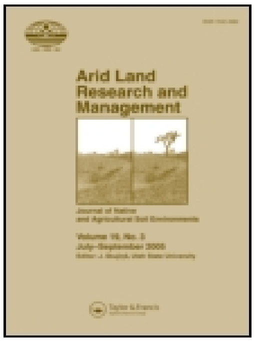

Taylor & Francis
Taylor & Francis Group

Arid Land Research and Management

ISSN: 1532-4982 (Print) 1532-4990 (Online) Journal homepage: http://www.tandfonline.com/loi/uasr20

The Caldenal ecosystem: Effects of a prescribed burning on soil chemical properties

María Sofía Larroulet, Estela Noemí Hepper, Mónica Patricia Álvarez Redondo, Valeria Belmonte & Ana María Urioste

ARID LAND RESEARCH AND MANAGEMENT
2016, VOL. 30, NO. 1, 105–119
http://dx.doi.org/10.1080/15324982.2015.1046198

The Caldenal ecosystem: Effects of a prescribed burning on soil chemical properties

María Sofía Larroulet, Estela Noemí Hepper, Mónica Patricia Álvarez Redondo, Valeria Belmonte, and Ana María Urioste

Facultad de Agronomía, Universidad Nacional de La Pampa, Santa Rosa, La Pampa, Argentina

ABSTRACT

Before and after a prescribed burning, the upper 2.5 cm of soil in patches of forage, nonforage, and shrub vegetation were sampled. Then, bulk density, gravimetric moisture, pH in water, available phosphorus, exchangeable cations, cationic exchange capacity, total nitrogen, total, particulate, and mineral organic carbon contents were determined. Maximum temperature ranges reached over the ground during burning were measured and the highest values were registered in shrubs. Results showed that total, particulate, and mineral organic carbon and total nitrogen contents and percent base saturation increased in all soils after burning, without detecting differential effects between vegetation patches. After burning, available phosphorus content increased both for forage and shrub patches. A Na^{+} content decrease was observed for all soils in the different patches while Mg^{2+} content increased. No changes in the other analyzed variables were observed. Prescribed burning, as studied in the present work, might improve the Caldenal soils' chemical fertility, mainly due to an increase in labile organic matter and some nutrients essential for plant growth.

ARTICLE HISTORY
Received 13 May 2014
Accepted 26 April 2015

KEYWORDS
Fire; semi-arid region; soil fertility; vegetation patch

Introduction

The Calden (*Prosopis caldenia* Burkart) forest, located in La Pampa, Argentina, currently shows a great structural heterogeneity with its vegetation distributed in patches as an effect of grazing (Morici et al. 2009). Previous studies conducted in this ecosystem have shown that the vegetation covering the soil surface influences the total organic carbon content and its fractions, total nitrogen, available phosphorus, exchangeable calcium, and bulk density value (Hepper et al. 2013).

Fire constitutes, in some cases, an equilibrium factor necessary to maintain the ecosystems biodiversity, although it can also become in one of the main causes of its degradation, which is demonstrated by the important loss of forests and pastures affecting agricultural, farming and forestry activities. The Calden forest is no stranger to this problem, which added to the widespread use of prescribed burning, has led many local researchers to study the effect of its management on diverse components of the ecosystem (Pelaez et al. 2001; Castelli and Lazzari 2002; Llorens and Frank 2003). Prescribed burning is man-generated fire with a determined aim, restricted to pre-established areas. Thus, in the Caldenal region

CONTACT María Sofía Larroulet sofialarroulet@agro.unlpam.edu.ar Facultad de Agronomía, Universidad Nacional de La Pampa, Ruta 35 km 334, C. P: 6300, C. C: 300, Santa Rosa, La Pampa, Argentina.
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uasr.

where farming is the main productive activity, fire is used as a way to restore summer and winter forage species after continuous grazing, or as a tool to limit the spread of wildfires.

Fire can produce physical, chemical and biological alterations in soil properties. The magnitude and duration of these changes depend on several factors. One of these factors is fire severity, which is also dependent of fire intensity (Mataix-Solera et al. 2011). The effect of prescribed burning on the soil physical and chemical properties depends, among other things, on fire intensity and duration, type of soil, and moisture content at the moment of burning (Pyne, Andrews, and Laven 1996). On the other hand, the behavior of fire depends on the type and amount of fuel, its moisture content and arrangement, topography and wind (Bento-Gonçalves et al. 2012). The energy released during this practice is directly related to plant tissue death but poorly related to the properties under the soil surface (Kunst and Rodríguez 2003). This can be associated with low heat flux in the soil body during the burning, due to low thermal conductivity of the materials that compose it (Kunst and Bravo 2003). When soils have the same texture and compaction degree, thermal conductivity depends on moisture content (Abu-Hamdeh and Reeder 2000).

Quantity and quality of organic matter are significant attributes of soil qualities, mainly in semi-arid environments, because of their effect on physical and chemical characteristics and on the biota, as this is carbon and energy source (Doran, Sarrantonio, and Liebig 1996).

The effect of fire on the organic matter content in soils is highly variable: important losses due to the volatilization of organic compounds have been reported, as well as increases in its content due to the incorporation to the soil of partially-burned plant remains (González-Pérez et al. 2004). The total organic matter dynamics contributes little to the study of short-term effects of agricultural practices; however, its fractions are more sensible (Haynes 2000). While the use of soil organic fractions, physically separated, as indicators to trace changes produced by management practices have been widely studied (Galantini 2008; Cambardella and Elliott 1994), minimal research regarding the effects of prescribed burning on organic matter fractions in silvopastoral systems of the Pampean Caldenal ecosystem has been carried out. Galantini et al. (2008) defined the most dynamic fraction of organic matter in the soil as the youngest and highly active organic matter composed by particles bigger than humus and free of mineral matrix. Several authors have indicated that this is a more sensible indicator of the changes in soil quality than total organic carbon content and total nitrogen (Galantini 2008).

Although fire is considered to be a good tool to accelerate processes of nutrient release from residues, nutrients' contents in soils can increase, decrease or remain unchanged. Smith et al. (2001) found increases in total phosphorous and total calcium concentrations and decreases of total nitrogen. They attributed the increases to a physical reduction of soil surface layers, and the nitrogen decrease to its volatilization. Arocena and Opio (2003) found increases in pH values and in calcium, magnesium, potassium and exchangeable sodium content. Castelli and Lazzari (2002) detected increases in total phosphorus and available sulfur content, pH values and cationic exchange capacity in soils under a cover of woody species as well as increases in nitrogen availability, mainly in soils under a cover of herbaceous species. Enrichment can be attributed to a fire effect similar to that of organic matter degradation, since final products in both cases are similar. The differences lie in the speed of these processes, while biological degradation may take from days to years, depending on the degree of organic matter humification, fire induced decomposition and mineralization takes only seconds (García-Oliva, Sanford, and Kelly 1999). Nutrient

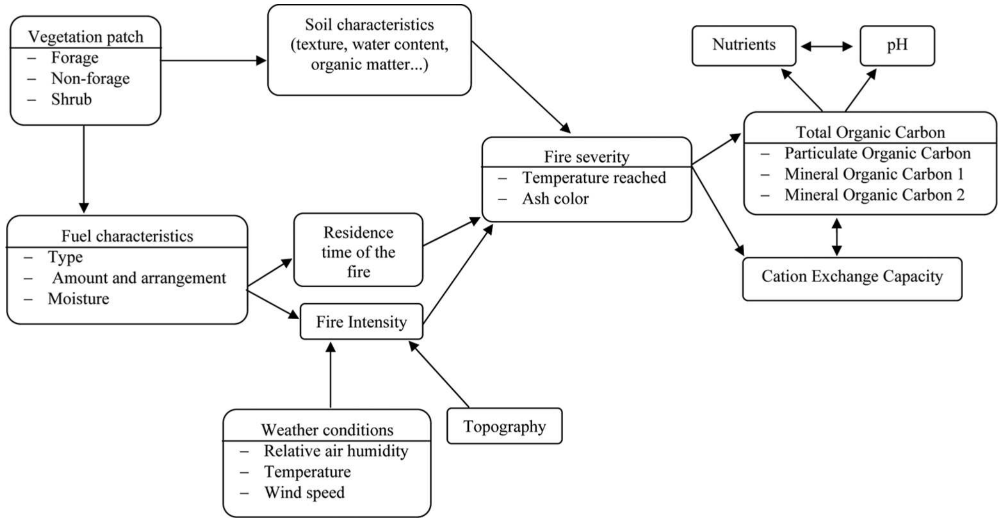

Figure 1. Summary diagram on factors affecting the changes of chemical properties immediately after a prescribed burning.

losses could be due to volatilization, washing, ashes scouring by convection currents during the burning or wind erosion after it (Giardina, Sanford, and Døckersmith 2000).

From the analysis of the available literature a summary diagram on factors affecting the changes of chemical properties immediately after a prescribed burning was developed (Figure 1). Our study objective was: to evaluate if prescribed burning affects in a different manner organic carbon contents and its fractions, nutrients, pH and cation exchange capacity according to different soil plant covers on a sandy loam soil in the Pampean Caldenal region (Argentina).

Materials and methods

Study area

The study area belongs to the phytogeografical region of the Espinal, specifically to the Calden District (or Caldenal) in La Pampa province, Argentina (Figure 2).The Caldenal is a forest formation, characteristic of the temperate semi-arid central region of Argentina, which is represented by xerophilous deciduous forests, shrubby steppe and Gramineae. The typical vegetation is a forest dominated by calden trees (*Prosopis caldenia*) associated to other arboreal species such as *Prosopis flexuosa* DC., *Geoffroea decorticans* (Gillies ex Hook. & Arn.) Burkart and *Jodina rhombifolia* (Hook. & Arn.) Reissek. Frequently, there is a middle stratum, composed of shrub species and an herbaceous stratum dominated mainly by Gramineae (Cabrera 1976).

The study area has a temperate weather, characterized by a high temperature range between the coldest and warmest month, with annual average temperatures between 14 and 16°C; it is located between the 500 and 600 mm isohyets, registering the highest average monthly precipitation from October to March (spring-summer), and showing a great monthly and annual variability in precipitation, being this a characteristic of both arid and semi-arid regions (Instituto Nacional de Tecnología Agropecuaria (INTA) Provincia de La Pampa and Universidad Nacional de La Pampa (UNLPam) 2004).

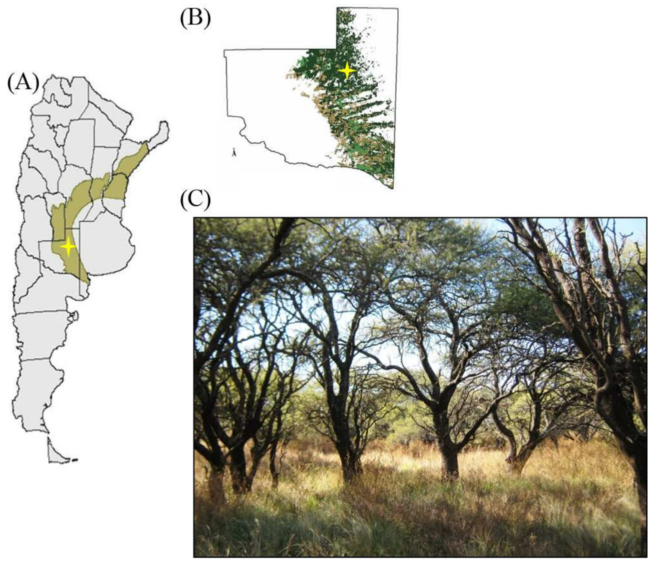

Figure 2. Location of the study area. (A) Espinal Phytogeographical Region, Argentina, (B) Calden District, Province of La Pampa, and (C) Calden Forest, Bajo Verde Farm.

The relief in this region is flat and the altitude varies among 80 and 120 m a.s.l. The parent materials of the soils are pleistocenic and holocenic eolian sands. The soil in the study area was classified as Entic Haplustoll of sandy loam texture (Hepper et al. 2013).

Prescribed burning

Prescribed burning was conducted on April 2008 in a 20 ha paddock used for grazing, which is part of a farm located 40 km NW of Santa Rosa city, La Pampa, Argentina (36° 29′ S latitude and 64° 37′ W longitude).

The average temperature registered during the burning day was 25°C, the relative air humidity was 25% and the wind direction was NW, ranging from 6 and 20 km h^{-1} speeds. The ignition technique consisted in starting the fire in the south and east ends of the paddock to windward along a fire line (backing fire). After that the burning was completed with a head fire, lighting a continuous line that advanced from the NW, downwind. Fires moving with the wind produce greater heat intensity than backfires, then, the progress of the flame front is slower and soil is exposed to high temperatures for a longer period (Raison 1979). The post-burning sampled plots were in the area affected by the head fire.

The temperature range (including the maximum temperatures reached during the burning) was measured over the soil surface, and at two depths: 2 and 4 cm. To determinate it, a set of ten heat sensitive crayons (tempils), covering a temperature range between 52 and 649°C, were placed in each of the five plots of each patch (without disturbing the land).

Sampling and laboratory analysis

Prior to the burning, three vegetation patches were selected.

Forage Patch (F): gramineous-herbaceous stratum dominated by forage species with a predominance of *Piptochaetium napostaenmse* (Speg.) Hack., with *Poa ligularis* Nees ex Steud., as secondary species.

Non-forage Patch (NF): gramineous-herbaceous stratum, under calden (*Prosopis caldenia*), dominated by non-forage species with a predominance of *Jarava ichu* Ruiz & Pav., *Nassella tenuissima* (Trin.) Barkworth, and *Amelichloa brachychaeta* (Godr.) Arriaga & Barkworth.

Shrub Patch (S): with a predominance of resprouts of *Prosopis caldenia* and gramineous-herbaceous stratum dominated by *Jarava ichu*., *Nassella tenuissima*, and *Amelichloa brachychaeta*.

Physical and chemical soil properties of each vegetation patch are listed in Table 1.

For each vegetation patch, five sampling plots (about 50 m^2 each) were selected. In each plot, three soil samples ($N = 45$) were collected randomly one day before (prefire) and one day after (postfire) the burning (sampling time). No rains were registered.

On the basis of the edaphic variables to be determined, several types of sampling were conducted:

- The first 6 cm of the profile were sampled to determine bulk density (BD) by the cylinder method (Schlichting, Blume, and Stahr 1995) and moisture was determined by gravimetry.
- The first 2.5 cm of the profile including the litter layer were sampled to conduct chemical analysis. These samples were air-dried, sieved by a 2 mm wire mesh and used to determine: pH in water (1:2.5 relation) by potentiometry; available phosphorus (Pa) by the Bray Kurtz method (Bray and Kurtz 1945); total organic carbon (TOC) by the wet oxidation method (Walkley and Black 1934); exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) and cationic exchange capacity (CEC) by extraction with ammonium acetate solution 1 mol dm^{-3}, pH 7, and subsequent determination of Ca^{2+} and Mg^{2+} in the extract by titration with EDTA and K^+ and Na^+ by flame photometry (Jackson 1970). With the same samples, a physical fractioning of the soil by particle size was performed; to achieve this, the wet sieve method was used (Galantini 2005), obtaining two fractions: 2000–100 μm and 100–56 μm. In each fraction, the organic carbon content was determined by the Walkley and Black (1934) method, obtaining the particulate organic carbon (POC) and mineral organic carbon (MOC 1) content, respectively. Carbon content in the fraction smaller than 56 μm (MOC 2) was calculated as the difference:

$$\text{MOC 2} = TOC - (\text{POC} + \text{MOC1})$$

Composed samples obtained from three subsamples from each patch were used to total nitrogen content determination (Nt) conducted by the Kjeldahl method (Bremner and Mulvaney 1982). The TOC/Nt ratio was calculated for each sample.

Statistical analysis

In order to compare the means, the data statistical analysis were performed by means of mixed linear models (Littell et al. 2006). The "vegetation patch" and "sampling time"

Table 1. Main characteristics of the soils studied.

Vegetation patch	Soil sampling depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density ($g\,cm^{-3}$)	Organic carbon ($g\,kg^{-1}$)	pH	Cation exchange capacity ($cmol\,kg^{-1}$)
Forage	0–2.5	66.7	22.1	11.2	1.06	16.25	6.24	15.70
Non-forage	0–2.5	66.6	12.8	20.5	0.86	38.81	5.79	16.80
Shrub	0–2.5	71.1	19.6	9.3	0.91	20.88	6.65	16.35

factors were considered as fixed effects while the sampling plots were considered as random effects. When the interaction "vegetation patch" × "sampling time" was significant, the means of each variable studied before and after burning were compared in each vegetation patch by the LSD Fisher method ($p < 0.05$).

Results and discussion

Fuel characteristics

The fuel in the F and NF patches was only composed by fine material (less than 0.5 cm in diameter), while in the S patches was found to be a combination of fuels derived from fine, medium, and thick materials (more than 0.5 cm in diameter). The soil surface covered by litter was 11.7, 20.1, and 21.8% in the F, NF, and S patches, respectively. The thickness of this layer did not exceeded 1 cm in any patch. The aerial biomass deposited in the gramineous-herbaceous stratum of the F patch was 2496 ± 140 kg ha^{-1} of dry matter and in the NF patch was 7500 ± 250 kg ha^{-1} of dry matter. In the S patch, the aerial biomass of the shrub stratum was 32500 ± 400 kg ha^{-1} of dry matter, while gramineous-herbaceous stratum was 7500 ± 250 kg ha^{-1} of dry matter (Ernst 2014). Flores Garnica (2009) reported that there should be a minimum of 1230 kg ha^{-1} of dry matter of fine fuel material and it should be distributed in a homogeneous way, in order to have a correct fire spread. In our study, every vegetation patch exceeded this minimum value of fine fuel material and its distribution was homogeneous, which allowed the prescribed burning to be successful.

Prescribed burning characteristics

The flame height reached between 1.20 m and 1.50 m and the rate of spread was 180 m h^{-1}. After burning it was observed that the fuel in each patch had been completely consumed, calden trees had not been damaged by the fire and no plants had been killed. Although the bushes (calden resprouts) had been burnt, they resprouted sometime after the burning. In the F and NF patches dark ashes were observed, while in the S patch dark grey to white ashes were found under the bushes (Figure 3). The ash color is an indirect estimator of the severity of fire, through organic matter consumption. Brownish and reddish colors represent low fire severity, black to very dark grey moderate fire severity and dark grey to white ash, high fire severity (Ubeda et al. 2009). The color observed in the ashes of the F and NF patches indicated that the severity of the burn was moderate, whereas in the S patch, it could be estimated as higher severity.

According to the measures of the crayons, the temperatures reached in the soil surface did not exceeded the 163°C and 246°C in the F and NF patches, respectively, while in the soil surface of the S patch the maximum temperatures reached presented values between 427–538°C (Table 2). The higher temperatures observed in the S patch could be explained by the presence of coarse fuel, added to a larger total quantity of aerial biomass and litter respect the F and NF patches. The differences observed in the maximum temperatures reached in the soil surface agrees with Certini (2005), who indicated that in presence of heavy fuels, temperatures between 500–700°C are reached at the soil surface. In each patch the maximum temperatures reached at 2 and 4 cm were lower than in soil surface (Table 2).

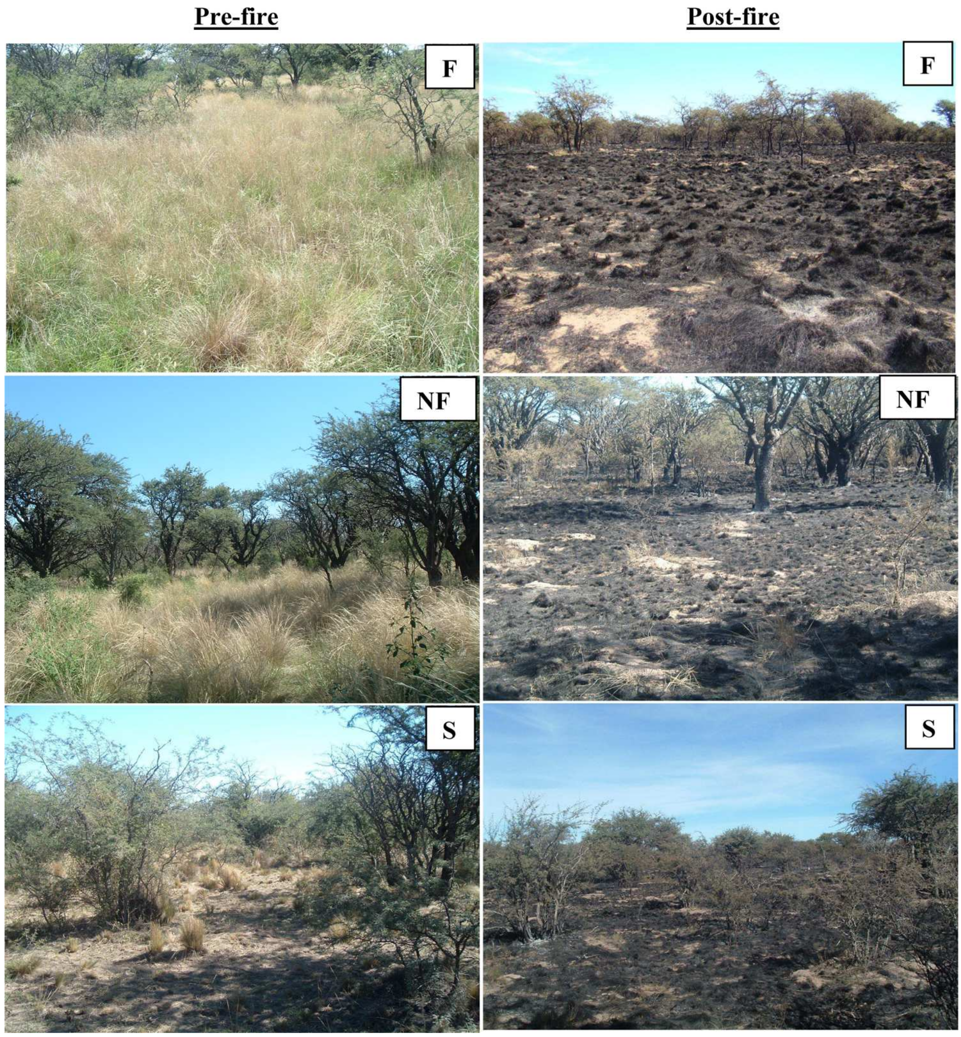

Figure 3. Photographs of the three vegetation patches studied: forage (F), nonforage (NF), and shrub (S) in the two sampling times (prefire and postfire).

This can be associated with low heat flux in the soil body during the burning, due to the low thermal conductivity of the materials that compose it (Kunst and Bravo 2003).

In F patch, there was less heat conduction through the soil, in contrast to what had been observed in NF and S patches. This was an expected result due to the fact that during the

Table 2. Temperature ranges containing the maximum temperatures reached during a prescribed burning at different depths and gravimetric moisture pre-fire, in soils of different vegetation patches: forage (F), nonforage under Calden (NF), and shrub (S).

	Temperature ranges at different depths (°C)			
Patches	Soil surface	2 cm	4 cm	Gravimetric moisture pre-fire (%)
F	121–163	Under 52	Under 52	2.39 ± 0.26b
NF	204–246	121–163	52–93	3.81 ± 0.26a
S	427–538	163–204	121–163	3.60 ± 0.27a

pre-burning the gravimetric moisture content was significantly lower than those observed in the other patches (Table 2). This determined the lowest thermal conductivity, which is a property directly related to the soil water content (Abu-Hamdeh and Reeder 2000). Furthermore, this result agrees with DeBano, Neary, and Ffolliott (2005) who indicate that dry soils are poor conductors of heat and thereby do not heat substantially below about 5 cm unless heavy long-burning fuels are combusted.

Soil chemical properties

Gravimetric moisture in all vegetation patches was not affected either by the interaction between type patch and sampling time or by the prescribed burning (Table 3). According to previous results shown by other researchers, a decrease in its content after fire was expected, since water stored near the soil surface was evaporated by the thermal energy released during combustion (Hubbert et al. 2006; Granged et al. 2011). This difference could be due to the initial moisture contents (pre-fire), which were lower than those reported by other authors.

In this study TOC content and POC and MOC 1 fractions were affected in the same way by the prescribed burning in the three vegetation patches studied, which indicates that there was no differential effect of this management practice on these variables as a function of the type of dominating vegetation. In post-burning, an increase in TOC, POC and MOC 1 content was observed (Table 4). The higher TOC and POC contents could be associated with the input of dry and partially burned vegetation remains into the soil and to the incorporation of the litter layer in the form of particulate material with a particle size smaller than 2 mm (González-Pérez et al. 2004). The MOC 1 fraction can include both recent organic remains such as organic-mineral complexes and microaggregates, with sizes that may be bigger than 50 μm (Galantini 2005); therefore, the increase in MOC 1 content could reflect the fact that the fire, on the decomposition of organic matter, acts similarly to biological mineralization. The difference is the time involved in each process: while fire acts in seconds, biological mineralization can take years (Hungerford et al. 1991; García-Oliva, Sanford, and Kelly 1999). The MOC 2 content was not affected by the interaction between sampling time and vegetation patch, or by the prescribed burning (Table 4). This fraction, associated with lime and clay particles size in the form of organic-mineral complexes, represents the most transformed and stable form of soil organic material and, therefore, chemically protected from thermal energy.

Nt content increased in the same way after the prescribed burning in the three vegetation patches, which indicates that there was no differential effect of this management

Table 3. Estimated mean and standard error for gravimetric moisture and pH (at 2.5 cm of the profile), classified by sampling time (pre-fire and post-fire) in soils of different vegetation patches: forage (F), non-forage under Calden (NF) and shrub (S).

	Gravimetric moisture (%)		pH	
	Pre-fire	Post-fire	Pre-fire	Post-fire
F	2.6 ± 0.3	2.1 ± 0.3	6.2 ± 0.2	6.5 ± 0.2
NF	4.1 ± 0.3	3.5 ± 0.3	5.8 ± 0.2	6.1 ± 0.2
S	3.8 ± 0.4	3.4 ± 0.3	6.6 ± 0.2	6.8 ± 0.2
Vegetation patch X Sampling time	ns		ns	
Mean content per sampling time	3.52 ± 0.2 ns	3.02 ± 0.2 ns	6.2 ± 0.2 ns	6.5 ± 0.2 ns

Table 4. Estimated mean contents and standard error for total organic carbon (TOC), particulate organic carbon (POC), mineral organic carbon 1 and 2 (MOC 1 and MOC 2), total nitrogen (N_t) and total organic carbon/total nitrogen ratio (TOC/N_t) (at 2.5 cm of the profile), classified by sampling time (pre-fire and post-fire) in soils of different vegetation patches: forage (F), non-forage under Calden (NF) and shrub (S).

	TOC (g kg^{-1})		POC (g kg^{-1})		MOC 1 (g kg^{-1})		MOC 2(g kg^{-1})		Nt (g kg^{-1})		TOC/Nt (g kg^{-1})	
	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire
F	16.2 ± 4.3	28.2 ± 4.3	6.3 ± 2.0	13.2 ± 2.0	2.9 ± 0.4	4.0 ± 0.4	7.1 ± 0.9	11.0 ± 1.3	1.1 ± 0.1	1.6 ± 0.1	14.1 ± 1.4	17.0 ± 1.4
NF	38.8 ± 5.2	50.4 ± 5.2	15.8 ± 2.0	26.2 ± 2.0	4.7 ± 0.4	6.0 ± 0.4	17.4 ± 4.8	16.5 ± 3.3	2.8 ± 0.5	4.1 ± 0.5	14.2 ± 1.4	12.8 ± 1.4
S	20.9 ± 3.2	33.9 ± 3.2	9.1 ± 2.0	19.4 ± 2.0	3.8 ± 0.4	3.8 ± 0.4	8.0 ± 1.8	10.7 ± 2.0	1.6 ± 0.3	2.4 ± 0.3	14.2 ± 1.4	14.4 ± 1.4
Vegetation patch X Sampling time	ns		ns		Ns		ns		ns		ns	
Mean content per sampling time	25.3 ± 2.5b	37.5 ± 2.5a	10.4 ± 1.2b	19.6 ± 1.2a	3.8 ± 0.2b	4.6 ± 0.2a	10.8 ± 3.5 ns	12.7 ± 2.5 ns	1.8 ± 0.2b	2.7 ± 0.2a	14.2 ± 0.8 ns	14.7 ± 0.8 ns

practice on these variable as a function of the type of dominating vegetation (Table 4). Different authors have found losses of this nutrient due to volatilization after fire (Raison 1979; Giardina, Sanford, and Døckersmith 2000; Certini 2005). However, this process does not occur at temperatures under 200°C (Knoepp, DeBano, and Neary 2005). This agrees with that observed in our study, given that the measured temperatures at the sampling depth were found within this range (Table 2). The observed increase in Nt content could be due to the fact that the loss through volatilization (Giardina, Sanford, and Døckersmith 2000) was compensated by the input of dry and partially burned vegetation remains into the soil and to the incorporation of the litter layer in the form of particulate-material with a particle size smaller than 2 mm (González-Pérez et al. 2004). Also, this increase was in agreement with that of the TOC content, reflected in the TOC/Nt ratio, which had not been affected by the prescribed burning, showing that both variables increased in a similar way after the burning (Table 4). Moreover, the fact that the TOC/Nt ratio did not change would indicate that the organic matter quality was unaffected.

The pH was not affected either by the interaction between vegetation type and the sampling time or the burn (Table 3). Certini (2005) states that in noncalcareous soils the pH increases because of the release of the alkaline cations (Ca^{2+}, Mg^{2+}, and K^{+}) bound to the organic matter. However, Arocena and Opio (2003) argue that significant increases occur only at high temperatures (>450–500°C). This can explain that in our study no significant differences were detected in the pH, given that in the soil body (2–4 cm) no temperatures higher than 450°C were found in any of the three vegetation patches studied.

Pa content was affected by the interaction between patch type and sampling time, showing that burning influenced this nutrient content in the studied soil patches in a different way. In soil F and S patches, significant increases in the Pa content were found (Figure 4). In forest ecosystems, a great amount of nutrients is contained in the organic matter found in the forest soil (Litton and Santelices 2003). The increase of Pa in F and S patches could be explained by the burning of this organic matter, which would leave relatively high amounts of available phosphorus in the ashes found in the soil surface immediately after the burning (Knoepp, DeBano, and Neary 2005). Debano and Conrad (1978) suggested that 100% of the phosphorus from plants and litter consumed during a fire, returns to the soil surface as ash. If this ash is not removed from its place by the wind and/or surface

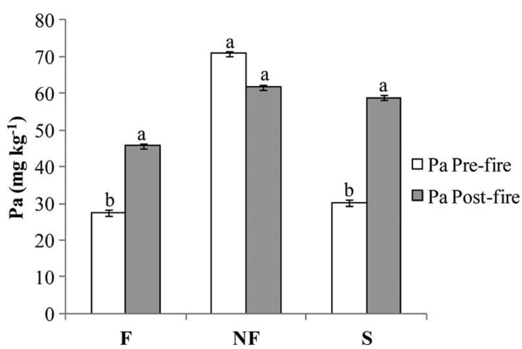

Figure 4. Mean contents of available phosphorus (Pa), classified by sampling time (prefire and post-fire), in soils of different vegetation patches: forage (F), nonforage under Calden (NF), and shrub (S). Error bars indicate the standard error of the observed data. Different letters within the same vegetation type indicate significant differences between sampling times ($p < 0.05$).

Table 5. Estimated mean contents and standard error for exchangeable cations (Na^{+}, K^{+}, Ca^{2+} and Mg^{2+}), cation exchange capacity (CEC) and base saturation (BS) (at 2.5 cm of the profile), classified by sampling time (pre-fire and post-fire) in soils of different vegetation patches: forage (F), non-forage under Calden (NF) and shrub (S).

	Na^{+} (cmol kg^{-1})		K^{+} (cmol kg^{-1})		Ca^{2+} (cmol kg^{-1})		Mg^{2+} (cmol kg^{-1})		CEC (cmol kg^{-1})		BS (%)	
	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire
F	0.61 ± 0.06	0.44 ± 0.06	1.32 ± 0.03	1.19 ± 0.12	10.17 ± 0.45	10.62 ± 094	1.63 ± 027	2.05 ± 0.27	15.70 ± 0.81	14.16 ± 0.81	86.27 ± 4.43	96.87 ± 1.29
NF	0.73 ± 0.06	0.57 ± 0.06	1.27 ± 0.09	1.31 ± 0.33	13.05 ± 0.64	15.37 ± 1.32	2.06 ± 0.27	2.98 ± 027	16.80 ± 0.91	18.51 ± 0.81	88.27 ± 5.94	96.47 ± 1.72
S	0.63 ± 0.06	0.55 ± 0.06	1.40 ± 0.06	1.12 ± 0.22	13.51 ± 0.97	15.93 ± 2.00	1.80 ± 0.27	1.97 ± 0.27	16.35 ± 0.81	14.99 ± 0.81	94.87 ± 2.01	98.87 ± 1.29
Vegetation patch X Sampling time	ns		ns		ns		ns		ns		ns	
Mean content per sampling time	0.66 ± 0.04a	0.52 ± 0.04b	1.33 ± 0.09 ns	1.21 ± 0.09 ns	12.24 ± 0.68 ns	13.97 ± 0.68 ns	1.83 ± 0.16b	2.33 ± 0.16a	16.28 ± 0.51 ns	15.89 ± 0.48 ns	89.80 ± 2.56b	97.40 ± 0.74a

runoff, it will be incorporated to the mineral soil, generating an increase in the extractable phosphorus levels after a fire (Litton and Santelices 2003). On the other hand, the observed Pa increase cannot be attributed to the shift of the calcium phosphate solubility equilibrium predominating in these soils because no significant differences were found in pH values after the burning (Table 3). No significant differences were found in the Pa content in the NF patch (Figure 4), which would indicate that the burning of the plant material in this patch could have generated ashes rich in calcareous-substances, which immobilized the phosphorus released during the burning (Knoepp, DeBano, and Neary 2005).

Exchangeable cation contents, CEC values and percentages of base saturation were not affected by the interaction between patch type and sampling time (Table 5). The content of Na^+ decreased significantly after burning. This effect cannot be associated with its volatilization, since this process takes place when temperatures are higher than 800°C (Neary et al. 1999; Albanesi and Anriquez 2003) but these losses can be associated with particle transfer in the generated smoke (Knoepp, DeBano, and Neary 2005). The Mg^{2+} content increased significantly after burning, this could be due to the chemical composition of the ash deposited on the soil surface, which contains higher levels of this cation. Exchangeable Ca^{2+} and K^+ contents were not affected by the burning. Kang and Sajjapongse (1980), working under controlled laboratory conditions, found changes in K^+ and Ca^{2+} content when working with a temperature above 500°C. In the same way, CEC was not affected by the controlled burning. Hepper et al. (2008), when working under controlled laboratory conditions and with soils from the Caldenal region, found that CEC values started to be affected when temperatures exceeded 400°C, because higher temperatures decreased the finest textural fractions, particularly silt and clay. These fractions offer the highest amount of exchange sites in these soils (Hepper et al. 2006). The base saturation percentage increased after burning as a consequence of the prevailing release of bases from the combusting organic matter (Certini 2005). This result is in agreement with previous studies conducted by Arocena and Opio (2003) after a burning in soils collected from sub-boreal forests in Canada. On the other hand, the changes observed in cations did not coincide with the results obtained by Castelli and Lazzari (2002) after a controlled burning carried out in the southeast region of the Pampean Caldenal, because they showed an increase in the amount of K^+ content while the content of the remaining cations was not affected. It is very difficult to predict how the soil will behave during the burning, as burning severity is influenced not only by both intensity and duration but also by atmospheric conditions, landscape features, soil moisture level, and vegetation type and distribution (Thomaz, Antoneli, and Doerr 2014).

Conclusions

The temperatures reached during the fire in the different vegetation patches were related to the quantity and quality of the present fuel and the color observed in the ashes of each patch. Higher temperatures in the soil surface were reached in shrub patch. Therefore, the observed color of the ashes was clearer than in the other two patches, which indicates a higher consumption of organic matter and a higher severity of the fire. This is not consequent with the effect of this fire on the analyzed chemical properties of the soil, given that most of them were equally affected in every vegetation patch. The available phosphorous was the only nutrient whose content was modified by the prescribed burning in a differential way in every vegetation patch. In patches F and S, significant increases in their content were found; however, in NF patch no significant differences were observed.

This prescribed burning generated an increase in the contents of total organic carbon, particulate organic carbon, mineral organic carbon, total nitrogen and exchangeable Mg^{2+}. The contents of exchangeable Ca^{2+} and K^{+}, the cation exchange capacity, the pH, and the content of gravimetric moisture did not change. Furthermore, the only nutrient that decreased was the exchangeable Na^{+}.

In the Caldenal ecosystem, a prescribed burning with the characteristics described in this study would produce an improvement in the chemical soil fertility.

Acknowledgments

This research was financially supported by Facultad de Agronomía – Universidad Nacional de La Pampa, Argentina. The field work was carried out in an area owned by the University.

References

Abu-Hamdeh, N. H., and R. C. Reeder. 2000. Soil thermal conductivity: Effects of density, moisture, salt concentration and organic matter. *Soil Science Society of America Journal* 64: 1285–90.

Albanesi, A., and A. Anriquez. 2003. El fuego y el suelo. In *Fuego en los ecosistemas argentines*, ed. C. R. Kunst, S. Bravo, and J. L. Panigatti, 47–59. Santiago Del Estero, Argentina: INTA-Santiago Del Estero.

Arocena, J. M., and C. Opio. 2003. Prescribed fire-induced changes in properties of sub-boreal forest soils. *Geoderma* 113: 1–16. doi:10.1016/s0016-7061(02)00312-9

Bento-Gonçalves, A., A. Vieira, X. Úbeda, and D. Martin. 2012. Fire and soils: Key concepts and recent advances. *Geoderma* 191: 3–13. doi:10.1016/j.geoderma.2012.01.004

Bray, R., and L. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* 59: 39–45. doi:10.1097/00010694-194501000-00006

Bremner, J. M., and C. S. Mulvaney. 1982. Total nitrogen. In *Methods of soil analysis. Part 2: Chemical and microbiological properties*, ed. A. L. Page et al., R. H. Miller, and D. R. Keeney, 2nd ed., 595–624. Madison, WI: ASA and SSSA.

Cabrera, A. L. 1976. Regiones fitogeográficas Argentinas. In *Enciclopedia Argentina de Agricultura y Jardinería, Tomo II fascículo I*, ed. W. F. Kugler, 85. Buenos Aires, Argentina: Editorial Acme.

Cambardella, C. A., and E. T. Elliott. 1994. Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grassland soils. *Soil Science Society of America Journal* 58: 123–30. doi:10.2136/sssaj1994.03615995005800010017x

Castelli, L. M., and M. A. Lazzari. 2002. Impact of fire on soil nutrients in central semiarid Argentina. *Arid Land Research Management* 16: 349–64. doi:10.1080/15324980290000467

Certini, G. 2005. Effects of fire on properties of forest soils: A review. *Oecologia*. 143: 1–10. doi:10.1007/s00442-004-1788-8

Debano, L. F., and C. E. Conrad. 1978. The effect of fire on nutrients in a chaparral ecosystem. *Ecology* 59: 489–97. doi:10.2307/1936579

DeBano, L. F., D. G. Neary, and P. F. Ffolliott. 2005. Chapter 2: Soil physical properties. In *Wildland fire in ecosystems: Effects of fire on soils and water*, ed. D. G. Neary, K. C. Ryan, and L. F. DeBano, 29–52. General Technical Report. RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Doran, J. W., M. Sarrantonio, and M. A. Liebig. 1996. Soil health and sustainability. In *Advances in agronomy*, ed. D. L. Sparks, vol. 56, 1–54. San Diego, CA: Press Inc.

Ernst, R. D. 2014. Efecto de la quema controlada sobre la vegetación y el banco de semillas de gramíneas en la región del caldenal. Unpublished master's thesis. Universidad Nacional de La Pampa. Facultad de Agronomía. Provincia de La Pampa.

Flores Garnica, J. G. 2009. *Impacto ambiental de incendios forestales*. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. 325. Madrid, Spain: Mundi Prensa.

Galantini, J. A. 2005. Separación y análisis de las fracciones orgánicas. In *Tecnología en análisis de suelos: Alcances a laboratorios agropecuarios*, ed. L. Marban, and S. Ratto, 95–106. Capital Federal, Argentina: AACS.

Galantini, J. A. 2008. Fraccionamiento de la materia orgánica del suelo, In *Estudio de las fracciones orgánicas en suelos de la Argentina*, ed. J. A. Galantini, 19–40. Bahía Blanca, Argentina: Ediuns.

Galantini, J. A., J. Iglesias, M. Landriscini, L. Suñer, and G. Minoldo. 2008. Calidad y dinámica de las fracciones orgánicas en sistemas naturales y cultivados, In *Estudio de las fracciones orgánicas en suelos de la Argentina*, ed. J. A. Galantini, 71–96. Bahía Blanca, Argentina: Ediuns.

García-Oliva, F., R. Sanford, and E. Kelly. 1999. Effects of slash-and-burn management on soil aggregate organic C and N in a tropical deciduous forest. *Geoderma* 88: 1–12. doi:10.1016/s0016-7061(98)00063-9

Giardina, C. P., R. L. Sanford Jr., and I. C. Døckersmith. 2000. Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. *Soil Science Society of America Journal* 64: 399–405. doi:10.2136/sssaj2000.641399x

González-Pérez, J. A., F. J. González-Vila, G. Almendros, and H. Knicker. 2004. The effect of fire on soil organic matter—A review. *Environment International* 30: 855–70. doi:10.1016/j.envint.2004.02.003

Granged, A. J. P., L. M. Zavala, A. Jordán, and G. Bárcenas-Moreno. 2011. Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: A 3-year study. *Geoderma* 164: 85–94. doi:10.1016/j.geoderma.2011.05.017

Haynes, R. J. 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. *Soil Biology and Biochemistry* 32: 211–19. doi:10.1016/s0038-0717(99)00148-0

Hepper, E. N., D. E. Buschiazzo, G. G. Hevia, A. M. Urioste, and L. Antón. 2006. Clay mineralogy, cation exchange capacity and specific surface area of loess soils with different volcanic ash contents. *Geoderma* 135: 216–23. doi:10.1016/j.geoderma.2005.12.005

Hepper, E. N., M. S. Larroulet, V. Belmonte, and A. M. Urioste. 2013. Propiedades edáficas de un suelo del caldenal pampeano en parches con diferente vegetación. *Revista de la Facultad de Agronomía UNLPam* 23(2): 5–15.

Hepper, E. N., A. M. Urioste, V. Belmonte, and D. Buschiazzo. 2008. Temperatura de quema propiedades físicas y químicas de suelo de la región semiárida pampeana central. *Ciencia del Suelo* 26(1): 29–34.

Hubbert, K. R., H. K. Preisler, P. M. Wohlgemuth, R. C. Graham, and M. G. Narog. 2006. Prescribed burning effects on soil physical properties and soil water repellency in a steep chaparral watershed, southern California, USA. *Geoderma* 130: 284–98. doi:10.1016/j.geoderma.2005.02.001

Hungerford, R., M. Harrington, W. Frandsen, K. Ryan, and G. Niehoff. 1991. Influence of fire on factors that affect site productivity. In *Proceedings management and productivity of western-montane forest soils*, ed. A. Harvey and L. Neuenshwander, 32–50. Ogden, UT: USDA Forest Service GTR INT-280.

Instituto Nacional de Tecnología Agropecuaria (INTA) Provincia de La Pampa and Universidad Nacional de La Pampa (UNLPam). 2004. *Inventario integrado de los recursos naturales de la Provincia de La Pampa. Clima, geomorfología, suelo y vegetación*. Santa Rosa, La Pampa, Argentina: INTA-Buenos Aires.

Jackson, M. L. 1970. Determinaciones de los cationes metálicos canjeables de los suelos. In *Análisis químico de suelos*, ed. J. Beltrán Martínez (traductor), 2nd ed., 123–59. Barcelona, Spain: Ediciones Omega S. A.

Kang, B. T., and A. Sajjapongse. 1980. Effect of heating on properties of some soils from southern Nigeria and growth of rice. *Plant and Soil* 55: 85–95. doi:10.1007/bf02149712

Knoepp, J. D., L. F. DeBano, and D. G Neary. 2005. Chapter 3: Soil Chemistry. In *Wildland fire in ecosystems: Effects of fire on soils and water*, ed. D. G. Neary, K. C. Ryan, and L. F. DeBano, 53–72. General Technical Report. RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Kunst, C., and S. Bravo. 2003. Fuego, calor y temperatura, In *Fuego en los ecosistemas argentinos*, ed. C. R. Kunst, S. Bravo, and J. L. Panigatti, 39–45. Santiago del Estero, Argentina: INTA-Santiago Del Estero.

Kunst, C., and N. Rodriguez. 2003. Comportamiento del fuego: Una introducción, In *Fuego en los ecosistemas argentinos*, ed. C. R. Kunst, S. Bravo, and J. L. Panigatti, 189–98. Santiago del Estero, Argentina: INTA-Santiago Del Estero.

Littell, R. C., G. A. Milliken, W. W. Stroup, R. D. Wolfinger, and O. Schabenberger. 2006. *SAS System for Mixed Models*, 2nd ed. Cary, NC: SAS Institute Inc.

Litton, C. M., and R. Santelices. 2003. Effect of wildfire on soil physical and chemical properties in a Nothofagus glauca forest, Chile. *Revista Chilena de Historia Natural* 76: 529–42.

Llorens, E. M., and E. O. Frank. 2003. El fuego en la provincial de La Pampa. In *Fuego en los ecosistemas argentinos*, ed. C. R. Kunst, S. Bravo, and J. L. Panigatti, 259–68. Santiago del Estero, Argentina: INTA-Santiago Del Estero.

Mataix-Solera, J., A. Cerdà, V. Arcenegui, A. Jordán, and L. M. Zavala. 2011. Fire effects on soil aggregation: A review. *Earth-Science Reviews* 109: 44–60. doi:10.1016/j.earscirev.2011.08.002

Morici, E. F. A., W. Muiño, R. Ernst, M. A. Berrueta, A. M. Urioste, and E. N. Hepper. 2009. Respuesta del pastizal del caldenal a una quema controlada. In *Actas V Congreso Nacional, II Congreso del Mercosur y I Jornada Técnica de Productores sobre Manejo de Pastizales Naturales*, ed. M. H. Ottavis, 132. Corrientes, Argentina: Amanecer Rural.

Neary, D. G., C. C. Klopatek, L. F. DeBano, and P. F. Ffolliott. 1999. Fire effects on belowground sustainability: A review and synthesis. *Forest Ecology and Management* 122: 51–71. doi:10.1016/s0378-1127(99)00032-8

Pelaez, D. V., R. M. Boo, M. D. Mayor, and O. R. Elia. 2001. Effect of fire on perennial grasses in central semiarid Argentina. *Journal of Range Management* 54: 617–21. doi:10.2307/4003593

Pyne, S. J., P. L. Andrews, and R. D. Laven. 1996. *Introduction to wildland fire*. 2nd ed.. New York, NY: Wiley.

Raison, R. J. 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review. *Plant and Soil* 51: 73–108. doi:10.1007/bf02205929

Schlichting, E., K. H. Blume, and K. Stahr. 1995. *Bodenkundliches Praktikum*. Parey, Hamburg-Berlin: Blackwell Wissenschafts-Verlag.

Smith, S. M., S. Newman, P. B. Garrett, and J. Á. Leeds. 2001. Differential effects of surface and peat fire on soil constituents in a degraded wetland of the Northern Florida Everglades. *Journal of Environmental Quality* 30: 1998–2005. doi:10.2134/jeq2001.1998

Thomaz, E. L., V. Antoneli, and S. H. Doerr, 2014. Effects of fire on the physicochemical properties of soil in slash-and-burn agriculture. *CATENA* 122: 209–15. doi:10.1016/j.catena.2014.06.016

Ubeda, X., P. Pereira, L. Outeiro, and D. Martin. 2009. Effects of fire temperature on the physical and chemical characteristics of the ash from two plots of cork oak (*Quercus suber*). *Land Degradation and Development* 20: 589–608. doi:10.1002/ldr.930

Walkley, A., and I. A. Black. 1934. An examination of Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* 37: 29–38. doi:10.1097/00010694-193401000-00003