

COMPARISON OF DIFFERENT METHODS TO MEASURE SOIL EROSION IN THE CENTRAL EBRO VALLEY

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ABSTRACT. Fire is a natural factor of landscape evolution in Mediterranean ecosystems. Due to social and economical changes, wildfires have caused hydrological and geomorphological changes to be more pronounced, resulting in enhanced soil erosion. The study area is located in the Zuera Mountains, near the city of Zaragoza (Spain) in the Middle Ebro Valley. These mountains were affected by two wildfires in 2008 and 2009, burned around 2000 ha and 6000 ha, respectively. Middle Ebro Valley has extreme aridity, which results in a low plant cover and high soil erodibility enhanced by the fire effects. Soil infiltration is one of the properties affected by fire as a consequence of litter and vegetation removal, heating of and changes to the biological, chemical and physical soil properties. The objective was to compare two different methods –rainfall simulations and erosion plots–, to assess soil erosion after forest fires. We compared different measurements with rainfall simulators and erosion plots, applying a woodchip cover –in order to reduce the rain splash effect–, and to measure the erosion reduction. The work showed low sediment rates in both experiments covered with woodchips.

Comparación de diferentes métodos para medir la erosión del suelo en el sector central del valle del Ebro

RESUMEN. El fuego es un factor natural de la evolución paisajística de los ecosistemas Mediterráneos. Debido a los cambios sociales y económicos, los incendios forestales han causado cambios hidrológicos y geomorfológicos aún más pronunciados, provocando una mayor erosión del suelo. El área de estudio se localiza en las Montañas de Zuera, cerca de la ciudad de Zaragoza (España), en el sector central de la Depresión del Ebro. Estas montañas fueron afectadas por dos incendios en 2008 y 2009, quemándose en torno a 2000 ha y 6000 ha, respectivamente. El sector central del Valle del Ebro tiene una aridez extrema, lo que se traduce en una cubierta vegetal baja y alta erosionabilidad del suelo y ésta se ve reforzada por los efectos del fuego. La infiltración del suelo es una de las propiedades afectadas por el fuego como consecuencia de la eliminación de la vegetación y la hojarasca, por el aumento

de temperatura y los cambios en las propiedades físicas, químicas y biológicas del suelo. Nuestro objetivo fue comparar dos métodos diferentes –simulaciones de lluvia y parcelas de erosión–, para evaluar la erosión del suelo tras incendios forestales. Se compararon diferentes mediciones con un simulador de lluvia y con parcelas de erosión, aplicando una cubierta de astillas –con el fin de reducir el efecto de la salpicadura de las gotas de lluvia–. El trabajo muestra bajas tasas de sedimentos en ambos experimentos cubiertos con astillas de madera.

Key words: erosion plots, forest fire, infiltration, runoff, rainfall simulator, sediment yield, wood-chips mulch.

Palabras clave: parcelas de erosión, incendios forestales, infiltración, escorrentía, simulador de lluvia, producción de sedimentos, acolchado de astillas.

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1. Introduction

Fire is a natural factor of landscape evolution in Mediterranean ecosystems. Forest fires destroy the vegetation cover, alter the soil properties and trigger higher erosion rates by splash erosion that can contribute to modify the laminar flow and to rejuvenate the gullies (Hyde *et al.*, 2007). The important socio-economic changes that occurred in the last decades have contributed to an increase in forest fires (Shakesby, 2011), altering the fire regimes in terms of frequency, size, seasonality and recurrence as well as fire intensity and severity (Doerr and Cerdà, 2005; Keeley, 2009) causing severe effects on soils, water and vegetation (Bento-Gonçalves *et al.*, 2012; Guénon *et al.*, 2013).

Research on soil erosion following fires in the Mediterranean basin has a brief history. Publications date back only to the early 1960s (SanRoque and Rubio, 1982; Díaz-Fierros *et al.*, 1987) compared with research on fires in the USA, where investigations began in the 1930s (Connaughton, 1935). The research activity in the Mediterranean basin expanded and has been increasingly internationally oriented since the 1990s, when there was an exponential risk of fire activity (Moreno *et al.*, 1998; Pausas, 2004) and an average of 600 000 ha burned annually, linked to 50 000 fires in the late last century (Lloret and Zedler, 2009).

Fire affects soil properties directly by heat impact and ash incorporation and reduction or elimination of plant cover (Bodí *et al.*, 2014). Raindrop impact on burnt soils can lead to the structural degradation of the soil surface (Bresson and Boiffin, 1990; Poesen and Nearing, 1993; Ramos *et al.*, 2003). Aggregate breakdown liberates small soil particles forming a surface crust with low permeability to air and water (Llovet *et al.*, 2008; Mataix Solera *et al.*, 2011, León *et al.*, 2013). Besides, ash plays an important role in soil protection after the forest fire and after the first storms and winds (Cerdà and Doerr, 2008; León *et al.*, 2013a,b; Pereira *et al.*, 2013). These are the reasons why research on the effect of restoration measures

in burnt areas started since the second half of the 20th century (Gross *et al.* 1989; Miles *et al.* 1989; Cerdà and Robichaud 2009). These measures include apply different types of covers or mulch (straw, wood-chip or shredded mulching, straw pellets, pine straws) or sowing and building barriers in order to reduce erosion and runoff (Bautista *et al.* 1996; Badía and Martí 2000; Wagenbrenner *et al.* 2006; Cerdà and Doerr 2008; Groen and Woods 2008; Fernández *et al.* 2011; León *et al.*, 2012).

Soil erosion by water is an extremely active process in soils affected by forest fires and decisive for the evolution of burned areas because it eliminates the layer of ash and the organic horizon, the most abundant nutrient reservoir. The recovery of the soil, vegetation and water quality all depend on the post-fire erosion processes. Thus, the details regarding post-fire erosion are critical for elucidating the magnitude of the impact of fire on soils (Mataix-Solera and Cerdà, 2009). The first experimental studies on soil erosion after fires used an estimation method based on Universal Soil Loss equation (USLE: Wischmeier and Smith, 1965; Rubio, 1987; Díaz-Fierros *et al.*, 1987). Another method uses erosion plots in which specific areas of a slope are delineated to measure runoff and the amount of sediment exported for the calculation of erosion rates. This method was used to contribute data that were necessary to understanding the effect of fire on soil erosion in Spain (Vega and Díaz-Fierros, 1987; Soler and Sala, 1990; Sánchez *et al.*, 1994; Úbeda and Sala, 1998; Badía and Martí, 2000; Pardini *et al.*, 2004).

The study of soil erosion after forest fires has followed two strategies: monitoring plots for years to compare control and burned plots (paired) or taking plot measurements to determine the evolution of soil loss until the erosion rates recover to levels typical of pre-fire forest soils (Shakesby, 2011; Bento-Gonçalves *et al.*, 2012; Malvar *et al.*, 2015). There are methodological problems with both strategies because of the spatial and temporal variability in rainfall. Rainfall simulators have helped to overcome these problems and understand why, under identical rainfall conditions, soils affected by fire erode at higher rates than those unaffected by fire (Calvo and Cerdà, 1994; Llovet *et al.*, 1994; Badía and Moreu, 1996; Cerdà, 1998; Badía and Martí, 2008; León *et al.*, 2013a).

In general, an increase in the erosion rate has been quantified after fire (Soler and Sala, 1990; Mayor *et al.*, 2007). However, certain studies have noted contrasting behavior by burned soil in studies with high prefire variability in soil loss and rainfall between the burned and the reference or control plots (Cerdà and Lasanta, 2005). In addition to the high spatial and temporal variability of soil loss in Mediterranean ecosystems because of erratic rains, the following factors may also influence these contrasting behaviors of burned areas: the soil rockiness (Cerdà and Navarro, 1997a,b; Rubio *et al.*, 1997); fire intensity and severity (Neary *et al.*, 1999; Shakesby, 2011), and their recurrence (Gimeno *et al.*, 2000); the post-fire management, particularly as affected by ploughing (Edeso *et al.*, 1998; Malvar *et al.*, 2011, 2013); and the measures taken to control the subsequent erosion (Bautista *et al.*, 1996), such as the application of straw mulch (Fernández and Vega, 2014; Robichaud *et al.*, 2014), seeding or mulching (Badía and Martí, 2000; Vega *et al.*, 2015) or other applications for soil conservation and erosion control (Abad *et al.*, 2000).

Measurements taken over intervals of 30 years have led to the conclusion that although erosion rates increase after fires, these rates return to their previous values after a few years

(Cerdà and Lasanta, 2005; Mayor *et al.*, 2007). Mediterranean erosion processes are governed by extreme events (González-Pelayo *et al.*, 2010). However, the increasing recurrence of fires due to climatic and anthropogenic factors causes higher erosion rates that may trigger land degradation processes (Mataix-Solera and Cerdà, 2009).

Soil infiltration is one of the properties affected by fire as a consequence of litter and vegetation removal, and heating of and changes to the biological, chemical and physical soil properties. Rainfall simulations are a remarkably useful tool to assess changes on soil properties and erosion by raindrop impact, especially in semiarid areas, where precipitation regime is irregular, having intense and short-duration events (Seeger, 2007; Cerdà *et al.*, 2009; León *et al.*, 2012). It is an essential tool for investigating the different erosion processes in the field and in the laboratory, quantifying rates of infiltration, runoff and sediment (Cerdà *et al.*, 2010; Iserloh *et al.*, 2013a). A rainfall simulator allows a fast and replicated assessment of the meaning and impact of several factors, such as slope, soil type, soil moisture, soil structure, aggregate stability, vegetation cover and vegetation structure (Schmidt, 1998). The small portable rainfall simulator (plot size below 5 m²) have become more widely used in current research (Cerdà *et al.*, 2010; Nadal-Romero *et al.*, 2011; León *et al.*, 2012; Iserloh *et al.*, 2013a) because it has many advantages such as low cost, easy handling, easy transport areas, low water consumption and high replication rates of measurements (Iserloh *et al.*, 2013a). However, in contrast, it presents some disadvantages such as the lack of standardization in design, rainfall intensities, rain spectra and drop size and distribution, which impede drawing a meaningful comparison between results. The Thies Laser Precipitation Monitor, which represents the most up-to-date and accurate measurement technique for obtaining information on drop-spectra and drop fall velocity was used (Iserloh *et al.*, 2013a). The quantity and spatial distribution of the simulated rain can be easily monitored with rain gauges.

The aim of this work was to compare i) the sediment yield with two different measurements –with a rainfall simulator and erosion plots– and ii) to compare the sediment yield with two different treatments –with and without wood chips.

2. Material and methods

2.1. Study area

The Zuera Mountains, located north of the city of Zaragoza (NE-Spain), have suffered more than 40 fires during the period 1920–2006 (Villar, 2006). The mountain vegetation has a good natural recovery, especially in north-facing slopes. However, the long anthropogenic influence, the semiarid climate and shallow soils have been very harmful with respect to the effects and recurrence of fire, particularly those burning in degraded areas. The last large fires were in 2008 (2 000 ha) and 2009 (more than 6 000 ha). This study was carried out in Castejón (UTM 30T, X671106, Y4644584) under an Aleppo pine forest that burned in 2008, and in Remolinos (UTM 30T, X656794, Y4639884) under shrubland that burned in 2009 (Fig. 1).

The vegetation at Castejón is characterized by a mixed forest (*Pinus halepensis* Mill. and *Quercus coccifera* L.) and scrubs (*Brachypodium phoenicoides* L., *Brachypodium retusum*

Pers., *Juniperus oxycedrus* L., *Lonicera etrusca* G., *Genista scorpius* L., *Helianthemum marifolium* Mill., *Osyris alba* L., *Pistacea lentiscus* L., *Rhamnus lyciodes* L. subsp. *lyciodes*, *Rosmarinus officinalis* L.), whereas in the *Remolinos* area, the scrub formation is dominant (*Genista scorpius* L., *Retama sphaerocarpa* L., *Rosmarinus officinalis* L., *Gypsophila struthium* Willk subsp. *Hispanica*, *Ononis tridentata* L., and *Quercus coccifera* L.) and *Pinus halepensis* Mill. The climate is the same in both areas. It is Mediterranean continental, with a mean annual rainfall up to 450 mm and a temperature variation from -7.1°C to 36.5°C. The mean annual reference evapotranspiration is approximately 1406 mm (using FAO56 by Penman Monteith method) and is enhanced by strong winds, which cause the water deficit to be one of the highest in Europe (Herrero and Synder, 1997). The geomorphological units (between 200 and 748 m a.s.l.) are platforms on carbonate and evaporitic tertiary formations and flat bottom valleys. The soils on limestone parent material are *Rendzic Phaeozem* with a clay loam textural class on Ah horizons (Badía *et al.*, 2013) in both areas.

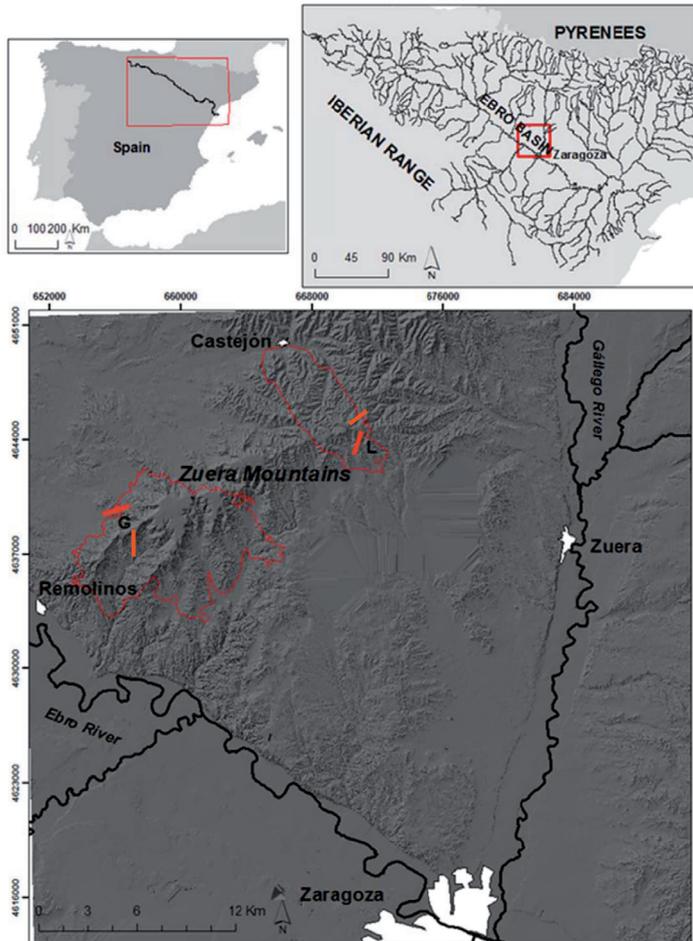


Figure 1. Study area: Remolinos fire in 2009 (G) and Castejón fire in 2008 (L).

2.2. Rainfall simulation

The rainfall simulator was previously described by Cerdà *et al.* (1997) and Lasanta *et al.* (2000), with four metallic legs, a plastic cover to protect the trial from the wind, a cone spray nozzle (Lechler 460.688) and a 0.7 kw motorized pump (Garland GTP25). The rain simulator was gauged with a Laser Disdrometer (Thies) –detailed in Fister *et al.* (2011): raindrop distribution of 97.8% of the Christiansen Coefficient, rain intensity of 52.5 mm h⁻¹, average drop size of 0.5•1 mm (D50) and kinetic energy around 4.16 J m⁻² mm⁻¹(Iserloh *et al.*, 2013b). A circular simulation plot was used having a surface area of 0.21 m² and rain was applied from a 2.2 m height (Fig. 2).



Figure 2. Rainfall simulator in Castejón fire and rainfall plots.

Rainfall simulations were used as a tool to compare the hydrogeomorphological behavior after the fire and to validate the use of wood chips as a resource to stop erosion in the area of Castejón. In total, 16 rainfall simulations were carried out (November 2008 until June 2009): 8 simulations with wood chips and 8 simulations without wood chips on burnt soils. Each of the simulations lasted 60 minutes.

Erosion plots and rainfall simulation plots were similar in terms of slope and topographic exposure –hillsides facing northeast with an inclination of around 10%. Each plot was characterized according to the percentage of vegetation cover, stoniness, soil humidity, and bulk density (including the organic horizon –litter, fallen leaves or ashes). The presence of ashes having different color and thickness provided information relative to fire intensity, which was higher in pinewood areas and lower in scrub areas.

2.3. Erosion plots

We built 12 open erosion plots (2 m²) in Remolinos area with six replicates by treatment (November 2009 until June 2010): 6 burnt and 6 burnt with wood-chips, with a meter separation between plots to avoid overlap (Fig. 3). The experiment finished due to external problems.

The sediment washed away by runoff was collected in a “Gerlach” or sediment trap at the lower end of each of the plots (1 m). We collected, identified and analysed in laboratory the sediment after rainfall events.

2.4. Application of wood chips

In order to test the mulching effect, wood chips from the burnt pine trees were used in situ (*Pinus halepensis* Mill.), covering 100% of the plot with 2.85 kg m^{-2} of chips having different size and thickness –between 0.5 and 2 cm (Fig. 2). By applying wood-chip mulching we can study the effects on erosion after the fire, as wood-chips are very easy to obtain due to the high availability of dead wood after a fire. Wood chips reduce the rain impact, loss of soil by rain splash and the effects of runoff and runoff geomorphological effects. We measured the vegetation cover and the stone cover in the soils before to apply the mulching. We chose wood chips instead of straw because this area is faced mainly northwest, where there is a strong and predominant wind with mean monthly wind speeds around 20 km h^{-1} , which removes the straw mulch.

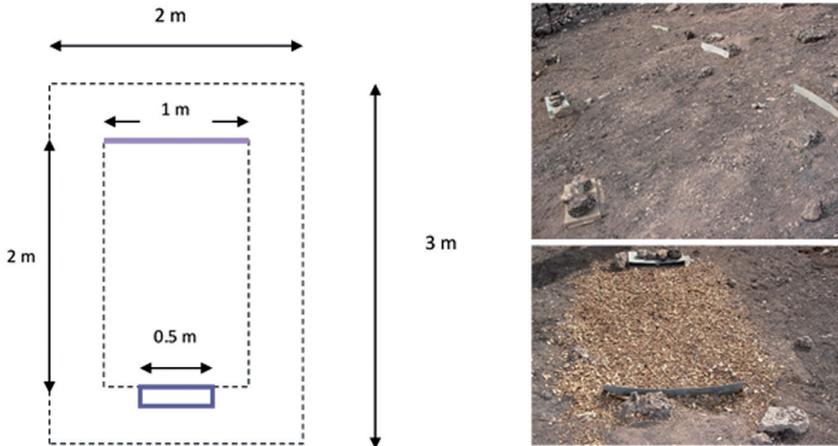


Figure 3. Erosion plots in Remolinos fire.

3. Results

3.1. Rainfall simulation

The results obtained from the rainfall simulations indicate that average runoff rates are much higher on burnt soils ($9.39 \pm 5.81 \text{ mm h}^{-1}$) than on burnt soils covered with wood-chips ($4.36 \pm 3.85 \text{ mm h}^{-1}$). Wood-chip applications reduce erosion as a result of the protective effect of wood chips, such that the sediment yield was $3.82 \pm 2.90 \text{ g m}^{-2}$ in the case of burnt soils and $1.91 \pm 2.43 \text{ g m}^{-2}$ in the case of burnt soils covered with wood-chips (Table 1 and Fig. 4). Using woodchips acidifies runoff water; however it does not significantly affect the electric conductivity (EC) or the organic matter content (OM) of runoff water (Table 1).

Table 1. Mean value and standard deviation during rainfall simulations.

	Calcareous soils	
	Burnt	Burnt + wood-chips
Slope (%)	9.62±1.78	13.57±4.71
Vegetation cover (%)	2.50±4.18	6.89±14.57
Stone cover (%)	34.00±24.31	25.83±13.99
Soil moisture (%)	14.00±11.39	6.70±3.48
Bulk density (g l ⁻¹)	0.73±0.05	0.67±0.03
Ponding time (min)	5.24±2.35	5.03±2.69
Runoff (mm h ⁻¹)	9.39±5.81	4.36±3.85
Runoff reduction (%)	46.43	
Sediment (g m ⁻²)	3.82±2.90	1.91±2.43
Soil erosion reduction (%)	50.00	
pH	7.44±0.38	7.03±0.03
EC (μS cm ⁻¹)	996.82±469.38	610.83±82.07
OM (mg l ⁻¹)	0.07±0.06	0.12±0.16

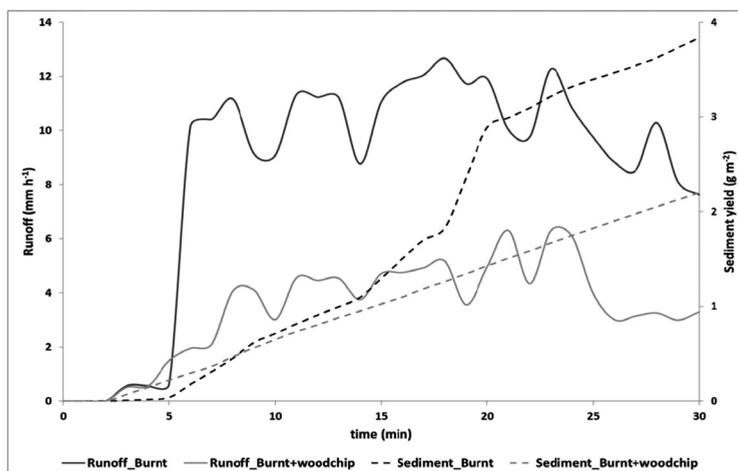


Figure 4. Runoff and sediment yield with a rainfall simulator.

3.2. Erosion plots

In the case of the soil erosion plots, the application of mulch with wood-chip reduces the sediment yield (Table 2) in the burnt soils ($20.01 \pm 18.70 \text{ g m}^{-2}$) compared with burnt soils without wood-chips ($25.70 \pm 20.96 \text{ g m}^{-2}$). From the first rain the application of mulch wood-chips reduced soil loss (Fig. 5). The percentage of bare soil at the time of trial stood was at 80% on average, and reduced to less than 3% with the application of mulch wood-chips. However, this percentage dropped sharply because of the northwest wind in the next months, which led to a progressive standardization of results between treatments.

Table 2. Sediment yield in the erosion plots.

	SEDIMENT YIELD (g m ⁻²)										mean	
	dec-09	jan-10	feb-10	mar-10	apr-10	may-10	jun-10					
Burnt (n=6)	5.88±0.41	37.04±39.08	39.09±22.49	32.18±9.53	6.65±2.31	2.14±1.89	56.92±45.00					25.70±20.96
Burnt + wood-chip (n=6)	4.53±1.31	19.88±18.13	26.45±16.11	27.36±20.09	5.32±4.67	1.69±0.66	54.82±38.40					20.01±18.70
Soil erosion reduction (%)	77.02	53.68	67.65	85.00	79.92	79.16	96.32					77.85
Precipitation (l m⁻²)	7.93	64.03	27.16	19.4	33.86	10.05	22.58					26.43±18.90
Events	4	19	14	7	13	2	8					9.57±6.02

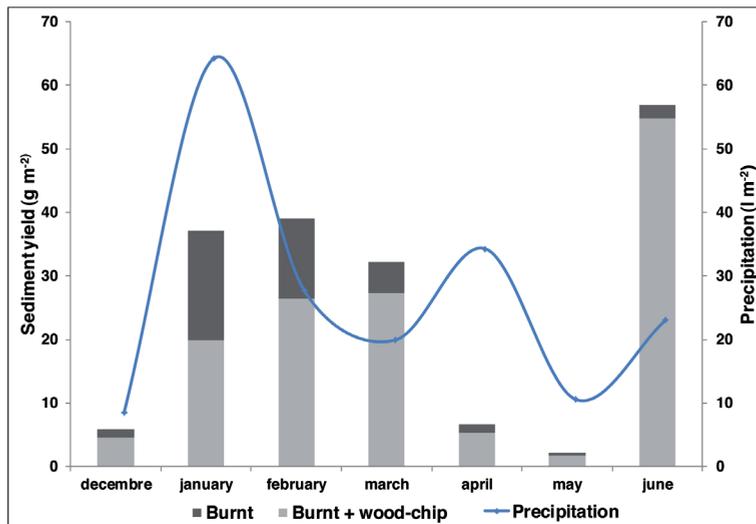


Figure 5. Sediment yield in the erosion plots (period 2009-2010).

4. Discussion

As shown by another research conducted in the central sector of the Ebro Depression (Badía and Martí 2000), where different mulch techniques were applied on burnt areas, they are efficient to reduce the sediment yield in soils affected by wildfires.

Introducing wood-chips means reducing erosion. Firstly, a decrease of 50% for calcareous soils was observed as a consequence of runoff reduction. Runoff reduction is also observed in other studies where different mulch types are applied, such as straw or wood chips (e.g. Bautista *et al.* 1996; Badía and Martí 2000; Wagenbrenner *et al.* 2006; Groen and Woods 2008; Cerdà and Robichaud 2009; Fernández *et al.* 2011). Nevertheless, mulching allows the production of runoff, but the amount of sediment decreased, compared to the bare soil situation: a decrease of 22% in the case of both areas. Badía and Martí (2000) observed similar values (37%) in soils affected by forest fires in calcareous soils. Bautista *et al.* (1996) and Wagenbrenner *et al.* (2006) indicate reductions of 95 and 91% with straw mulching compared to untreated soils. In these studies mulch was applied to cover between 70 and 100% of the plot. Robichaud *et al.* (2000) suggests that for mulching to be effective at least 60% of the surface be covered. Fernández *et al.* (2011) used wood chips to cover 45% of the plot and straw mulch that covered 80% of the plot, but they found wood chips to be not useful. Cerdà and Doerr (2008) assessed the role of pine needles deposited on the soil after a fire, and found an erosion reduction of 10% compared to unprotected surfaces.

Foltz and Wagenbrenner (2010) demonstrated the effectiveness of wood chips with 50 and 70% cover, with a reduction in runoff and sediment concentration. Similarly,

Bautista *et al.* (2009) suggested that a mixture of wood chips, pine needles and twig applied as mulch reduced erosion in a burned area in Alicante (2002), without altering the plant auto succession. However, Cerdà and Robichaud (2009) remarks that the mulch can be ineffective to reduce runoff and erosion if rainfalls are intense. Other authors showed how the straw mulch applied in Southern California after a fire in late 2003 was removed by strong winds (Bautista *et al.*, 2009; Foltz and Wagenbrenner, 2010). For Robichaud *et al.* (2014) unlike seeding, straw mulch has been found to be quite effective in reducing post-fire erosion, which has led to the development and use of other mulches, such as hydromulch and wood strands, for post-fire stabilisation. For Prats *et al.* (2013) hydromulching was highly effective during the first 19 months after its application, reducing total runoff volumes by 70% and total soil losses by 83%, and continued effectively during the third year following the wildfire. And for Vega *et al.* (2015) mulching with seeding was clearly much more efficient than seeding alone in terms of minimizing soil erosion.

Finally Foltz and Wagenbrenner (2010) suggest that we must not forget, when applying different types of mulching on a large scale, the cost-effective, ecologically sustainable and environmentally benign, widely available and easily transported, and durable and stable enough to provide protection until natural ground cover has been reestablished.

5. Conclusions

Both methods –rainfall simulation and erosion plots– are useful to assess soil erosion. The application of wood chip mulch after a wildfire in both methods, reduces runoff rates by half, and soil erosion in 22%. Therefore, post-fire mulching is very effective for reducing runoff but showed a limited effectiveness in reducing soil erosion.

The application of mulching with wood chips is expensive, such that it is only efficient if the wood of dead vegetation can be used. We suggest that some factors such as the vegetation recovery capacity, the soil type, the slope distribution and the fire severity must be considered before selecting the material to apply. The results from this research can help the land managers to select the most appropriate material.

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