

Impact of prescribed burning on soil properties in a Mediterranean area (Granada, SW Spain)

Impacto de las quemas preventivas en las propiedades de los suelos en una zona mediterránea (Granada, SW España)

Impacto de queimadas preventivas nas propriedades dos solos numa zona Mediterrânica (Granada, SW Espanha)

AUTHORS

Montoya S.^{@1}
smonsc@correo.ugr.es

Marín G.²

Ortega E.¹

@ Corresponding Author

¹ Departamento de Edafología y Química Agrícola. Facultad de Farmacia. Universidad de Granada. Campus Universitario Cartuja s/n. 18071 Granada. Spain.

² Departamento de Biología Vegetal. Facultad de Farmacia. Universidad de Granada. Campus Universitario Cartuja s/n. 18071 Granada. Spain.

Received: 07.10.2013 | Revised: 11.11.2013 | Accepted: 15.11.2013

ABSTRACT

We report here on the effects of preventive burning or low intensity fires on Mediterranean soils. The aim of this study is to determine the modifications of the main soil properties for cultivation: pH, organic matter, carbonates and organic nitrogen. The sampling area, located close to the Sacromonte Abbey on the outskirts of the city of Granada (S Spain), used to be agricultural land devoted to cultivating olive trees and cereals but is now abandoned to scrub and a few trees. Controlled burning was conducted for six hours over an area of 13,300 m² and 11 samples were taken at three different times: before burning, four days afterwards and a year afterwards. The results reveal that whilst organic matter and nitrogen contents increased, pH and carbonates decreased after burning, which may cause an increase in soil fertility.

RESUMEN

Este trabajo pretende estudiar el efecto de las quemas preventivas o fuegos de baja intensidad en suelos mediterráneos. El objetivo de este estudio es determinar las modificaciones producidas en las propiedades del suelo más importantes para el cultivo: pH, materia orgánica, carbonatos y nitrógeno orgánico. El área de muestreo se localiza cerca de la Abadía de Sacromonte, en las afueras de la ciudad de Granada (S España), que solía ser una zona dedicada al cultivo de olivos y cereales que actualmente está abandonada y solo se encuentran matorrales y algunos árboles. Se efectuó una quema controlada de seis horas sobre un área de 13.300 m² y se tomaron 11 muestras antes de la quema, a los cuatro días y al año. Los resultados muestran diferencias significativas en los contenidos de materia orgánica y nitrógeno que sufren un aumento, mientras pH y carbonatos disminuyen después de la realización de la quema. Todo esto puede producir un incremento en la fertilidad.

RESUMO

Neste trabalho pretende-se estudar o efeito das queimadas preventivas ou fogos de fraca intensidade em solos mediterrânicos. O objetivo deste estudo foi determinar as modificações produzidas nas propriedades do solo mais importantes para o cultivo: pH, matéria orgânica, carbonatos e azoto orgânico. A área de amostragem situa-se próximo da Abadia de Sacromonte, nos arredores da cidade de Granada (S Espanha), que tendo sido uma zona dedicada ao cultivo de oliveira e cereais está atualmente abandonada só se encontrando matos e algumas árvores. Realizou-se uma queimada controlada de seis horas sobre uma área de 13.300 m² e colheram-se 11 amostras antes da queimada, aos quatro dias e ao fim de um ano. Os resultados mostraram diferenças significativas nos teores de matéria orgânica e azoto que sofreram um aumento, enquanto pH e carbonatos diminuíram após realização da queimada, o que pode contribuir para um aumento da fertilidade do solo.

DOI: 10.3232/SJSS.2014.V4.N1.06

1. Introduction

Forest fires have been one of the most important environmental problems in Spain in recent decades (Jordán and Cerdà 2010; Mataix-Solera and Cerdà 2009). Forest fires cause major changes in ecosystems (de Luis et al. 2006; Ferrán et al. 2005; Fulé et al. 2008; Rodrigo et al. 2007) and impact on the physical and chemical properties of the soil (Certini 2005; Mataix-Solera et al. 2011; Neary et al. 2005), altering the hydrological processes (Shakesby and Doerr 2006) and increasing soil erosion risk (Moody et al. 2013; Rulli et al. 2013; Shakesby 2011). Forest fires also cause direct damage to humans and structures, especially in densely populated areas of the Mediterranean countries (Pausas et al. 2008). According to MAGRAMA (2013), this was evident after the large number of forest fires that occurred in Spain throughout the summer of 2012, when the area affected by forest fires in a one-year period (209,855.21 ha) was the highest since 2002 (114,734.10 ha, on average).

Generally, major fires cause the most damaging environmental impact, not only because of the great difficulty involved in restoring burnt areas but also due to the regression of burnt ecosystems (Martínez Ruiz 1996). Forest fires can favour degradation of the ecosystem to such an extent that many researchers consider that wildfires are a major cause of desertification (Rubio 1987). According to Pausas et al. (2008), flammability of vegetation has been substantially increased after land use change, such as in sensitive ecosystems (for example, extensive pine plantations in abandoned crops, farms, human-induced savannas and grasslands), thus increasing post-fire soil erosion risk. Consequently, although the Mediterranean basin vegetation has developed adaptive strategies to fire, a large number of the ecosystems currently found in this region are still exposed to fire-induced soil erosion risk.

The major impacts of fire on soil properties are water repellency (DeBano 2000), changes in soil organic matter content and chemical properties (Almendros and González-Vila 2012; González-Pérez et al. 2004), increased soil pH and salinity (Arocena and Opio 2003; Granged et al. 2011a; Pereira et al. 2011; Ulery et al. 1993), changes in soil fertility (Durán et al. 2009; Úbeda and Mataix-Solera 2008) and alterations in the biological communities (Bárcenas-Moreno and Bååth 2009; Bárcenas-Moreno et al. 2009). The severity of fire-induced impact on soil properties depends upon fire intensity and severity and on the buffering capacity of soil (Mataix-Solera and Cerdà 2009; Xu et al. 2013). Depending on their properties, not all soils behave in the same way after a fire, nor do they show the same risk of physical and chemical degradation (Certini 2005; Pardini et al. 2004; Mataix-Solera et al. 2011; Moody and Ebel 2013; Terefe et al. 2008; Xu et al. 2013).

Our aim here was to find out whether soil properties are modified by preventive burning and thus to decide on the suitability of using this technique to prevent major fires in peri-urban interface areas.

KEY WORDS

Fire effects on soils,
low-severity fire,
Mediterranean
soils, medium term

PALABRAS

CLAVE

Efectos del fuego en
los suelos,
fuego de baja
intensidad, suelos
mediterráneos,
periodo medio

PALAVRAS-

CHAVE

Efeitos do fogo nos
solos, fogos de fraca
intensidade, solos
mediterrânicos,
período médio

2. Material and Methods

2.1. Study site and experimental design

A prescribed burn was carried out in an experimental area near the Sacromonte Abbey (Granada, southern Spain), approximately at the coordinates 37°11.06'N and 3°34.64'W (Figure 1) on 20 October 2011.

The burnt area, with a perimeter of 536 m, an overall area of 13,300 m² and a slope of 20%, located near the Sacromonte Abbey (Granada) with south orientation, is an abandoned olive-tree and cereal cropped area. Main soil types in the burnt area may be classified as calcareous regosols (IUSS Working Group WRB 2006) and lithic/typic xerothent entisols (Soil Survey Staff 2010). This zone has a Mediterranean continental climate exhibiting a xeric-to-mesic pattern of humidity and temperature. The vegetation stands out for a number of species of the genus "Quercus", the

main representative being "Quercus rotundifolia" (holm) and plants native to these forests.

Prescribed burning started at 12 h noon and was conducted for 6 hours during a single day.

For soil characterization, soil sampling was conducted immediately before burning (20/10/2011), four days afterwards (24/10/2011) and one year later (24/10/2012). In the three sampling periods we collected 11 random samples (100 g approximately) of the superficial soil fraction in the same localization, trying to avoid the organic matter and ash.

Experimental burning was carried out after a 30-day period without rainfall. Table 1 shows some environmental data (maximum temperature, minimum humidity and wind speed) for dates immediately before and after burning.

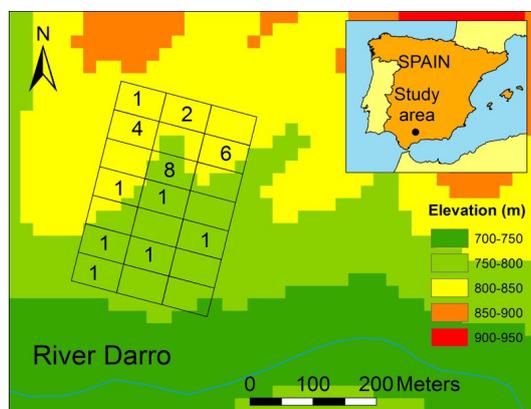


Figure 1. Experimental zone.

Table 1. Maximum temperature (°C), minimum air humidity (%) and wind speed (km/h) immediately before and after burning

VARIABLE	DAY	VALUE
Maximum temperature	Before (10 h)	25 °C
	After (10 h)	26 °C
Minimum air humidity	Before (10 h)	35%
	After (10 h)	40%
Wind speed	Before (10 h)	20 km/h
	After (10 h)	25 km/h

3. Results and Discussion

2.2. Analytical methods

Organic carbon content was determined using Tyurin method (Tyurin 1951). CaCO_3 content was determined using the Bernard's calcimeter (Ortega et al. 2012). Soil acidity (pH) was assessed and determined in a H_2O 1:1 suspension using a glass electrode pH-meter. Soil organic N was determined by Kjeldahl's method (Bremner 1965).

2.3. Data analysis

The normality of data from the variables studied (pH, organic matter content, CaCO_3 , water retention capacity and organic N) was examined using the Shapiro-Wilk test ($p \geq 0.05$). A box chart was included to detect the presence of lost values or outliers that might cause interference (Cook 1977). Since data fitted the normal distribution, parametric tests were used for statistical analyses and comparisons. Samples were characterized statistically by determination of mean, standard deviation, and minimum and maximum values. Student's t-test was used to compare means of different variables immediately before, at 4 days after and 1 year after burning. All tests were carried out using the SPSS software pack (IBM Corp. 2012).

3.1. Effects of burning on soil acidity

Soil pH values determined immediately before, at 4 days after and 1 year after burning are shown in **Table 2**. On average, soil pH decreased progressively with time from 8.15 ± 0.11 (immediately before burning) to 7.39 ± 0.18 (1 year after).

No significant differences were found for pH-values determined immediately before and 4 days after burning ($p=0.128$).

Nevertheless, soil fertility should increase with the pH reduction, considering that the pH value has changed from alkaline to neutral which is the optimum pH value for the majority of plants according to Ortega et al. (2012).

Commonly, soil pH increases after burning and the combustion of organic matter and ash production, which release basic ions in soils (Arocena and Opio 2003; Dikici and Yilmaz 2006; Fernandez et al. 1997; Ulery et al. 1995), the loss of OH groups from clay minerals and oxide formation (Giovannini et al. 1988; Ulery et al. 1993). In contrast, other authors have obtained different results depending on the intensity of the fire. Badía and Martí (2003) have shown that heating soil at 250°C contributes to decreased soil pH. In a laboratory experiment, Terefe et al. (2008) observed that soil pH decreased with increasing temperature between 25 and 200°C , although, generally, soil burning experiments under laboratory conditions do

Table 2. Minimum, maximum and average pH immediately before, at 4 days and 1 year after burning. N=11 cases

	Minimum	Maximum	Average	Standard Deviation
pH before burning	7.95	8.33	8.15	0.11
pH 4 days after burning	7.90	8.27	8.08	0.11
pH 1 year after burning	7.13	7.82	7.39	0.18

not consider the effect of ash. Our results are in agreement with results found by Úbeda et al. (2009) in their study of the consequences of fire and soil properties in Catalonia (NE Spain). They found no major differences between pH values reported in unburnt samples and soil samples burnt at 300 °C. Most prescribed fires do not induce temperatures above this threshold. In contrast, significant differences were found between initial and final (after 1 year period) soil pHs, which decreased to about 9% one year after the burning.

3.2. Effects of burning on soil organic matter

Table 3 shows the soil organic matter content determined immediately before (4.75%, on average), 1 day (7.84%) and 1 year after burning (9.24%). Soil organic matter increased significantly from $4.75 \pm 2.24\%$ (immediately after burning) to $7.84 \pm 3.00\%$ (4 days after burning) and $9.24 \pm 4.71\%$ (1 year after burning) from 65% of the pre-fire value four days after burning to 94% after one year.

Agricultural soils are more productive if they contain a large quantity of organic matter, allowing strong micro-organism activity (Kononova 1982). If we consider that there is a significant increase in organic matter after the burning, we can say the fertility has improved.

Burning can induce the complete destruction of soil organic matter by combustion or a decrease in relation to the severity of the fire (Carballas et al. 2009), although in some cases substantial increases may be found, caused by the addition of charred residues, as we observed in our study. Carballas et al. (2009) did not find significant changes in soil organic matter content after burning. Sertsu and Sánchez (1978) and Fernandez et al. (1997) reported complete destruction of soil organic matter after soil was exposed to 400 °C. In a laboratory experiment, Terefe et al. (2008) observed that soil organic matter content decreased significantly in samples of A horizons after heating at 200 and 300 °C, and organic matter was completely destroyed at 500 °C. After studying recent low intensity burnt areas and fire-suppressed stands of ponderosa pine/Douglas-fir, Hatten et al. (2005) observed that the organic carbon content decreased in the burnt areas when compared with the control areas, but no significant differences were found after burning in A horizons. They suggested that the unexpected low organic carbon content in > 8-year-old burnt areas was due to the erosion processes. In contrast, decreased soil organic matter content after burning may be balanced with new organic inputs such as residual ash, partly charred litter and falling leaves or other residues after burning (Afif Khouri and Oliveira Prendes 2006; Díaz-Fierros et al. 1982; Gimeno-García et al. 2000; Granged et al. 2011b; Sánchez et al. 1994; Úbeda 2001), which is in agreement with our results.

Table 3. Minimum, maximum and average OM immediately before, at 4 days and 1 year after burning. N=11 cases

	Minimum	Maximum	Average	Standard Deviation
OM before burning	1.20	7.90	4.75	2.24
OM 4 days after burning	3.70	13.60	7.84	2.99
OM 1 year after burning	3.60	19.10	9.24	4.71

3.3. Effects of burning on carbonate content

The carbonate content (Table 4) decreased significantly by 11% at 4 days and 17% 1 year after burning.

There is a reduction in the average carbonate content in experimental soils from 21.39% to

17.35%, which is the recommendation for the majority of crops according to Ortega et al. (2012). A high carbonate content is not recommendable due the fact that it may cause a deficiency in the absorption of other elements thus causing a lack of necessary elements for plant growth.

Table 4. Minimum, maximum and average carbonate content immediately before, 4 days and 1 year after burning. N=11 cases

	Minimum	Maximum	Average	Standard Deviation
CaCO₃ before burning	17.75	26.00	21.39	2.36
CaCO₃ 4 days after burning	14.52	22.14	18.96	2.08
CaCO₃ 1 year after burning	13.58	20.99	17.75	2.09

Some authors have attributed an increased carbonate content after fire to high-severity burning (Ulery et al. 1993). Increased carbonate content has been found to be related to decomposition of calcium oxalates (Pereira et al. 2010; Quintana et al. 2007), precipitation of calcite crystals from organic residues (Pereira et al. 2012; Ulery et al. 1993) and the production of calcium oxides during combustion, which is subsequently transformed to hydroxide and carbonate due to reaction with atmospheric CO₂ (Goforth et al. 2005; Ulery et al. 1993). However, Pereira et al. (2012) observed that production of calcium carbonates depends more on the plant species and temperature peaks. The decrease in carbonate content observed after low-severity burning in our experiment contrasts with these observations. If we assume that increased carbonate content after burning is mainly caused by ash production, small decreases may be observed after ash is removed by natural agents (wind or rainfall). The ash layer observed after

burning is usually ephemeral and redistribution occurs rapidly in the post-fire period (Cerdà and Doerr 2008; Pereira et al. 2013; Zavala et al. 2009). Although statistically significant, changes in average carbonate content are relatively small (3.64 percentage units) between samples collected immediately before and 1 year after burning. Consequently, small differences found in this experiment may be caused simply by spatial heterogeneity.

3.4. Effects of burning on soil water repellency

One impact of fire on soil is the development of an increase in water repellency (DeBano 1981; DeBano 2000), which decreases the soil infiltration capacity because of the formation of a hydrophobic coat on the surface of the aggregates. Soil water repellency has been observed in a range of soils with different vegetation types and climates (Doerr et al. 2009;

Jordán et al. 2009; Martínez-Zavala and Jordán-López, 2009; Mirbabaei et al. 2013; Neris et al. 2013), but fire may be considered as a triggering factor in many cases (Bodí et al. 2013; Mataix-Solera et al. 2013). There are many factors involved in the development of fire-induced soil water repellency, such as temperature peaks (DeBano 2000), time of heating (Doerr et al. 2004) and soil properties (organic matter content, texture or aggregation, for example). Depending on these factors, water repellency may be induced, enhanced, destroyed (Arcenegui et al. 2007; Arcenegui et al. 2008; Doerr et al. 2004; Jordán et al. 2011; Tessler et al. 2008) or stay unaffected in the short- (Cerdà and Doerr 2005; Granged et al. 2011b; Jordán et al. 2010) or in the long-term (Doerr et al. 2009).

According to DeBano (1981, 2000), organic coatings of aggregates are generated by

vaporization and the consequent condensation of organic compounds onto the surface of soil aggregates. Fire-induced soil water repellency can cause a decrease in soil moisture content during a period that can vary between seconds and months.

3.5. Effects of burning on organic N content

Organic nitrogen (ON) is one of the elements most affected by fire as a consequence of its low volatilization temperature of about 200 °C (Certini 2005). The evolution of the average soil ON content is shown in Table 5, but the changes are not significant in the medium-term. Nevertheless, a significant difference was found between values observed immediately before and four days after burning, which increased by 53%.

Table 5. Minimum, maximum and average organic nitrogen immediately before, 4 days and 1 year after burning. N=11 cases

	Minimum	Maximum	Average	Standard Deviation
ON before burning	0.81	3.46	1.99	0.92
ON 4 days after burning	1.47	4.72	3.05	0.82
ON 1 year after burning	0.92	4.38	2.55	1.04

Considering that there is an increase in organic matter after the burning, it is logical that the organic nitrogen content also increases since both parameters are directly related.

Our results are in agreement with findings by Úbeda et al. (2009). There was an increase in the percentage of total nitrogen in the burnt sample compared to the unburnt one after a fire reaching 400 °C. Carballas et al. (2009), in their investigation into forest fires on

Galician soils, reported that total N observed two years after burning tended to be similar to those corresponding to unburnt soils. During combustion, large amounts of nitrogen are lost, as it easily volatilizes (Certini 2005). Data on soil N cycling after forest fires are scarce, especially during the first years after the event. Studies have documented increased (Grogan et al. 2000), decreased (Turner et al. 2007) and no significant changes in N mineralization and nitrification after forest fires (Simard et al. 2001).

4. Conclusions

Preventive burning was conducted in a prescribed, experimental, peri-urban zone with a Mediterranean continental climate exhibiting a xeric-to-mesic pattern of humidity and temperature. The results have provided us with sufficient evidence to conclude that under the conditions in question soil properties are affected in a positive way for the possible future cultivation of crops.

As far as the soil properties are concerned, the organic-matter and nitrogen content of the soil had both increased considerably one year after the burning, producing increased fertility. Nevertheless, a decrease in pH and carbonates has been found. As soils in the Mediterranean zone tend to be slightly alkaline and quite highly carbonated these reductions are two important advantages for improving soil fertility and avoiding any kind of deficiency in the vegetation.

Thus, we conclude that preventive burning in Mediterranean areas does not harm the intrinsic nature of the soil for future agricultural use.

6. Acknowledgements

The authors thank the University of Granada, the Granada Municipal Government and Fire Brigade for their contribution to this study. Especial thanks go to Sergio Iglesias Asenjo for making it all possible. We also thank Pilar González Cifuentes for her willingness to help in the collection of samples and for the analyses.

REFERENCES

- Afif Khouri E, Oliveira Prendes JA. 2006. Efectos del fuego prescrito sobre matorral en las propiedades del suelo. *Invest Agrar.* 15(3):262-270.
- Almendros G, González-Vila FJ. 2012. Wildfires, soil carbon balance and resilient organic matter in Mediterranean ecosystems. A review. *Spanish Journal of Soil Science* 2:8-33.
- Arcenegui V, Mataix-Solera J, Guerrero C, Zornoza R, Mataix-Beneyto J, García-Orenes F. 2008. Immediate effects of wildfires on water repellency and aggregate stability in Mediterranean calcareous soils. *Catena* 44:219-226.
- Arcenegui V, Mataix-Solera J, Guerrero C, Zornoza R, Mayoral AM, Morales J. 2007. Factors controlling the water repellency induced by fire in calcareous Mediterranean forest soils. *European Journal of Soil Science* 58:1254-1259.
- Arocena JM, Opio C. 2003. Prescribed fire-induced changes in properties of sub-boreal forest soils. *Geoderma* 113:1-16.
- Badía D, Martí C. 2003. Plant ash and heat intensity effects on chemical and physical properties of two contrasting soils. *Arid Land Research and Management* 17:23-41 .
- Bárcenas-Moreno G, Bååth E. 2009. Bacterial and fungal growth in soil heated at different temperatures to simulate a range of fire intensities. *Soil Biology and Biochemistry* 41:2517-2526.
- Bárcenas-Moreno G, Gómez-Brandón M, Rousk J, Bååth E. 2009. Adaptation of soil microbial communities to temperature: comparison of fungi and bacteria in a laboratory experiment. *Global Change Biology* 15:2950-2957.
- Bodí MB, Muñoz-Santa I, Armero C, Doerr SH, Mataix-Solera J, Cerdà A. 2013. Spatial and temporal variations of water repellency and probability of its occurrence in calcareous Mediterranean rangeland soils affected by fires. *Catena* 108:14-25.
- Bremner J. 1965. Total nitrogen. In: Black CA, editor. *Methods of soil analysis.* Agron. 9. Madison, Wisconsin: American Society of Agronomy. p. 374-390.
- Carballas T, Marín A, Diaz-Raviña M. 2009. Efecto de los incendios forestales sobre los suelos de Galicia. In: Cerdà A, Mataix-Solera J, editors. *Efectos de los incendios forestales sobre los suelos en España. El estado de la cuestión visto por los científicos españoles.* Valencia: Cátedra de Divulgació de la Ciència, Universitat de València, FUEGORED.p. 269-301.

- Cerdà A, Doerr SH. 2005. Influence of vegetation recovery on soil hydrology and erodibility following fire: an 11-year investigation. *International Journal of Wildland Fire* 14:423-437.
- Cerdà A, Doerr SH. 2008. The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *Catena* 74:256-263.
- Certini G. 2005. Effects of fire on properties of forest soils: a review. *Oecologia* 143:1-10.
- Cook RD. 1977. Detection of influential observations in linear regression. *Technometrics* 19:15-18.
- de Luis M, Raventós J, Gonzalez-Hidalgo JC. 2006. Post-fire vegetation succession in Mediterranean gorse shrublands. *Acta Oecologica* 30:54-61.
- DeBano LF. 1981. Water repellent soils: A state-of-the-art. United States Department of Agriculture Forestry Service General Technical Report, PSW- 46, 21. Berkeley, California.
- DeBano LF. 2000. The role of fire and soil heating on water repellency in wildland environments: A review. *Journal of Hydrology* 231-232:195-206.
- Díaz-Fierros F, Gil Soltres F, Cabaneiro A, Carballas T, Leiros Pena MC, Villar Celoiro M.C. 1982. Efectos erosivos de los incendios forestales en los suelos de Galicia. *Anales de Edafología y Agrobiología* 41:627-639.
- Dikici H, Yilmaz CH. 2006. Peat fire effects on some properties of an artificially drained peatland. *Journal of Environmental Quality* 35:866-870.
- Doerr SH, Blake WH, Shakesby RA, Stagnitti F, Vuurens SH, Humphreys GS, Wallbrink P. 2004. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. *International Journal of Wildland Fire* 13:157-163.
- Doerr SH, Woods SM, Martin MD, Casimiro M. 2009. 'Natural background' soil water repellency in conifer forests of the north-western USA: its prediction and relationship to wildfire occurrence. *Journal of Hydrology* 371:12-21.
- Durán J, Rodríguez A, Fernández-Palacios JM, Gallardo A. 2009. Changes in net N mineralization rates and soil N and P pools in a pine forest wildfire chronosequence. *Biology and Fertility of Soils* 45:781-788.
- Fernandez I, Cabaneiro A, Carballas T. 1997. Organic matter changes immediately after a wildfire in an Atlantic forest soil comparison with laboratory soil heating. *Soil Biology and Biochemistry* 29:1-11.
- Ferrán A, Delitti W, Vallejo VR. 2005. Effects of fire recurrence in *Quercus coccifera* L. shrublands of the Valencia region (Spain): II. Plant and soil nutrients. *Plant Ecology* 177:71-83.
- Fulé PZ, Ribas M, Gutiérrez E, Vallejo R, Kaye MW. 2008. Forest structure and fire history in an old *Pinus nigra* forest, eastern Spain. *Forest Ecology and Management* 255:1234-1242.
- Gimeno-García E, Andreu V, Rubio JL. 2000. Changes in organic matter, nitrogen, phosphorus and cations in soil as a result of fire and water erosion in a Mediterranean landscape *European Journal of Soil Science* 51:201-210.
- Giovannini G, Lucchesi SS, Giachetti. 1998. Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. *Soil Science* 146:255-262.
- 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. *International Journal of 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. *Environment International* 30:855-870.
- Granged AJP, Jordán A, Zavala LM, Muñoz-Rojas M, Mataix-Solera J. 2011b. Short-term effects of experimental fire for a soil under eucalyptus forest (SE Australia). *Geoderma* 167-168:125-134.
- Granged AJP, Zavala LM, Jordán A, Bárcenas-Moreno G. 2011a. Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: A 3-year study. *Geoderma* 164:85-94.
- Grogan P, Bruns TD, Chapin FS. 2000. Fire effects on ecosystem nitrogen cycling in a Californian bishop pine forest. *Oecologia* 122:537-44.
- Hatten J, Zabowski D, Scherer G, Dolan E. 2005. A comparison of soil properties after contemporary wildfire and fire suppression. *Forest Ecology and Management* 220:227-241.
- IBM Corp. 2012. IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp.
- IUSS Working Group WRB. 2006. World reference base for soil resources 2006. *World Soil Resources Reports* No. 103. Rome: FAO.
- Jordán A, Cerdà A. 2010. Avances metodológicos e innovación técnica en el estudio de los suelos afectados por incendios forestales. In: Cerdà A, Jordán A, editors. *Actualización en métodos y técnicas para el estudio de los suelos afectados por incendios forestales*. Valencia: Cátedra de Divulgació de la Ciència, Universitat de València, FUEGORED. p. 25-34.
- Jordán A, González FA, Zavala LM. 2010. Re-establishment of soil water repellency after destruction by intense burning in a Mediterranean heathland (SW Spain). *Hydrological Processes* 24:736-748.

- Jordán A, Zavala LM, Mataix-Solera J, Nava AL, Alanís N. 2011. Effect of fire severity on water repellency and aggregate stability on Mexican volcanic soils. *Catena* 84:136-147.
- Jordán A, Zavala LM, Nava AL, Alanís N. 2009. Occurrence and hydrological effects of water repellency in different soil and land use types in Mexican volcanic highlands. *Catena* 79:60-71.
- Kononova MM. 1982. *Materia Orgánica del suelo*. Barcelona: Ed. Oikos-tau.
- MAGRAMA. 2013. *Incendios forestales en España*. 1 enero – 31 diciembre 2012. Madrid: Ministerio de Agricultura, Alimentación y Medio Ambiente.
- Martínez Ruiz E. 1996. *Tres sierras tres culturas. Acabemos con los incendios forestales en España*. Ministerio de Agricultura, Pesca y Alimentación. 349 p.
- Martínez-Zavala L, Jordán-López A. 2009. Influence of different plant species on water repellency in Mediterranean heathland soils. *Catena* 76:215-223.
- Mataix-Solera J, Arcenegui V, Tessler N, Zornoza R, Wittenberg L, Martínez C, Caselles P, Pérez-Bejarano A, Malkinson D, Jordán MM. 2013. Soil properties as key factors controlling water repellency in fire-affected areas: Evidences from burned sites in Spain and Israel. *Catena* 108:6-13.
- Mataix-Solera J, Cerdà A. 2009. Incendios forestales en España. Ecosistemas terrestres y suelos. In: Cerdà A, Mataix-Solera J, editors. *Efectos de los incendios forestales sobre los suelos en España*. El estado de la cuestión visto por los científicos españoles. Valencia: Cátedra de Divulgació de la Ciència, Universitat de València, FUEGORED. p. 25-53.
- Mataix-Solera J, Cerdà A, Arcenegui V, Jordán A, Zavala LM. 2011. Fire effects on soil aggregation: a review. *Earth-Science Reviews* 109:44-60.
- Mirbababei SM, Shahrestani MS, Zolfachari A, Abkenar KT. 2013. Relationship between soil water repellency and some of soil properties in northern Iran. *Catena* 108:26-34.
- Moody JA, Ebel BA. 2013. Infiltration and runoff generation processes in fire-affected soils. *Hydrological Processes*. doi: 10.1002/hyp.9857.
- Moody JA, Shakesby RA, Robichaud PR, Cannon SH, Martin DA. 2013. Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews* 122:10-37.
- Neary DG, Ryan KC, DeBano LF, editors. 2005. *Wildland Fire in Ecosystems. Effects of Fire on Soil and Water*. General Technical Report RMRS-GTR-42- volume 4. Ogden, UT: United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Neris J, Tejedor M, Rodríguez M, Fuentes J, Jiménez C. 2013. Effect of forest floor characteristics on water repellency, infiltration, runoff and soil loss in Andisols of Tenerife (Canary Islands, Spain). *Catena* 10:50-57.
- Ortega E, Montoya S, Asensio CM. 2012. *Prácticas y seminarios de producción de materia prima*. Granada: Editorial Universidad de Granada.
- Pardini G, Gispert M, Dunjó G. 2004. Relative influence of wildfire on soil properties and erosion processes in different Mediterranean environments in NE Spain. *Science of the Total Environment* 328:237-246.
- Pausas JG, Llovet J, Rodrigo A, Vallejo R. 2008. Are wildfires a disaster in the Mediterranean basin? –A review. *International Journal of Wildland Fire* 17:713-723.
- Pereira P, Bodi M, Úbeda X, Cerdà A, Mataix-Solera J, Balfour V, Woods S. 2010. Las cenizas en el ecosistema suelo. In: Cerdà A, Jordán A, editors. *Actualización en métodos y técnicas para el estudio de los suelos afectados por incendios forestales*. Valencia: Cátedra de Divulgació de la Ciència, Universitat de València, FUEGORED. p. 351-401.
- Pereira P, Cerdà A, Úbeda X, Mataix-Solera J, Martin D, Jordán A, Burguet M. 2013. Spatial models for monitoring the spatio-temporal evolution of ashes after fire – a case study of a burnt grassland in Lithuania. *Solid Earth* 4:153-165.
- Pereira P, Úbeda X, Martín DA. 2012. Fire severity effects on ash chemical composition and water-extractable elements. *Geoderma* 191:105-114.
- Pereira P, Úbeda X, Martín D, Mataix-Solera J, Guerrero C. 2011. Effects of a low severity prescribed fire on water-soluble elements in ash from a cork oak (*Quercus suber*) forest located in the northeast of the Iberian Peninsula. *Environmental Research* 111:237-247.
- Quintana JR, Cala V, Parra JG. 2007. Effecting of heating on mineral components of the soil organic horizon from Spanish juniper (*Juniperus thurifera* L.) woodland. *Journal of Arid Environments* 71:45-56.
- Rodrigo A, Quintana V, Retana J. 2007. Fire reduces *Pinus pinea* distribution in the north-eastern Iberian Peninsula. *Ecoscience* 14:23-30.
- Rubio JL. 1987. Desertificación en la Comunidad Valenciana: antecedentes históricos y situación actual de la erosión. *Revista Valenciana d'Estudis Autònomic* 7:231-258.
- Rulli MC, Offeddu L, Santini M. 2013. Modeling post-fire water erosion mitigation strategies. *Hydrology and Earth System Sciences* 17:2323-2337.

- Sánchez JR, Mangas VL, Ortiz C, Bellot J. 1994. Forest fire effect on soil chemical properties and runoff. In: Sala M, Rubio JL, editors. Soil erosion and degradation as a consequence of forest fires. Logroño, España: Geofoma Ediciones. p. 53-65.
- Sertsu SM, Sánchez PA. 1978. Effects of heating on some changes in soil properties in relation to an Ethiopian land management practice. *Soil Science Society of America Journal* 42:940-944.
- Shakesby RA. 2011. Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth Science Reviews* 105:71-100.
- Shakesby RA, Doerr SH. 2006. Wildfire as a hydrological and geomorphological agent. *Earth Science Reviews* 74:269-307.
- Simard DG, Fyles JW, Paré D, Nguyen T. 2001. Impacts of clearcut harvesting and wildfire on soil nutrient status in the Quebec boreal forest. *Canadian Journal of Soil Science* 81:229-37.
- Soil Survey Staff. 2010. Keys to soil taxonomy, 11th ed. Washington, DC: USDA-Natural Resources Conservation Service.
- Terefe T, Mariscal-Sancho I, Peregrina F, Espejo R. 2008. Influence of heating on various properties of six Mediterranean soils. A laboratory study. *Geoderma* 143:273-280.
- Tessler N, Wittenberg L, Malkinson D, Greenbaum N. 2008. Fire effects and short-term changes in soil water repellency - Mt. Carmel, Israel. *Catena* 74:185-191.
- Turner MG, Smithwick EAH, Metzger KL, Tinker DB, Romme WH. 2007. Inorganic nitrogen availability after severe stand-replacing fire in the Greater Yellowstone ecosystem. *Proceedings on the National Academy of Sciences of the United States of America* 104:4782-4789.
- Tyurin V. 1951. Analytical procedure for a comparative study of soil humus. *Trudy Pochr. Inst. Dokuchaev* 38. Madrid.
- Úbeda X. 2001. Influencia de la intensidad de quemado sobre algunas propiedades del suelo después de un incendio forestal. *Edafología* 8:41-49.
- Úbeda X, Mataix-Solera J. 2008. Fire effects on soil properties: A key issue in forest ecosystems. *Catena* 74:175-176.
- Úbeda X, Outeiro L, Pereira P, Miguel A. 2009. Estudios sobre las consecuencias del fuego en las propiedades del suelo y la erosión en Cataluña. *Investigaciones del GRAM (Grupo de Recerca Ambiental Mediterrànea). Efectos de los incendios forestales sobre los suelos de España.* Valencia: Càtedra Divulgación de la Ciencia. Universitat de Valencia. p. 325-353.
- Ulery AL, Granham RC, Amrhein C. 1993. Wood ash composition and soil pH following intense burning. *Soil Science* 156:358-364.
- Ulery AL, Graham RC, Chadwick OA, Wood HB. 1995. Decade-scale changes of soil carbon, nitrogen, and exchangeable cations under chaparral and pine. *Geoderma* 65:121-134.
- Xu P-B, Qu M, Xue L. 2013. Effects of forest fire on forest soils. *Chinese Journal of Ecology* 32:1596-1606.
- Zavala LM, Jordan A, Gil J, Bellinfante N, Pain C. 2009. Intact ash and charred litter reduces susceptibility to rain splash erosion post-fire. *Earth Surface Processes and Landforms* 34:1522-1532.