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Soil Erosion and Conservation Measures in Semiarid Ecosystems Affected by Wildfires

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1. Introduction

Fire is a factor of the first order in the interpretation of current ecosystem composition and landscape shape. Wildfires are a common phenomena dating back to the Earth's origins when they were caused by volcanic events or lightning. However, nowadays fires are more often caused by human interventions, accidental or deliberate, than by natural ones. In the European Mediterranean regions wildfires increases from 1960s aided by a general warming and drying trend, but driven primarily by socio-economic changes, including rural depopulation, land abandonment and afforestation with flammable species (Shakesby, 2011). Within that global Mediterranean region, semiarid areas have plant communities of sclerophyllous evergreen shrubs, rich in essences and with low plant water content, especially in dry seasons. These conditions facilitates the burning of these ecosystems.

Wildfires can be considered as a disturbance with a relatively severe temporary impact (Cerdà & Doerr, 2005). Their severity will depend on key factors such as the intensity and frequency of fire, but also on the the ecosystem components (vegetation, soil, rainfall, etc). The burning of plant cover and litter leaves the soil unprotected against rain impact. Also, immediately following a wildfire, a layer of ash and charred material typically covers the ground. It can increase or decrease the post-fire runoff and erosion response, depending upon the soil and ash properties and the ash thickness (Bodí et al., 2011). Soil loss after wildfire increases as long as there is no a minimal recovery of both plant cover and soil properties (Mataix et al., 2007). Although some strategies, such as plant resprouting, allow them to recover quickly, high fire frequency or soils with low quality can requier restoration strategies (Cerdà & Robichaud, 2009); these aspects that will be discused in this chapter.

2. Erosion on contrasting soil types affected by fire

Soil loss after fire in different soil types and plant community structures were analyzed in the semi-arid central Ebro Basin (NE-Spain) after fire.

2.1 Methods

Soil loss after fire is affected by soil properties, plant community structure (i.e. seeders versus sprouters ratio) as well as fire and rainfall intensity. In this subchapter, we analyze

these effects by means of two field methods: (i) sediment traps or Gerlach boxes and (ii) a rainfall simulator. Sediment traps give us a continuous measurement of soil erosion in microplots. A total of six Gerlach collectors (50 x 16 x 16cm) were installed under different vegetation covers and limited in area of influence with foil of a meter in length. Rainfall simulators give us a measurement of sheet erosion in burned microplots against a rain of given intensity (80 mm h⁻¹) in comparison to paired unburned areas (n=9). Experiments were carried out after fire for different soil units, such as Calcaric Regosol developed on Oligocene marls (calcareous soils) and Rendzic Phaeozem developed on colluvium (colluvial soils) as well as gypsiferous soils, classified as Haplic Gypsisol.

2.2 Results and discussion

Runoff and soil loss increased significantly after fire with exposure to strong rainfall (80 mm h⁻¹) in a Calcaric Regosol below a *Pinus halepensis* forest (Fig.1).

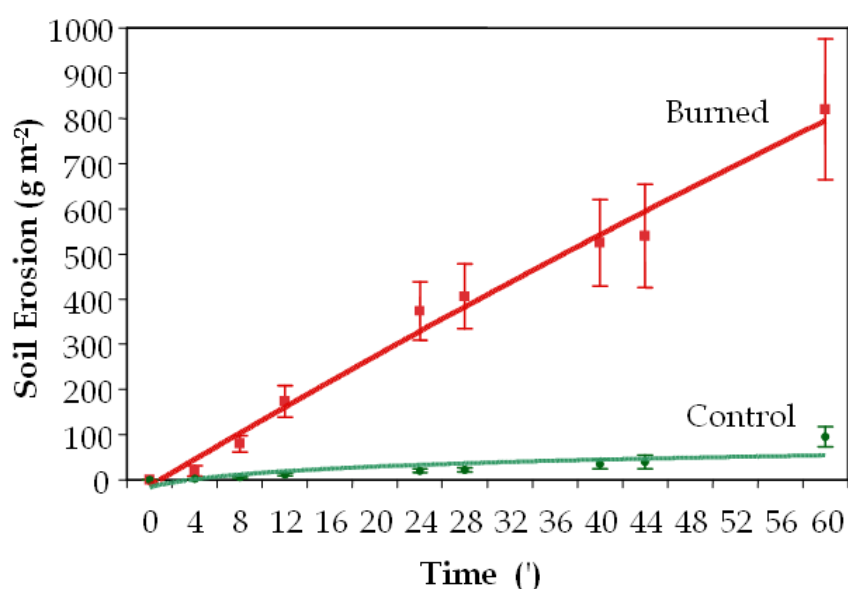


Fig. 1. Fire effects on soil erosion (g m⁻²) in a Calcaric Regosol (rainfall simulations=9).

The increase in soil erosion and runoff after fire is related to the decrease of soil surface cover, as well as in the soil aggregate stability on the surface by heat effect (Badía & Martí, 2003). Also, the different soil characteristics generate different responses closely related to their parent material, thus the erosion of soils developed on marls is greater than those developed in gypsum and colluvium (Fig. 2).

This relates to the low infiltration of marly soils, as well as temporary surface alteration due to fire (Cerdà & Doerr, 2005; Giovannini et al., 1990). Gypsiferous soils, with a lower fuel availability to alter the soil surface, and calcareous colluvial soils with more organic matter, stony and well-structured, did not reveal many problems of sheet erosion. The influence of the parent material of burned soils is shown in Figure 2 where we see a different curve for each soil type tested and confirm that the differences in soil characteristics generate different responses. The variability of these and other results is due to the diversity of variables under field conditions and confirms that the differences in soil characteristics generate different responses (Badía & Martí, 2003a). A compilation of tests performed with rainfall simulators in similar semi-arid Mediterranean environments can be found in Table 1.

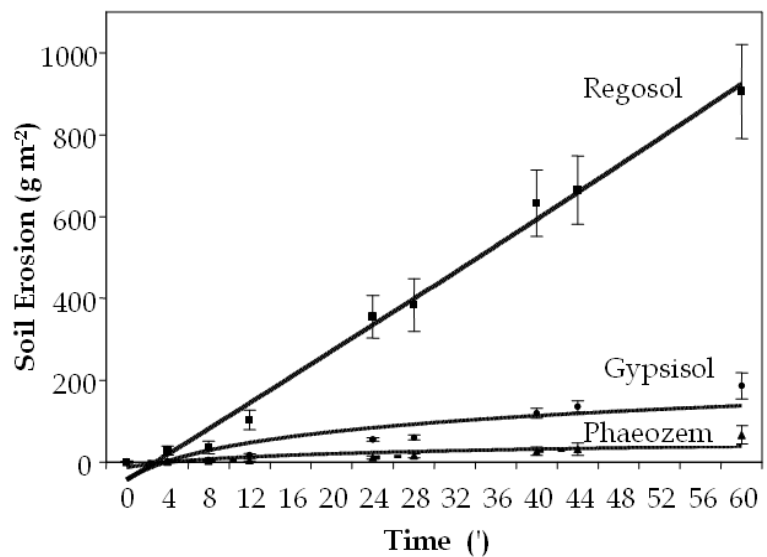


Fig. 2. Erosion (g m^{-2}) of the three types of burned soils ($n=9$). Rainfall simulator method.

In burned soils with a bare surface and therefore with the soil surface altered, the runoff coefficient ($\sim 90\%$ of applied water) and erosion ($\sim 850 \text{ g m}^{-2} \text{ h}^{-1}$) are very high. In different localites, the soil loss was lower in unburned plots ($\sim 0,2 \text{ Mg ha}^{-1} \text{ year}^{-1}$) than in burned plots, which accounted for between 2 and 20 $\text{Mg ha}^{-1} \text{ year}^{-1}$ over the first years. The following relationship between erosion and plant cover was established after the fire.

Sheet erosion (g m^{-2}) = 282 - 140,1 (Plant cover, %); $r = 0,97$, $n = 10$

(1)

The relevance of plant composition on plant cover evolution after fire and the effects on soil erosion has been demonstrated (Fig. 3). So, soil loss was significantly lower in a dense *Quercus coccifera* L. shrubland than in an open *Pinus halepensis* L. forest in Castej3n de Valdejasa. The figure 3 shows as plant community structure, as well as the sprouters:seeder ratio, explains differences in bare soil surface (Y2) and their relationship with soil loss (Y1) during the first months (X, time) after a wildfire.

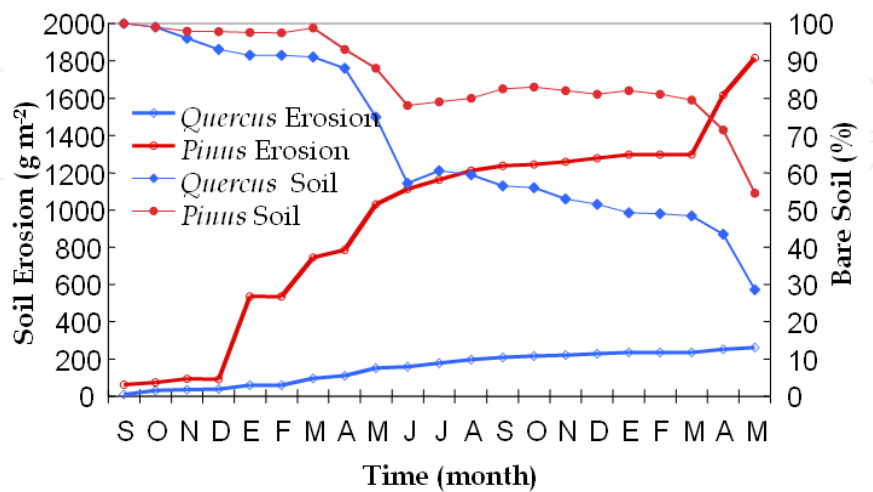


Fig. 3. Accumulated soil erosion (g m^{-2}) and bare soil (%) evolution in burned Castej3n de Valdejasa hills (NE-Spain).

Author	Location and Mean Annual Precipitation	Slope (%)	Soil	Vegetation	Plot size (m ²)	Rainfall duration - intensity
Cerdà et al., 1995	Valencia 688 mm	24-31	Calcareous, sandy loam	Pine & shrubs	0,24	60' 55 mm h ⁻¹
Kutiel et al., 1995	Carmel Mont 690 mm	15-22	Chromic Luvisol	Aleppo pine and oak forest	1	120' 30 mm h ⁻¹
Cerdà & Lavee, 1995	Judea's Desert 260 mm	35-40	Limestones	Shrubland	0,24	60' 37 mm h ⁻¹
Cerdà et al., 1998	Cáceres 511 mm	35-40	Dystric Cambisol, silty	Dehesa	0,24	60' 50 mm h ⁻¹
Imeson et al., 1998	Benidorm 387 mm	36-40	Lithic Leptosol Limest. colluvium	Aleppo pine forest	0,24	60' 50 mm h ⁻¹
Imeson et al., 1998	Finestrat 400 mm	36-40	Lithic Leptosol Limest. colluvium	Shrubland	0,24	60' 50 mm h ⁻¹
Lasanta et al., 2000	Zaragoza 324 mm	<10	Calcisols, Gypsisols	Barley, weeds	13,85	30' 60 mm h ⁻¹
Johansen et al., 2001	Los Alamos, USA 300 mm	4-8	Loam	Ponderosa pine forest	32,4	120' 60 mm h ⁻¹
Cerdà, 2001	Valencia 688 mm	21-31	Leptosols & Luvisols	Shrubland	0,24	60' 55 mm h ⁻¹
Ortiz & Alcañiz, 2001	Taradell 563 mm	20-25	Luvisols, sandy surface	Pines & oaks burned	0,24	40' 95 mm h ⁻¹
Cerdà, 2002	Alacant 358 mm	36-58	Badlands	Negligible vegetation	0,24	60' 55 mm h ⁻¹
Cerdà & Doerr, 2005	Valencia 688 mm	16-25	Lithic Leptosols & Luvisols	Aleppo pine forest	0,24	60' 55 mm h ⁻¹
Desir, 2002	Zaragoza 350 mm	25-45	Gypsisol, silty	Shrubland	0,24	60' 45 mm h ⁻¹
Calvo et al., 2003	Callosa 474 mm	40-50	Calcaric Regosol	Pine forest & shrubland	0,24	60' 55 mm h ⁻¹
Calvo et al., 2003	Benidorm 387 mm	40-50	Lithic Leptosol	Pine forest & shrubland	0,24	60' 55 mm h ⁻¹
De Luis et al., 2003	Alicante 466 mm	50	Kastanozem, loamy	Gorse shrubland	4	105' 156 mm h ⁻¹
Arnáez et al., 2004	La Rioja 800 mm	10-60	Kastanozem eroded	Bare soil to shrubs	0,24	30' 75 mm h ⁻¹
Badía & Martí, 2008	Fraga 318 mm	28-32	Calcaric Regosols	Aleppo pine forest	0,24	60' 85 mm h ⁻¹
León et al, 2011	Zuera 560 mm	30-40	Rendzic Phaeozem	Shrubland	0,21	60' 60 mm h ⁻¹
León et al, 2011	Zuera 560 mm	30-40	Haplic Gypsisol	Shrubland	0,21	60' 60 mm h ⁻¹

Table 1. Runoff and erosion data with rainfall simulator method in semi-arid Mediterranean ecosystems (arranged by publication date).

Author	Treatment or variable	Soil loss (Kg ha ⁻¹ mm ⁻¹)	Runoff (%)	Other parameters
Cerdà et al., 1995	Fire, time and N-S aspect	0-68,2	0-73	I=15-55 mm h ⁻¹ ; Tr=138-872 s
Kutiel et al., 1995	Fire, time and N-S aspect	0-11,6	0-56	I=16-40 mm h ⁻¹
Cerdà & Lavee, 1995	Plant cover	1,4-62,2	50-91	Sc=0-2-9,4 g L ⁻¹
Cerdà et al., 1998	Plant cover	-	24-50	I=24-37 mm h ⁻¹ , Wf=5-7 cm Tr=266-510 s
Imeson et al., 1998	Plant cover	0,8-9,4	34-58	EC=0,13-0,16 dS m ⁻¹ Sc=0,88-2,85 g L ⁻¹ ; Tr=186-360s
Imeson et al., 1998	Plant cover	24,8-39,8	27-35	EC=0,28-0,29 dS m ⁻¹ Sc=9,4-11,3 g L ⁻¹ ; Tr=260-360 s
Lasanta et al., 2000	Abandonment, fertilisers, crops	3,9-14,7	40-75	Wf=5-23 cm , Sc= 1,2-6,1 g L ⁻¹ EC=0,95-1,65 dS m ⁻¹
Johansen et al., 2001	Sever wildfire effect	3-76	23-45	-
Cerdà, 2001	Rock fragments cover	0,36-14,1	12-38	I=27-44 mm h ⁻¹
Ortiz & Alcañiz, 2001	Seeding and treatments	5-105	5-95	Tr=53-253 s
Cerdà, 2002	Parent material and season	24-374	36-85	EC=0,03-1,10 dS m ⁻¹ Tr=70-430 s
Cerdà & Doerr, 2005	Vegetation type, season and time from burning	0,03-9,4	5-45	I=25 to 52 mm h ⁻¹ Sc=0,03-0,84g L ⁻¹
Desir, 2002	N-S Aspect	2,6-21,7	14-53	I=3,6-35,5 mm h ⁻¹ Wf=5-31 cm EC=1,0-2,5 dS m ⁻¹
Calvo et al., 2003	N-S Aspect and soil moisture effect	0,2-8,6	2-55	I=17-49 mm h ⁻¹ Sc=0,46-1,06 g L ⁻¹ , Tr=67-665 s
Calvo et al., 2003	N-S Aspect and soil moisture effect	0,2-8,6	0,1-29	I=33-42 mm h ⁻¹ Sc=0,43-0,97g L ⁻¹ , Tr=116-406 s
De Luis et al., 2003	Fire intensity effect	0,07-30,8	-	-
Arnáez et al., 2004	Slope gradient	1,4-23,0	34-58	Wf=5,2-8,5 cm
Badía & Martí, 2008	Fire effects and raindrop size	0,73-39,9	41-81	I=14-49 mm h ⁻¹ Sc=0,22-4,81 g L ⁻¹ EC=0,45-1,01 dS m ⁻¹ Tr=74-97 s ; Wf=10,4-25,2 cm
León et al., 2011	Fire effects (control vs burned)	8,5-18,8	24-25	I=44-45 mm h ⁻¹ , Tr=197-379 s EC=0,62-0,91 dS m ⁻¹
León et al., 2011	Fire effects (control vs burned)	25-152	22-60	I=24-47 mm h ⁻¹ , Tr=199-232 s EC=1,54-1,71 dS m ⁻¹

Abbreviatures: I, Infiltration (mm h⁻¹); Tr, Time to runoff (s); Sc, Sediment concentration (g L⁻¹); Wf, Wetting front (cm); EC, Electrical conductivity of runoff (dS m⁻¹) of overland flow.

Table 1bis. Runoff and erosion data with rainfall simulator method in semi-arid Mediterranean ecosystems (arranged by publication date).

In Figure 3, there are also some turning points in the vegetation cover and erosion evolution related to environmental conditions. Thus, in spring vegetation the cover rate is accelerated then decreases during the summer period mainly dominated by therophytes plants; the pulses in the soil erosion are related to the greatest intensity of rainfall.

It must be taken into account that in burned kermes evergreen oak shrubland, the average erosion is 7 times higher than in unburned plots; in Aleppo pinewood soil loss can be as much as 36 times higher in the early years (Rodríguez et al., 2000). This is due to the differential evolution of vegetation to cover the soil surface after the fire.

3. Rainfall energy effects on soil erosion and runoff generation in semi-arid forested lands

The effects of fire and torrential rainfall, two important factors in Mediterranean semiarid environments, on the soil erosion and hydrology, are analyzed in this section.

3.1 Methods

Experiments were carried out using a portable sprinkler-based rainfall simulator with different nozzles and pressures. Two levels of rainfall energy ($12,6 \text{ J m}^{-2} \text{ mm}^{-1}$ and $24,7 \text{ J m}^{-2} \text{ mm}^{-1}$) and similar intensity ($85 \pm 8 \text{ mm h}^{-1}$) reproduce torrential rainfall characteristics. Rainfall simulations were conducted immediately after Aleppo pine (*Pinus halepensis* L.) litter covering soil surface was burned. The experiments were conducted on calcareous, loamy clay soils classified as Calcaric Regosol, frequent in the semi-arid Central Ebro Valley (NE-Spain). Paired burned areas were established in nine micro-plots and compared with paired not burned control areas (2-soil status x 2 rainfall energy x 9 plots or replicates). In each rainfall simulation the soil loss, soil infiltration (calculated by Horton model), wetting front, runoff coefficient and runoff quality (EC and pH) were measured (Badía & Martí, 2008).

3.2 Results and discussion

The results indicate that when litter cover was burned rainfall significantly increases the sediment yield. Burned plots generated 18.5 times more sediment than unburned plots (control) for fine rainfall energy (Raindrop $D_{50} = 1,0 \text{ mm}$) and 33.6 times more for coarse rainfall energy (Raindrop $D_{50} = 1,4 \text{ mm}$) (Fig. 4).

The return period for a single storm with I_{30} (rainfall intensity for 30 min) ranged from 5 to 200 years from the East Mediterranean areas to semiarid Central Ebro Valley, respectively (Fomento, 2001). These rainfalls of high intensity are especially frequent in autumn, just after summer, the season of maximum risk of wildfires. Sediment loss was given as solutes dissolved in overland flow, mainly in unburned plots, and as particles in suspension, mainly in burned plots. However, soil erosion rates were without significant differences between both rainfalls. Fire increased runoff quantity (about 1,6 times) and decreased its quality temporarily by increasing significantly both pH and specially EC in relation to unburned plots (Fig. 5).

The results indicate that when vegetation and litter cover of soils were burned, the first rainfalls duplicate runoff, soil infiltration decreases significantly and soil erosion increases 20 – 30 times in relation to unburned plots, especially with the highest rainfall energy. Because of the dynamic climate of the area that we discussed, a restoration strategy for a short-term response would be an interesting response, especially in conditions where plant succession is very slow, e.g., high slopes and soils of low permeability materials, thus highly erodible.

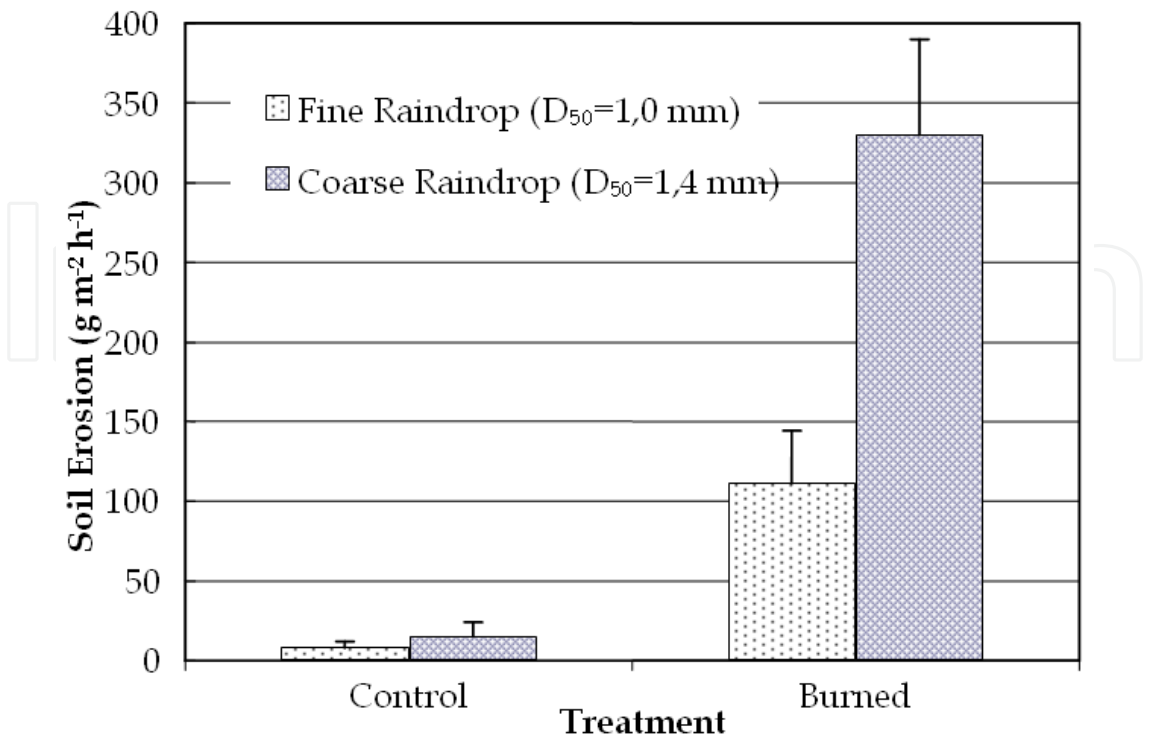


Fig. 4. Fire and drop size effects in the soil erosion ($\text{g m}^{-2} \text{h}^{-1}$) with rainfall simulator method.

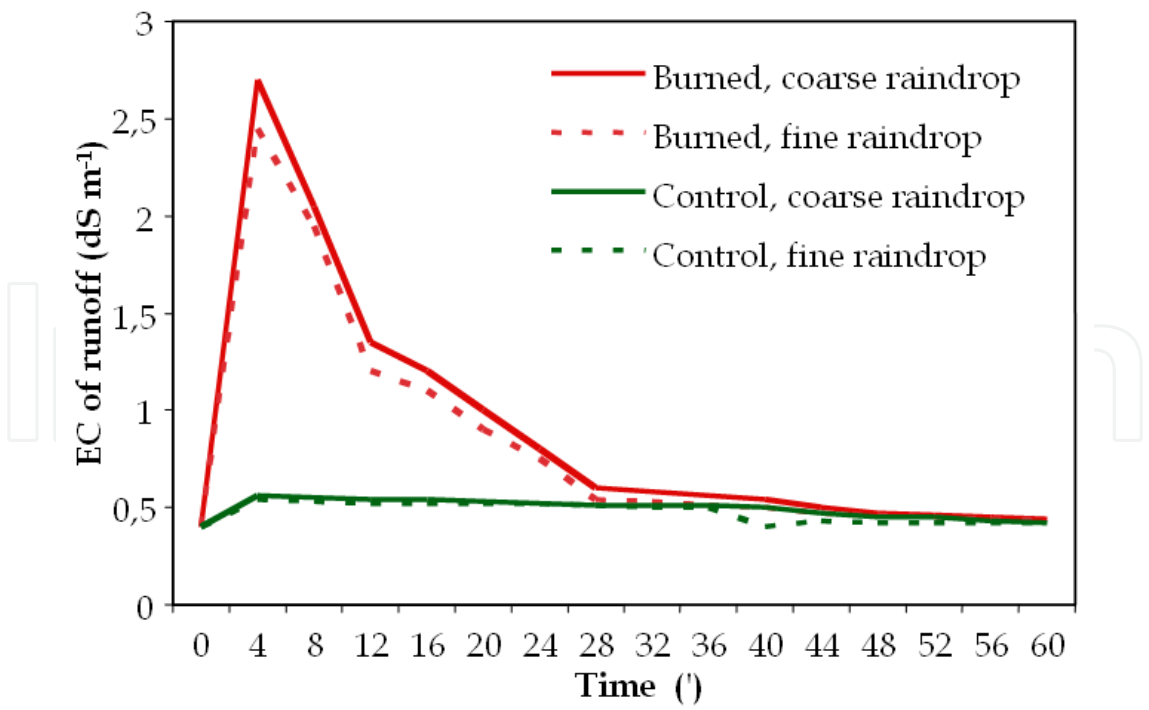


Fig. 5. Evolution of electrical conductivity of runoff (EC, dS m^{-1}) in burned and control plots with rainfall simulator method (in a Calcaric Regosol).

4. Fire effects on soil properties under laboratory–controlled heatings

Wildfire passage is accompanied by a heat wave and a deposition of ash as a result of biomass combustion (Fig. 6). Fire effects are directly related to the soil type affected as well as fire severity, i.e. the heat reached and the quantity and quality of ashes deposited on soil surface. To test these variables we treated two contrasting soils under laboratory conditions, the most frequently found soils in the semi-arid Central Ebro Valley (NE-Spain), a Calcaric Regosol developed on marls and a Haplic Gipsisol, developed on gypsiferous marls.

4.1 Methods

Samples of both soils (calcareous and gypsiferous soil) were collected randomly and analyzed separately with 4 replicates for each soil type. Soil samples were heated for 30 minutes in a muffle furnace at temperatures of 25°, 150°, 250° and 500°C. These temperatures cover the range that is habitually reached in surface soils affected by fires (Chandler et al., 1983; Giovannini & Lucchesi, 1997; Walker et al., 1986). Soil sample treated at 250°C was selected for adding black ashes, in a quantity related to plant biomass growing on each soil (Martí, 1998). The amount of ashes added to calcareous soil was twice (10 g kg⁻¹) that added to gypsiferous soil (5 g kg⁻¹).



Fig. 6. Appearance of a recently burned soil surface in Mountains of Zuera and Castejón de Valdejasa (Zaragoza).

4.2 Results and discussion

Similar changes in chemical properties were found for both soils at highest temperatures but differences between soils were observed at intermediate temperatures (Table 2).

Treatment	Gypsiferous Soil, G					Calcareous Soil, C				
	G25	G150	G250	G250A	G500	C25	C150	C250	C250A	C500
SAS (%)	75b	72b	48d	45d	0.8e	86a	83a	65c	63c	0.9e
Particle density (Mg m ⁻³)	2.45c	2.44c	2.48c	2.49c	2.68a	2.55b	2.57b	2.58b	2.57b	2.65a
Water available (%)	22.6b	23.9b	24.4b	24.8b	27.8a	12.6d	12.6d	13.1d	12.7d	18.4c
CaCO ₃ (mg kg ⁻¹)	96b	95b	103b	122b	136b	308a	319a	320a	326a	328a
pH 1:2,5 (H ₂ O)	7,8d	7,7de	7,3f	7,5e	8,8b	8,2c	8,1c	7,6e	7,8d	9,4a
OM (g kg ⁻¹)	27d	28d	22e	25d	3f	42a	42a	32c	35b	4f
Total N (g kg ⁻¹)	1,5b	1,6b	1,5b	1,5b	0,5c	2,7a	2,6a	2,5a	2,3a	0,7c
C/N ratio	10,4a	10,1a	8,5a	9,7a	3,5d	9,0ab	9,4a	7,4c	8,8b	3,3d
CEC (cmol _c kg ⁻¹)	12,7c	13,9c	12,4c	12,1c	9,9d	27,2a	28,8a	22,0b	21,7b	14,4c
P-Olsen (mg kg ⁻¹)	0,4g	0,4g	1,2f	1,3f	1,7e	2,3d	2,7d	9,1c	9,8b	11,5a
K ⁺ -exc (mg kg ⁻¹)	46,0f	36,5f	48,0f	102,0e	186,0d	176,0d	154,0d	204,0c	286,0b	528,0a
ECe (dS m ⁻¹)	2,6e	5,6b	8,5a	8,7a	3,3d	0,9f	1,2f	3,4d	3,7c	2,4e
Basal respiration	100.1e	89.2f	86.9f	98.3e	29.2g	153.7d	198.6c	254.8b	277.0a	33.4g
Biomass C (mg C kg ⁻¹)	635c	532d	387e	426e	217f	737b	742b	812a	821a	353e

Table 2. Changes induced by simulated fire at different temperatures and ash addition (A) in the physical, chemical and biological properties of gypsiferous (G) and calcareous (C) soils in the semi-arid Central Ebro Basin. In each row, treatment data with the same letters are not significantly different (LSD test, P>0.05). Basal respiration (mg CO₂ soil kg⁻¹ day⁻¹)

Among the results it should be noted that heating soil to 250°C caused a decrease in pH and an increase in electrolytic conductivity (ECe) and soluble Ca. Heating soil to 500°C caused an increase in pH and a decrease in ECe and soluble Ca. Increasing heat intensity increased organic matter loss by combustion, which was accompanied by an increase of available nutrients content. Total N content decreased at temperatures greater than 250°C, with about one-third being volatilized. Cation exchange capacity (CEC) was reduced for gypsiferous soil heated to 500°C and to 250°C for calcareous soil. As for physical soil properties, heating increased the quantity of sand-sized particles by fusion of clay with

the greatest increase occurring in soil heated to 500°C. Soil aggregate stability (SAS) of both soils was reduced by heating to 250°C with greater reductions at 500°C, likely due to a reduction in organic matter and clay size particle content. Bulk density and particle density increased in both soils when heated to 500°C. Water availability (difference between field capacity and permanent wilting point) increased when soils were heated to the highest temperature, likely due to texture and structural modifications. The addition of ashes increased organic matter content, C/N ratio, and pH in both soils and increased nutrient availability, especially in the calcareous soil where soil addition was higher than in gypsiferous one.

Soil respiration were quickly enhanced in calcareous soil but depleted in gypsiferous soil for intermediate heating treatments (150°C and 250°C). At the highest temperature (500°C), these biological properties were significantly reduced in both soil types and on a long term basis. Black ash addition increased basal respiration in both soils but did not affect other biological properties. These results demonstrate the existence of both labile and permanent effects of soil burning and a differential response to C dynamics as a function of soil properties (Badía & Martí, 2003b).

The unburned or control soils (25°C) have originally contrasting properties (C versus G soil) that are not strongly altered at intermediate temperatures (150°C, 250°C). But the highest heat treatment (500°C) conducted on both soils (C500 vs G500) showed a lot of similarities as result of the degradation of their initial properties (Fig. 7).

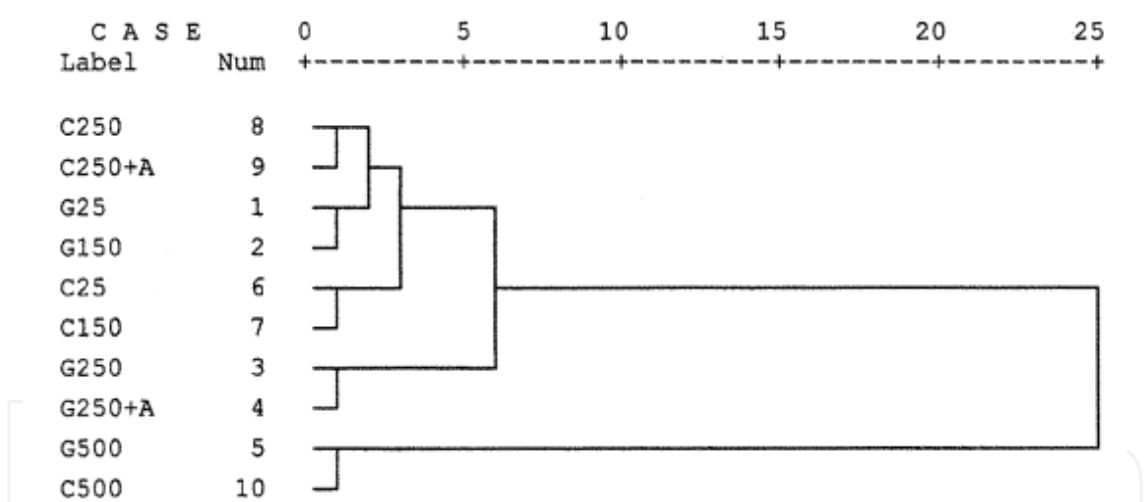


Fig. 7. Dendrogram of experimental calcareous (C) and gypsiferous (G) soils at different temperatures (25°C, 150°C, 250°C, 500°C) and ash addition (A). Numbers 0 to 25 shows the rescaled distance cluster combine, and 1 to 10 are the case numbers.

5. Fire effects on soil water repellency: A laboratory approach with contrasted soils

5.1 Methods

Water repellency is a soil property that affects its hydrological response and its erodibility (Cerdà & Doerr, 2008; Jordán et al., 2010). In this chapter, the effect of an experimental fire is studied on the soil water repellency of three different ecosystems. Three experimental soils have been selected in the NE of Spain with different properties (Table 3).

Soil Unit (FAO)	Rendzic Phaeozem	Hypercalcic Calcisol	Haplic, Eutric Cambisol
Plant community	Aleppo pinewood with moss	Evergreen oakwood	Meadow
Soil moisture regime	Xeric-aridic	Xeric	Udic
Soil temperature regime	Thermic	Mesic	Mesic
Soil parent material	Marls & limestones (Miocene)	Calcareous coluvium (Pleistocene)	Coluvium (Pleistocene)
Organic matter in A (%)	9.8 %	4.1 %	7.0 %
Textural class in A (%)	Clay Loam	Loam	Loam
Location: municipality	Zuera	Arascués	Linás de Broto
UTM 30T (X-Y)	671-464	708-467	733-472
Altitude (m)	630	581	1218

Table 3. Some characteristics of the studied soils and their ecosystems.

Non-altered blocks of soil have been obtained in the field in every area. All treatments have been carried out three times. Once in the laboratory, all the soil blocks have been air-dried and they have been burnt with a blowlamp (Llovet et al., 2008) up to reaching a maximum of 250°C at 1 cm depth (Fig. 8).



Fig. 8. Soil blocks were burned with a blowlamp reaching 250°C at 1 cm soil depth.

In order to evaluate the soil water repellency, the water drop penetration time (WDPT) test has been used, applying three drops per soil block. In addition, the water repellency variation is assessed in three different levels of depth (at the surface, at 2 cm and 5 cm-depth). The water repellency classification criterion is the one used by Doerr et al., 2009).

5.2 Results and discussion

Fire affect soil water repellency in a different way according to soil type and soil depth (Table 4). Fire decreased significantly the presence of water repellency on the surface of all experimental soils: Phaeozems, Calcisols and Cambisols. The fire reduced water repellency even in depth in Phaeozems (to 5 cm depth) and Calcisols (to 2 cm depth). Unlike, fire increased water repellency in Cambisols at 5 cm depth, from hydrophilic (unburned soil samples) to strongly hydrophobic (burned soil samples).

Soil Group	Soil depth (cm)	Unburned Soil	Burned Soil	P
Phaeozem	0	833.6±656.0	0.69±0.14	0.003
	2	1100.6±479.3	12.80±22.0	<0.001
	5	835.3±438.6	13.0±11.3	<0.001
Calcisol	0	666.0±333.2	8.0±20.2	0.001
	2	382.2±412.9	16.6±39.9	0.029
	5	79.0±87.4	40.0±67.4	0.305
Cambisol	0	14.2±6.9	0.81±0.1	<0.001
	2	1.4±0.9	107.9±207.3	0.162
	5	3.7±1.3	273.9±293.7	0.025

Table 4. Effect of fire on water repellency (WDPT, s) of Phaeozems, Calcisols and Cambisols at different soil depths (mean values and standard deviation; n=9).

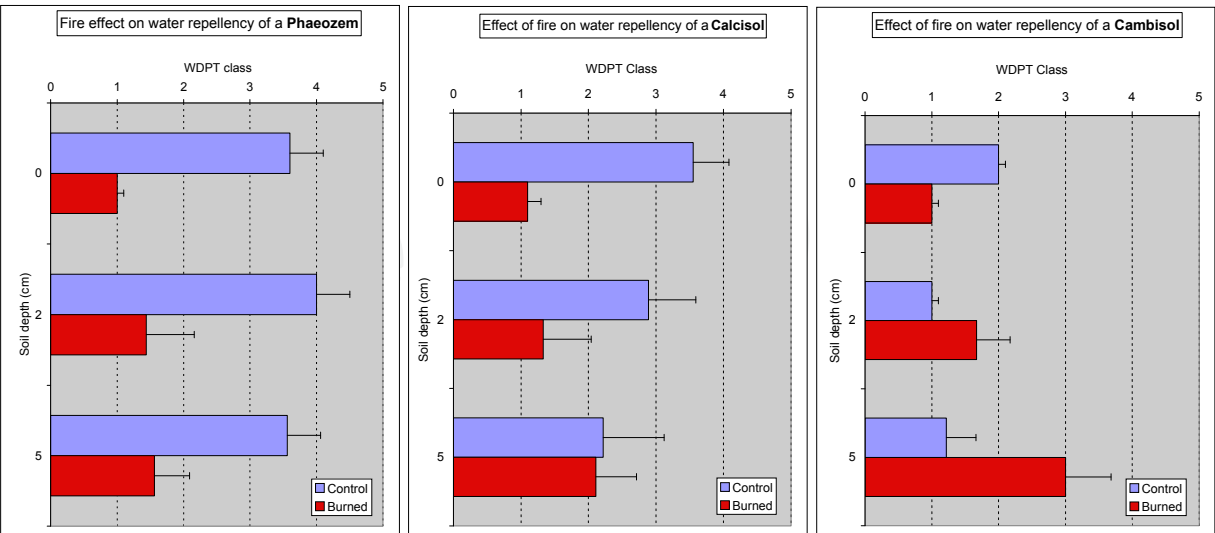


Fig. 9. Fire effect on water repellency (WDPT classes) in the studied soils.

Waxes and similar lipid materials could be mostly responsible for the original soil water repellency, which can be enhanced or reduced according to soil properties (Fig. 9). The increase in water-repellent conditions at 5 cm depth in Cambisol could be attributed to the

translocation into the soil depth of lipid fractions released from burning organic matter or biomass (González et al., 2004).

6. Rehabilitation practices in areas affected by wildfires

Some rehabilitation practices have been implemented as urgent measures to control soil erosion in areas affected by wildfire in the semiarid Central Ebro Valley (Figure 10): rehabilitation practices include herb seeding, re-mycorrhization and mulching with barley straw and pine woodchip. The effectiveness of these treatments are discussed in this section.



Fig. 10. Rural depopulation, land abandonment and afforestation with flammable species increased wildfires in Mediterranean semiarid ecosystems: Burned Aleppo pine afforestation in Fraga mountains (left) and abandoned terraces in Sarsa Castle (right).

6.1 Methods

In a paired plots design, treatments of seeding, seeding and mycorrhized, seeding and mulching, and control (untreated) erosion plots were established in four different slopes and on calcareous one (*Calcaric Regosols*) and gypsiferous (*Haplic Gipsisols*) soils (Fig. 11).



Fig. 11. Left: detail of seeding and mulching plots under slow and poor conditions of post-fire cover regeneration. Right: planting oak species on hillslopes which have been removed because of high fire frequency.

All sites were north-facing with a slope of around 20°. The seeding treatment consisted of the addition of legumes and grass seed mixture, either native or established through cultivation in the region: *Medicago sativa* L., *Medicago truncatula* Gaertn., *Onobrychis viciifolia* Scop., *Vicia villosa* Roth, *Agropyron cristatum* (L.) Gaertn., *Dactylis glomerata* L., *Lolium rigidum* Gaud. and *Phalaris canariensis* (L.). Planting was done manually in rows, perpendicularly to the maximal slope (parallel contour seeding). The sowing rate for the whole mixture was 30 g m⁻², with an equivalent weight for each species. Mulching consisted of barley (*Hordeum vulgare* L.) straw covering the soil surface at a 100 g m⁻² rate (Badía & Martí, 2000). And mycorrhization has consisted of contribution of vesicular-arbuscular mycorrhizae (*Glomus mossae*) to increase the nutrient and water potential of sown plants (Mataix et al., 2007; Vallejo, 1996).

6.2 Results and discussion

Plant cover (native and sown plants) in both soils (calcareous and gypsiferous) after four months of seeding treatments are shown (Fig. 12).

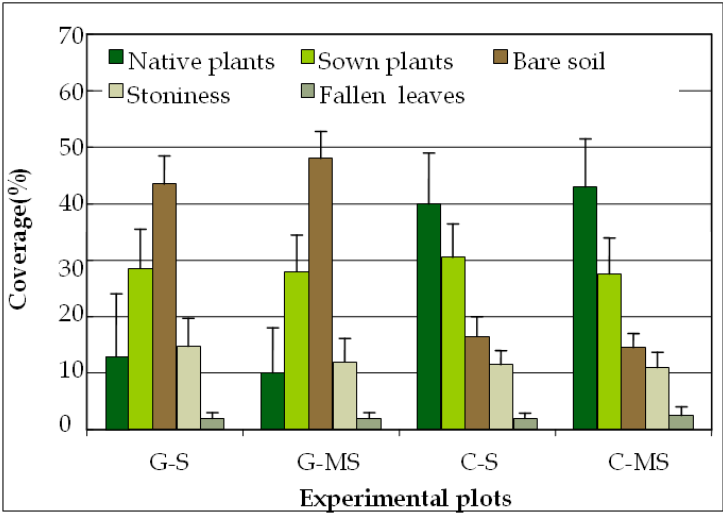


Fig. 12. Soil cover (%) in seeded plots (S) and seeded+mycorrhized plots (MS) on calcareous (C) and gypsiferous (G) soils after four months of treatments application.

Native plant coverage in calcareous soils (40%) is greater than in gypsiferous soils (10%) where physical, chemical and biological properties are relatively worse. Moreover, in calcareous soils the resprouters are higher than in gypsiferous one. In gypsiferous plots the principal native species was *Helianthemum syriacum* while *Brachypodium retusum* was dominant in calcareous plots, in some cases reaching 50% of total plant cover.

It is important to remark that plant cover of seeded plants is similar in both soils (~30%). Among the introduced species *Lolium rigidum* covered about 12% of soil surface. The other seeded species had a similar importance, 5% of the total for *Onobrychis viciifolia* and about 2-4% for each of the other six species.

Regarding the effectiveness of applied measures on soil erosion, we found differences between soils because bare soil after treatments was about 45% in gypsiferous soils and only 15% in calcareous one (Fig. 9). The soil loss in gypsiferous soils twice that one in calcareous soils (Table 4). The cumulative annual erosion rate measured in Gerlach boxes was about 4 Mg ha⁻¹ year⁻¹ for gypsiferous soils, 3 times more than treated soil. And in calcareous soils, soil losses was about 2 Mg ha⁻¹ year in control plots were about 2 times higher than treated plots (Table 5).

Treatments	Gypsiferous Soil				Calcareous Soil			
	C	S	SM	SMS	C	S	SM	SMS
Mg ha ⁻¹ year ⁻¹	3,63a	1,24c	1,21c	1,11cd	1,78b	0,97cd	0,98cd	0,67d
Control/ treatment	-	2,9	3,0	3,3	-	1,8	1,8	2,7

Table 5. Average erosion rate (n=4) in Gerlach collectors under different soil treatments: burned control plots (C), seeded plots (S), seeded and mycorrhized plots (SM), and seeded and mulched with straw (SMS). The plots were monitorized during two years after wildfire in Fraga hillslopes (NE-Spain). Different letters between treatments and soils indicates significant differences (LSD test, P<0,05).

The parallel contour seeding treatment increases soil cover and acts as a sucessive micro-barriers to the maximal slope to reduce flow velocity and runoff coefficient while increasing infiltration and trapping sediments. This was verified in experiments with rainfall simulator (Badía et al., 2008). The runoff coefficient was significantly lower for seeding plots (13 to 38%) than for control soils (45 and 58% for calcareous and gypsiferous soils respectively). The lower calcareous soils runoff is associated with better physical and chemical properties than gypsiferous soils, differences in soil characteristics which are also reflected in the vegetation cover (Fig. 9). Because of the heterogeneity of rainfall in the region, the erosion is generated in the most rainy months of the study on both the gypsiferous and calcareous soils, and then is when there are significant differences between seeding and control plots. The Figure 13 note these differences on gypsiferous burned soils, and is representative also for calcareous soils.

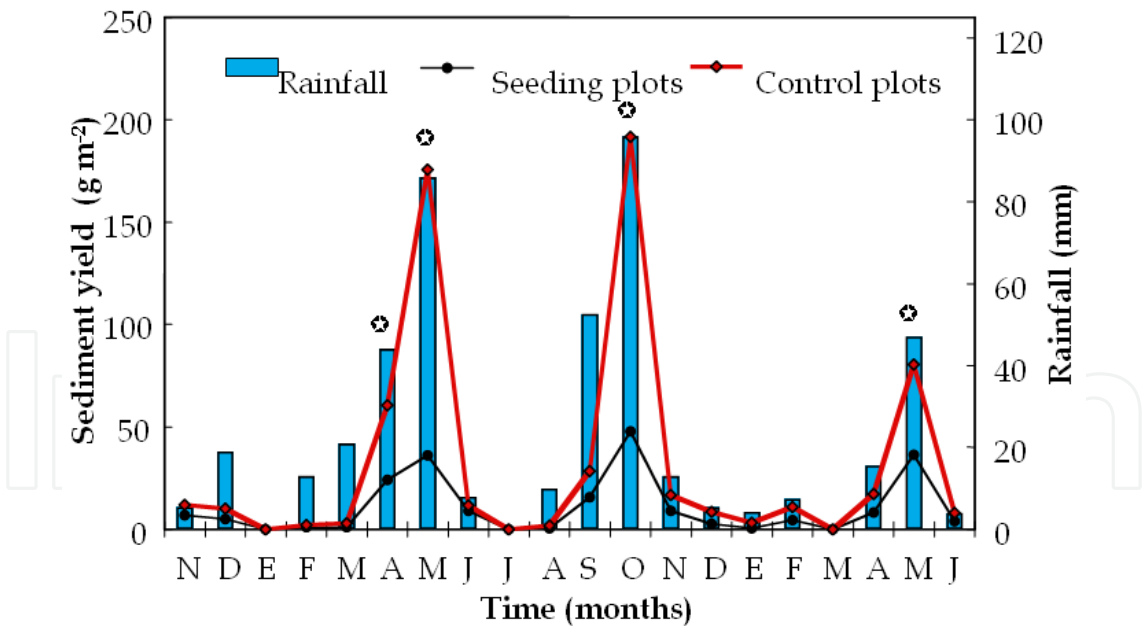


Fig. 13. Sediment yield (g m⁻²) under different treatments (control and seeding) on gypsiferous burned soils (n=4) and monthly rainfall (mm) along the period of study. Asterisks indicate the significant differences between seeding and control plots in the reporting month. From Badía & Martí, 2000.

Cumulative soil loss was higher in gypsiferous soils than in calcareous soils for control plots (untreated). Although the application of any of the treatments reduced these rates and the

benefits are clearly apparent, the erosion levels of post-fire degradation with no treatment cannot be classified as severe. These facts are consistent with other studies where wildfires are considered as a perturbation with a relatively severe temporary impact (Cerdá & Doerr, 2005). Analyzing the vegetal cover from the point of view of the pastoral value (Badía et al., 1994), fresh and dry plant matter increased with sowing as well as non-nitrogenous products. Straw mulching is the most effective treatment against soil erosion, inducing some improvement both in quantity and quality of plant matter in both types of soils. Remycorrhization did not affect these parameters. Endomycorrhizae recovery after the fire has been rapid (Table 4), hence the low response of a mycorrhizal inoculum allochthonous (Badía & Martí, 1994a and 1994b). Although at intermediate temperatures soil microbial activity is quickly enhanced, for specific organisms, such as endomycorrhizal fungi, linked to the recovery of vegetation, this recovery is slower (Table 6).

	Gypsiferous Soil (G)		Calcareous Soil (C)	
	Control	Burned	Control	Burned
Nº spores /g dry soil	50.0±16.9	33.60±14.3	48.2±22.1	37.8±11.8
Diversity index	1.266±0.19	0.980±0.12	1.586±0.2	1.025±0.35

Table 6. Characterization of endomycorrhizal state ($\bar{x} \pm sd$) in burned soils (n=4) one year after wildfire in NE-Spain (Barceló et al., 1994).

6.3 Other treatment: planting of shrubs and trees

In this case the treatment was applied only on young soils developed on calcareous marls (*Xeric Torriorthent*) in Fraga (Fig. 14). Five plant species were transplanted in man-made holes: two woody species (*Pinus halepensis*, *Quercus ilex*) and three shrub species (*Juniperus phoenicea*, *Pistacia lentiscus*, *Retama sphaerocarpa*); all of them ectomycorrhizae and with only one sap. After a year of monitoring, the portentaje of survival is almost null for *Quercus ilex* while for the other species is between 94 and 100%. Height growth rate is significantly different between the five species (average of the different slopes in which were transplanted): *Pinus halepensis* (16,4±5,8 mm/year), *Pistacia lentiscus* (10,3±3,9 mm/year), *Retama sphaerocarpa* (5,0±1,6 mm/year), *Juniperus phoenicea* (2,5±1,1 mm/year) and *Quercus ilex* (0,5±0,4 mm/year). In a similar way, diameter growth rate maintains the following order: *Pinus halepensis* (2,3±0,08 mm/year), *Retama sphaerocarpa* (1,4±0,09 mm/year), *Pistacia lentiscus* (1,1±0,06 mm/year), *Juniperus phoenicea*, (0,04±0,03 mm/year) and *Quercus ilex* (0,03±0,02 mm/year). These latter species show a relative diameter growth rate not statistically differentiated (0,4-0,6 mm mm⁻¹ year⁻¹), whereas the relative height growth rate follows the order: *Pinus halepensis* and *Pistacia lentiscus* (0,5 mm mm⁻¹ year⁻¹), *Retama sphaerocarpa* (0,4 mm mm⁻¹ year⁻¹), *Juniperus phoenicea* (0,25 mm mm⁻¹ year⁻¹). All the species studied show a clear sensitivity to soil water content, showing growth increments in spring and autumn, as well as greater increments in north slopes than in the southern slopes (Viñuales & Badía, 1995).

Table 7 summarizes the growth parameters (survival, height growth rate and diameter growth rate) of the species mentioned, used for reforestation in areas degraded by fire and other disturbances, and studied for different authors.

Species	Survival and/or growth	Location /Rainfall	Years	Author
<i>P. halepensis</i>	S: 94,5% (90,7-97,5). HGR=35,8cm/year (30,7-42,3). DGR=9,7mm/year(8,7-11,6)	Alloza, Teruel 391 mm	10	Badía et al., 2007
<i>P. halepensis</i>	S < 50%	Almería, 200 mm	6	Oliet et al., 2000
<i>P. halepensis</i>	S (1-2-3 years): 56-43-36% HGR: 15-52 cm/year	Paracuellos del Jarama, 430 mm	1-3	Peñuelas et al., 1997
<i>P. halepensis</i>	S: 13-56 %	Sierra Estancias 400 mm	1	Carrera et al., 1997
<i>P. halepensis</i>	S: 60 %	Montes de Málaga, 400 mm	1	Navarro et al., 1997
<i>P. halepensis</i>	S: 73-95% HGR: 11, 8 to 18,5 cm/year	Aspe, 306 mm; Agost, 301 mm	4	Baeza et al., 1991a and 1991b
<i>P. halepensis</i>	S: 20-48 %. HGR: 6,1-9,4 cm/year. DGR: 1,6-2,4 mm/year	Alicante, 277 mm	6	Cortina et al., 2004
<i>P. halepensis</i>	S:88%(S)100%(N).HGR:14,7cm/yea r(S)-23,2(N).DGR: 1,9(S) to 3.3mm/year(N)	Murallot de Fraga, 345 mm	1	Viñuales and Badía, 1995
<i>P. halepensis</i>	HGR: 0,85 -2,73 cm/year	Castillonroy, 414 mm	40	Olarieta et al., 2000
<i>P. halepensis</i>	HGR=4,1-6,5 cm/year DGR=3,8-4,8 mm/year	Sant Simó, Fraga 350 mm	0,4	Martí and Badía, 1995
<i>P. halepensis</i>	S: 80%	Alicante 277 mm	1	Maestre and Cortina, 2004
<i>P. halepensis</i>	S: 68-71%	Valencia 400 mm	1	Alloza and Vallejo, 1999
<i>P. halepensis</i>	HGR: 8,9-11.2 cm/year DGR: 0,29-0,37 cm/year	Garraf 500 mm	1	www.creaf.uab.es /iefc
<i>P. halepensis</i>	HGR: 17,7-26,1 cm/year DGR: 1,52-2,59 cm/year	Almatret 420 mm	28-46	www.creaf.uab.es /iefc
<i>P. halepensis</i>	S: 8-59% S: 40,7%(27,5-64,2%).HGR=7,5 cm/year (4,8-11,3%). DGR=2,0 mm/year(1,0-2,1)	Montseny 1000 mm Alloza, Teruel 391 mm	1 10	Espelta et al., 1993 Badía et al., 2007
<i>Q. ilex</i>	S: < 40 %	Montes de Málaga, 400 mm	1	Navarro et al., 1997
<i>Q. ilex</i>	S: 2-51 %	Sierra Estancias 400 mm	1	Carrera et al., 1997
<i>Q. ilex</i>	S: 35-49%. HGR:2,4 cm/year - 1,3 cm/year	Aspe, 306 mm; Agost, 301 mm	4	Baeza et al., 1991a and 1991b
<i>Q. ilex</i>	DGR: 1.05 mm/year	Puechbon (Francia), 807 mm	1	Ducry and Toth, 1992

Species	Survival and/or growth	Location /Rainfall	Years	Author
<i>Q. ilex</i>	DGR: 0.87 mm/year	Montseny 1000 mm	1	Mayor and Rodà, 1992
<i>Q. ilex</i>	S: 92-70-38%	Montseny 1000 mm	1	Espelta et al., 1993
<i>Q. ilex</i>	S: 5-95%. HGR: 6,3-12,6 cm/year. DGR: 1,4-2,7 mm/year	Alcalá de Henares, 416 mm	3	Rey et al., 2005,
<i>Q. ilex</i>	S: 58% (1992 year), 54% (1993) and 11% (1994)	Spain 300-400 mm	1	Alloza and Vallejo, 1999
<i>Q. ilex</i>	DGR: 0,87-0,94 mm/year	Almatret 420 mm	40	www.creaf.uab.es/ iefc
<i>Q. coccifera</i>	S: 34,1 % (17,9-54,2). HGR=1,5-6,6 cm/year. DGR=1,0-1,5 mm/year	Alloza, Teruel 391 mm	10	Badía et al., 2007
<i>Q. coccifera</i>	S: 40% (1993) and 0% (1994)	España 300 mm	1	Alloza and Vallejo, 1999
<i>Q. coccifera</i>	S: 10-20%	Campello 300 mm	3	Maestro et al., 2003
<i>Q. coccifera</i>	S: <40 %. HGR: 1,6-4,7 cm/year. DGR: 0,055-1,05 mm/year	Alicante 277 mm	6	Cortina et al., 2004
<i>Q. coccifera</i>	S: 2.5-80%. HGR: 3,5-12,4 cm/year. DGR: 1,3-2,2 mm/year	Alcalá de Henares, 416 mm	3	Rey et al., 2005,
<i>P. lentiscus</i>	80,9 % (70,4-86,7). HGR=6,1 cm/year (2,9-8,2). DGR= 2,1 mm/year (1,5-3,0)	Alloza 391 mm	10	Badía et al., 2007
<i>P. lentiscus</i>	S: <40 % HGR: 5,3 cm/year. DGR: 1,4 mm/year	Alicante 277 mm	6	Cortina et al., 2004
<i>P. lentiscus</i>	S: 100%; HGR: 5,02 cm/year. DGR: 1,1 mm/year	Fraga 345 mm	1	Viñuales and Badía, 1995.
<i>P. lentiscus</i>	DGR: 1,9 mm/year	Garraf 700 mm	1	Abril and Gracia, 1989
<i>P. lentiscus</i>	S: 0-10%	Campello 300 mm	3	Maestro et al., 2003
<i>J. phoenicea</i>	S: 61,7%(45,8-71,4).HGR=11,1 cm/year. (8,3-14,0). DGR=2,1 mm/year (1,7-2,6)	Alloza, Teruel 391 mm	10	Badía et al., 2007
<i>J. phoenicea</i>	S: 94%. HGR: 2,51 cm/year. DGR: 0,1 mm/year	Fraga 345 mm	1	Viñuales and Badía, 1995
<i>J. phoenicea</i>	S: 47%	Peñaflor 305 mm	1	Blanco, 1991

Table 7. Survival and growth of woody species used in restoration of areas affected by fires and other disturbances. Abbreviatures: S. Survival; HGR. Height growth rate; DGR. Diameter growth rate.

In a parallel experience the two woody species, *Pinus halepensis* and *Quercus ilex*, were planted in man-made holes too, in gypsiferous and calcareous soils affected by wildfire. After almost three years, *P. halepensis* survival is high, 81,2% on gypsiferous soils and 41,7% on calcareous soils. The *Q. rotundifolia* just had a 17,1% in gypsiferous and 8,3% on calcareous soils (Martí & Badía, 1995). The low survival in calcareous soils (more fertile than gypsiferous soils), is due to competition with other species, especially with *Brachypodium ramosum* with which it has been important. In fact, the mortality of *Pinus halepensis* is inversely related to vegetal recovery, which highlights the competition for soil water reserves:

$$\text{Mortality, \%} = 2,054 (\text{Vegetation cover, \%}) - 23,513 \text{ } r^2 = 0,578; P < 0,01 \quad (2)$$

More evidence of the role of soil water as a limiting factor in the study area, is that when reforestation practices are accompanied by a support irrigation in the plantation phase of the species, the survival rate and growth rises significantly. This was observed in a study of reforestation of opencast surfaces in the Val of Ariño coalfield (Teruel, NE-Spain) (Badía et al., 2007). In this study, the effect of a slope gradient on the growth and survival of different species 10 years after the reconstruction of mining banks was evaluated. Their survival shows significant differences: 95% *Pinus halepensis*, 81% *Pistacia lentiscus*, 62% *Juniperus phoenicea*, 41% *Quercus ilex* and 34% *Quercus coccifera*. Aleppo pine has been the fastest growing both height (36 cm year⁻¹) and basal diameter (10 mm year⁻¹), because of its greater adaptation in semiarid environments. For the other species, height values are less than 12 cm year⁻¹ and 2,1 mm year⁻¹ for basal diameter values. Growth and survival obtained here were higher than those of the same species in other afforestations in semiarid conditions. This outcome demonstrates the adequacy of species and applied techniques of restoration, in particular irrigation of summer season support, that allow a long-term reliability of reclaimed mine slopes.

7. Conclusions

In the semi-arid environments of NE-Spain, there are different types of soil conditioned by the lithology of the substrate derived, and whose erosion response is significantly divergent. Thus the calcareous burned soils with low stoniness and loamy clay texture, as well as eroded gypsiferous soils, show runoff and erosion levels higher than gypsiferous soils, and especially that colluvial soils. The coverage provided by vegetation is a key element to stop sheet erosion on these soils. The combined effect of heat and ash incorporation involves a number of changes in physical, chemical and biological characteristics of soils affected by wildfire. These effects vary according to intensity of the fire, the amount of ash incorporated and soil characteristics starting. The protective measures such seeding and mulching treatments involve a significant reduction of sediment yield in the first years after fire, higher in eroded gypsiferous soils than in fertile calcareous ones. The mycorrhization is not effective when the soil mycorrhizal status has already been recovered from the effects of fire.

In the forest domain of the area there is a diversity of species whose response after the fire is clearly different. Those with resprouting shrub species tend to recover its previous status faster, the vegetal recovery is higher and temporarily stable. In mature Aleppo's pine forest, the germination of pine is high; the pine density is 3-times higher before than after fire, although it will be progressively reduced. The shrub and woody species introduced show a differential response according to the soil in which they are implanted and restoration techniques, especially related to soil water conditions.

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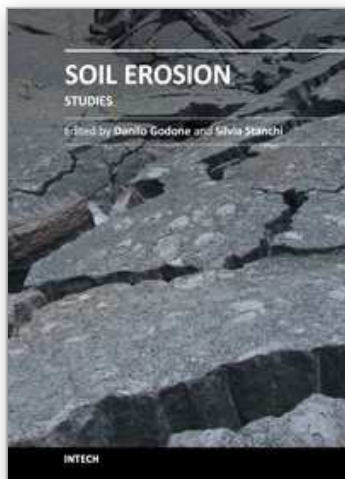
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