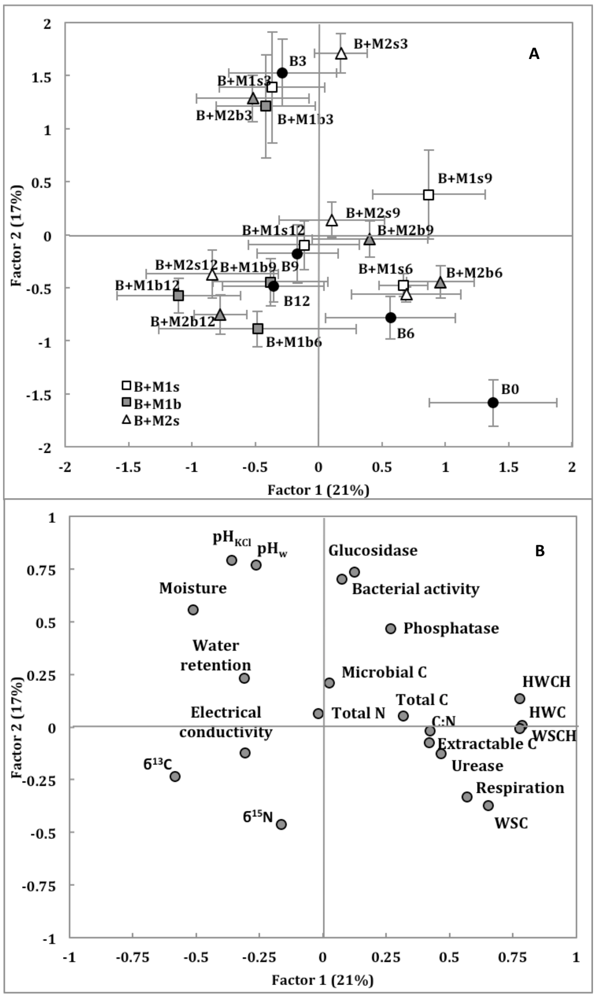

Figure 5. Score (mean ± SE, n = 4 field plots) (A) and loading plots (B) from a PCA performed on the PLFAs of the whole data set of the different soil treatments at different times (0, 3, 6, 9 and 12 months after the fire and the application of the stabilization treatments). Treatments: B, burned soil; B+M1s, treatment with 1 straw strip per plot, soil with straw mulching; B+M1b, treatment with 1 straw strip per plot, bare soil; B+M2s, treatment with 2 straw strips per plot, soil with straw mulching; B+M2b, treatment with 2 straw strips per plot, bare soil.

The distribution of the soil samples on the plane defined by factors I and II allow the separation of the burnt samples according to the sampling time (**Figure 5**). The samples collected immediately after the wildfire (having positive values along PC1) exhibited a high content of the labile C pools extracted by the cold and hot water (WSC, HWC, WSCH, HWCH). The samples collected after 3 months (having positive values along PC2) were characterized by relatively high values of glucosidase and bacterial activity that were attributed to variations in pH ($r = 0.648$ for glucosidase and $r = 0.448$ for bacterial activity, $p < 0.01$) and moisture content (positive influence although not significant). The samples collected after 12 months (having negative values along PC1) exhibited relatively low values of the labile pool of organic matter and high values of $\delta^{13}C$ and $\delta^{15}N$. The observed increase in $\delta^{13}C$ and $\delta^{15}N$ with the time after the fire is in agreement with previous studies (Goméz-Rey et al. 2013a) and suggests that the fire promoted immediate changes in the organic matter quality due to the volatilization of lighter isotopes and short- and medium term-changes due to the deposition of ^{13}C-depleted ashes and N outputs (lixiviation of nitrates which are ^{15}N depleted, and erosion of ^{15}N depleted sediments) (Rivas et al. 2012; Gómez-Rey et al. 2013b). The results clearly confirm that both amount and quality of the soil organic matter should be considered for soil status evaluation as well as the potential of both the labile fraction of the organic matter and the stable isotopes to assess alterations of the biogeochemical soil cycling. The data showed that C availability and microbial activity increased shortly after the fire but were negatively affected at the medium-term, supporting the indication that the soil organic matter was transformed into a recalcitrant substrate (Almendros and González-Vila 2012). A long lasting effect of the wildfire on soil quality was observed and, despite a transitory positive effect, the overall impact of the wildfire on the quality of this forest ecosystem located in the temperate humid zone is negative.

In relation to the application of mulching to the burnt soil, the results showed that its effect is masked by the sampling time effect, which was associated with intra-annual natural variability (seasonal fluctuations) as well as with the short- and medium term fire impact on soil properties. The data indicated that the fire effects persisted and were accentuated with the time, since samples collected immediately (0) and 12 months after the fire (same season) were clearly separated along PC1. The samples of the same sampling date tended to be clustered together independently of the post-fire treatment. This is consistent with marked seasonal fluctuations observed for properties of different forest soils located in the same area, which were associated with aboveground vegetation effects and variations in climatic conditions (Díaz-Raviña et al. 1993b, 1995; Martín et al. 2011). It should be noticed, however, that, as can be deduced from the distance along factor 1 for the same treatment (B+M1, B+M2) and sampling time, differences were observed between the samples from the bare and the straw strip zones, the effect being more accentuated for the B+M1 treatment after 6-12 months. Differences in the labile pool of the C fractions induced by the mulching cover can explain this behaviour, which is supported by the significant effect of the mulching treatment on $\delta^{13}C$ (14% of the variance explained), respiration (5% of the variance explained) and bacterial activity (9% of the variance explained) as well as by the small differences observed in the values of different soluble C pool in the same plots with and without straw mulch (WSC, HWC, WSCH, WHCH). It should be noted, however, that this effect is of minor importance as compared with that of the sampling time. Our results confirm those of recent studies showing minor changes in the soil quality due to the uniform application of straw mulch at a rate of 2.5 Mg ha^{-1} in two different shrubland soils highly susceptible to post-fire erosion, one developed over granite with 38-54% slope and affected by a prescribed fire and the other developed over phyllites with 50% slope and affected by a high intensity wildfire (Díaz-Raviña et al. 2012; Fontúrbel et al. 2012; Gómez-Rey et al. 2013a; Barreiro et al. 2014). Field studies concerning the evaluation of soil quality following the application of different post-fire stabilisation treatments are very scarce; therefore more investigations should be conducted in a wide range of burnt soils and post-fire conditions (soil, vegetation, and climate) for a longer time period in order to gain more insight on this topic.

4. Conclusions

The results of this study indicated that the evolution of the soil physicochemical, chemical and biochemical properties in the post-fire stabilisation treatments with wheat straw applied in mulch strips (0.8 and 1 Mg ha^{-1}) were mainly related to the time passed after the fire (short- and medium- term changes in soil properties induced by both fire and climatic conditions) rather than to the straw mulching effects. Therefore, since soil quality was not significantly affected by different mulching treatments, the selection of the best soil stabilisation technique should be based on their efficiency for reducing post-fire soil erosion during the first 12 months. Work is now in progress in our laboratory to examine the erosion data in these different post-fire stabilisation treatments in relation to the soil physical properties that are determinant for runoff and erosion processes.

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REFERENCES

• Almendros G, González-Vila FJ. 2012. Wildfires, soil carbon balance and resilient organic matter in Mediterranean ecosystems. A review. Spanish J Soil Sci. 2:8-33.

• Andreu V, Imeson AC, Rubio JL. 2001. Temporal changes in soil aggregates and water erosion after a wildfire in a Mediterranean pine forest. Catena 44:69-84.

• Bååth E, Petterson M, Söderberg KH. 2001. Adaptation of a rapid and economical microcentrifigation method to measure thymidine and leucine incorporation by soil bacteria. Soil Biol Biochem. 33:1571-1574.

• Badía D, Martí C. 2000. Seeding and mulching treatments as conservation measures of two burned soils in the central Ebro valley, NE Spain. Arid Soil Res Rehabil. 13:219-232.

• Bárcenas-Moreno G, García-Orenes F, Mataix-Solera J, Mataix-Beneyto J. Bååth E. 2011. Soil microbial recolonisation after a fire in a Mediterranean forest. Biol Fert Soils 47:261-272.

• Barreiro A, Fontúrbel MT, Lombao A, Martín A, Vega JA, Fernández C, Carballas T, Díaz-Raviña M. 2014. Using phospholipid fatty acid and community level physiological profiling techniques to characterize soil microbial communities following an experimental fire and different stabilization treatments. Catena (in press). doi:10.1016/j.catena.2014.07.011.

• Barreiro A, Martín T, Carballas T, Díaz-Raviña M. 2010. Response of soil microbial communities to fire and fire-fighting chemicals. Sci Total Environ. 408:6172-6176.

• Basanta MR, Díaz-Raviña M, Cuiñas P, Carballas T. 2004. Field data of microbial response to a fire retardant. Agrochimica 48:51-60.

• Bautista S, Robichaud PR, Bladé C. 2009. Post-fire mulching. In: Cerdá A, Robichaud PR, editors. Fire effects on soils and restoration strategies. Enfield, NH, USA: Science Publishers. p. 353-372.

• Benito E, Cerdá A, Soto B, Díaz-Fierros F, Rubio JL, Varela E, Rodríguez M. 2010. Métodos para el estudio de la erosionabilidad del suelo: su aplicación en suelos afectados por incendios forestales. In: Cerdá A, Jordán A, editors. Actualización en métodos y técnicas para el estudio de los suelos afectados por incendios forestales. FUEGORED. Valencia: Cátedra de Divulgación de la Ciencia. Universidad de Valencia. p. 85-108.

• Caon L, Vallejo VR, Ritsema, CJ, Geissen V. 2014. Effects of wildfire on soil nutrients in Mediterranean ecosystems. Earth-Sci Rev.139:47-58.

• Carballas T, Martín A, Díaz-Raviña M. 2009. Efecto de los incendios forestales sobre los suelos de Galicia. In: Cerdá A, Mataix-Solera J, editors. Efecto de los incendios forestales sobre los suelos en España. Valencia: Cátedra Divulgación de la Ciencia. Universitat de València. FUEGORED. p. 269-301.

• Cerdá A, Doerr SH. 2008. The effects of ash and needle cover on surface runoff and erosion in the immediate post-fire period. Catena 74:253-263.

• Certini G. 2005. Effects of fire on properties of forest soils: a review. Oecologie 143:1-10.

• Chandler C, Cheney Ph, Thomas Ph, Trabaud L, Williams D. 1983. Fire effects on soil, water and air. Fire in Forestry, Forest Fire Behaviour and Effects. Vol. 1. New York: Wiley.

• Díaz-Fierros F, Benito E, Vega JA, Castelao A, Soto B, Pérez R, Taboada T. 1990. Solute loss and soil erosion in burnt soil from Galicia (NW Spain). In: Goldammer JF, Jenkins MJ, editors. Fire in ecosystems Dynamics. Mediterranean and Northern Perspectives. The Hague: SPB Academic Publishing. p. 103-106.

• Díaz-Raviña M, Acea MJ, Carballas T. 1993a. Microbial biomass and its contribution to nutrient concentrations in forest soils. Soil Biol Biochem. 19:220-226.

• Díaz-Raviña M, Acea MJ, Carballas T. 1993b. Seasonal fluctuations in microbial populations and available nutrients in forest soils. Biol Fert Soils 16:205-210.

• Díaz-Raviña M, Acea MJ, Carballas T. 1995. Seasonal changes of microbial biomass and nutrient flush in forest soils. Biol Fert Soils 19:220-226.

• Díaz-Raviña M, Benito E, Carballas T, Fontúrbel MT, Vega JA. 2010a. Research and post-fire management: soil protection and rehabilitation techniques for burnt soil ecosystems. Santiago de Compostela: Andavira.

• Díaz-Raviña M, Fontúrbel MT, Guerrero C, Martín A, Carballas T. 2010b. Determinación de propiedades bioquímicas y microbiológicas de suelos quemados. In: Cerdá A, Jordán A, editors. Actualización en métodos y técnicas para el estudio de los suelos afectados por incendios forestales. FUEGORED. Valencia: Cátedra de Divulgación de la Ciencia. Universidad de Valencia. p. 465-497.

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

• Díaz-Raviña M, Prieto A, Acea MJ, Carballas T. 1992. Fumigation-extraction method to estimate microbial biomass in heated soils. Soil Biol Biochem. 24:259-264.

• Díaz-Raviña M, Prieto A, Bååth E. 1996. Bacterial activity in a forest soil after soil heating and organic amendments measured by the thymidine incorporation techniques. Soil Biol Biochem. 28: 419-426.

• Doutre M, Hay GW, Hood A, Van Loon GW. 1978. Spectrophotometric methods to determine carbohydrates in soil. Soil Biol Biochem. 10:457-462.

• Eivazi F, Tabatabai MA. 1988. Glucosidases and galactosidases in soils. Soil Biol Biochem. 20:601-606.

• Fernández C, Vega JA, Fontúrbel T, Jiménez E, Pérez JR. 2008. Immediate effects of prescribed burning, mastication and clearing on runoff, infiltration and erosion in a scrubland area in Galicia (NW Spain). Land Degrad Dev. 21:74-87.

• Fernández C, Vega JA, Jiménez E, Fontúrbel T. 2011. Effectiveness of three post-fire treatments at reducing soil erosion in Galicia (NW Spain). Int J Wildland Fire 20(1):104-114.

• Fernández C, Vega JA, Jiménez E, Vieira DCS, Merino A, Ferreiro A, Fontúrbel T. 2012. Seeding and mulching + seeding effects on post-fire runoff, soil erosion and species diversity in Galicia (NW Spain). Land Degrad Dev. 23(2):150-156.

• Fontúrbel MT, Barreiro A, Vega JA, Lombao A, Martín A, Jiménez E, Carballas T, Fernández C. 2012. Effects of an experimental fire and post-fire stabilization treatments on soil microbial communities. Geoderma 191:51-60.

• Ghani A, Dexter M, Perrott KW. 2003. Hot-extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. Soil Biol Biochem. 35:1231-1243.

• Gómez-Rey MX, Couto-Vázquez A, García-Marco S, González-Prieto SJ. 2013a. Impact of fire and post-fire management techniques on soil chemical properties. Geoderma 195-196:155-164.

• Gómez-Rey MX, Couto-Vázquez A, García-Marco S, Vega JA, González-Prieto SJ. 2013b. Reduction of nutrients losses with eroded sediments by post-fire stabilisation techniques. Int J Wildland Fire 22: 696-706.

• Guitián-Ojea F, Carballas T. 1976. Técnicas de Análisis de Suelos. Santiago de Compostela: Pico Sacro.

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

• IUSS Working Group WRB. 2006. World Reference Base for Soil Resources 2006. 2nd ed. World Soil Resources Reports No. 103. Roma: FAO.

• Kandeler E, Gerber H. 1988. Short-term assay of soil urease activity using colorimetric determination of ammonium. Biol Fert Soils 6:68-72.

• Lombao A, Barreiro A, Carballas T, Fontúrbel MT, Martín A, Vega JA. 2014. Changes in soil properties after a wildfire in Fragas do Eume natural Park (Galicia, NW Spain). Catena (in press). doi:10.1016/j.catena.2014.08.007.

• Martín A, Díaz-Raviña M, Carballas T. 2009. Evolution of composition and content of soil carbohydrates following forest wildfires. Biol Fert Soils 45:511-520.

• Martín A, Díaz-Raviña M, Carballas T. 2011. Seasonal changes in the carbohydrate pool of an Atlantic forest soil under different vegetation types. Spanish J Soil Sci. 1:38-53.

• Martín A, Díaz-Raviña M, Carballas T. 2012. Short- and medium term evolution of soil properties in Atlantic forests ecosystems affected by wildfires. Land Degrad Dev. 23:427-439.

• Mataix-Solera J, Guerrero C, García-Orenes F, Bárcenas GM, Torres MP. 2009. Forest fire effects on soil microbiology. In: Cerdá A, Robichaud PR, editors. Fire Effects on Soils and Restoration Strategies. Enfield, USA: Science Publishers. p. 133-175.

• Ministerio de Agricultura y Medio Ambiente. 2012 (internet). Available in: http://www.magrama.gob.es/es/biodiversidad/temas/defensa-contra-incendios-forestales/estadisticas-de-incendiosforestales/ (accessed 2012-06-15).

• Neary DG, Klopatek CC, DeBano LF, Ffolliott PF. 1999. Fire effects on belowground sustainability: a review and synthesis. Forest Ecol Manag. 122:51-71.

• Prats SA, MacDonald L, Monteiro MSV, Ferreira AJD, Coello COA, Keizer JJ. 2012. Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. Geoderma 191:115-124.

• Prieto-Fernández A, Villar MC, Carballas M, Carballas T. 1998. Soil microbial and extractable C and N after wildfires. Biol Fert Soils 27:132-142.

• Rivas Y, Huygens D, Knicker H, Godoy R, Matus F, Boeckx P. 2012. Soil nitrogen dynamics three years after a severe *Araucaria-Nothofagus* forest soil. Austral Ecol. 37:153-163.

• Robichaud PR, Lewis SA, Wagenbrenner JW, Ashmun LE, Brown RE. 2013. Post-fire mulching for runoff and erosion mitigation. Part I: effectiveness at reducing hillslope erosion rates. Catena 105:75-92.

• Rovira P, Romanyà J, Duguy B. 2012. Long-term effects of wildfires on the biochemical quality of soil organic matter: a study on Mediterranean shrublands. Geoderma 179-180:9-19.

• Santín C, Knicker H, Fernández S, Menéndez-Duarte R, Álvarez MA. 2008. Wildfires influence on soil organic matter in an Atlantic mountainous region (NW of Spain). Catena 74:286-295.

• Shakesby RA. 2011. Post-wildfire soil erosion in the Mediterranean: Review and future research directions. Earth-Sci Rev. 105:71-100.

• Trasar-Cepeda MC, Gil-Sotres F, Guitián-Ojea F. 1985. Determinación de la actividad de la fosfatasa en suelos gallegos. Precisiones al método de Saratchandra y Perrott. An Edafol Agrobiol. 44:987-991.

• Varela ME, Benito E, de Blas E. 2005. Impact of wildfires on Surface water repellency in soils of northwest Spain. Hydrol Process. 19:3649-3657.

• Varela ME, Benito E, Keizer JJ. 2010. Wildfire effects on soil erodibility of woodlands in NW Spain. Land Degrad Dev. 21:75-82.

• Vega JA, Fernández C, Fontúrbel MT. 2005. Throughfall, runoff and soil erosion after prescribed burning in gorse shrubland in Galicia (NW Spain). Land Degrad Dev. 15:1-15.

• Vega JA, Fontúrbel T, Fernández C, Arellano A, Díaz-Raviña M, Carballas T, Martín A, González-Prieto S, Merino A, Benito E. 2013a. Acciones urgentes contra la erosión en áreas forestales quemadas. Guía para su planificación en Galicia. Santiago de Compostela: Andavira.

• Vega JA, Fontúrbel T, Merino A, Fernández C, Ferreiro A, Jiménez E. 2013b. Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical and microbial properties in pine forests and shrubland. Plant Soil 369:73-91.

• Vieites Blanco C. 2014. Evaluación de dos técnicas de estabilización de emergencia post-incendio en base a sus efectos sobre las propiedades químicas de los suelos y los sedimentos erosionados. Trabajo Fin de Máster, Universidad de Santiago de Compostela.

• Villar MC, Petrikova V, Díaz-Raviña M, Carballas T. 2004. Changes in soil microbial biomass and aggregate stability following burning and soil rehabilitation. Geoderma 122:73-82.

• Wang Q, Zhong M, Wang S. 2012. A meta-analysis on the response of microbial biomass, dissolved organic matter, respiration, and N mineralization in mineral soil to fire in forest ecosystems. Forest Ecol Manag. 271:91-97.