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EFFECTIVENESS OF HYDROMULCHING TO REDUCE RUNOFF AND EROSION IN A RECENTLY BURNT PINE PLANTATION IN CENTRAL PORTUGAL

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ABSTRACT

Forest fires can greatly increase runoff and surface erosion rates. Post-fire soil erosion control measures are intended to minimize this response and facilitate ecosystem recovery. In a few recent cases, hydromulch has been applied, and this consists of a mixture of organic fibers, water and seeds. The objectives of this research were to (i) analyze the effectiveness of hydromulch in reducing post-fire runoff and sediment production and (ii) determine the underlying processes and mechanisms that control post-fire runoff and erosion. After a wildfire occurred in August 2008, 14 plots ranging in size from 0·25 to 10 m^2 were installed on a 25 degree slope in a burnt pine plantation that had also been subjected to salvage logging. Half of the plots were randomly selected and treated with hydromulch. One of two slope strips adjacent to the plots was also hydromulched and used for monitoring some soil properties. Measurements made in each of the first 3 years following the wildfire included (i) the plot-scale runoff volumes and sediment yields; (ii) soil shear strength, soil moisture, and soil water repellency; and (iii) surface cover. The hydromulch reduced overland flow volume by 70% and soil erosion by 83%. The decrease in runoff was attributed to the increase in soil water retention capacity and the decrease in soil water repellency, whereas the reduction in soil erosion was initially attributed to the protective cover provided by the hydromulch and lately to an enhanced vegetative regrowth in the third year after burning. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: wildfire; post-fire erosion; overland flow; soil water repellency; ash

INTRODUCTION

Soil erosion is a key process in the functioning of Mediterranean ecosystems (Cantón *et al*., 2001; Ceballos *et al*., 2003; Cerdà *et al*., 2010), and wildfires represent one of a number of disturbances in forests and shrublands that can greatly increase soil and fertility losses (Cerdà, 1998a, 1998b; Shakesby & Doerr, 2006; Shakesby, 2011). The consumption of the vegetation and litter layer by fire increases both overland flow—because of the reduction of rainfall interception and resistance to flow—and sediment losses by increasing the splash erosion by raindrops (Soto & Diaz-Fierros, 1997; Llorens & Domingo, 2006). Additionally, the fire-induced heating of the soil can reduce aggregate stability, decrease porosity, and increase soil water repellency (SWR), and these changes can decrease infiltration and increase soil erodibility (DeBano, 2000; Ferreira *et al*., 2008; Keizer *et al*., 2008; Malvar *et al*., 2011; Prats *et al*., 2012).

The association of wildfire with on-site soil erosion and downstream flooding and massive sediment deposition has become increasingly recognized (Kraebel, 1934) and, in the early part of the last century, led to the first systematic soil erosion control treatments following wildfires (Munns, 1919). The first post-fire rehabilitation efforts consisted of building engineering structures (check dams) in stream channels to trap the sediments and of seeding hillslopes to increase ground cover (Wohlgemuth *et al*., 2009). However, it was proved to be unrealistic to build check dams in the short periods between the occurrence of the wildfires and the occurrence of the erosion-producing rains; also, various studies started to question the effectiveness of seeding to reduce soil erosion during the 1980s (Gautier, 1983; Taskey *et al*., 1989).

During the 1990s and the 2000s, research on post-fire erosion mitigation concerned seeding (e.g., Pinaya *et al*., 2000; Fernández-Abascal *et al*., 2003; Beyers, 2004; Robichaud *et al*., 2006; Groen & Woods, 2008; Peppin *et al*., 2010), construction of erosion barriers by using logs (Wagenbrenner *et al*., 2006; Robichaud *et al*., 2008), and straw mulching (Bautista *et al*., 1996; Badía & Martí, 2000; Wagenbrenner *et al*., 2006). In a nutshell, these studies found seeding to be effective in some cases but not in others, log erosion barriers to be ineffective unless rain events are few and small, and mulching to be highly effective. The effectiveness of mulching was also well-established for agriculture lands (Harris & Yao, 1923; Meyer *et al*., 1970; Lyles *et al*., 1974; Meyer *et al*., 1999; Wilson *et al*., 2004; García-Orenes *et al*., 2009, 2010; Giménez-Morera *et al*., 2010; Jordán *et al*., 2010), cut slopes, and unpaved roads (Grismer & Hogan, 2005; Jordán & Zavala, 2008).

Post-fire straw mulching at rates of c.a. 2 $Mg\,ha^{-1}$ has been proved to reduce sediment yields by more than 80%

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(Bautista *et al*., 1996; Badía & Martí, 2000; Wagenbrenner *et al*., 2006; Groen & Woods, 2008; Fernández *et al*., 2011; Robichaud *et al*., 2013b). However, straw may be available in only limited quantities in certain regions, including Portugal (Prats *et al*., 2012), and may be redistributed by strong winds as a result of its low weight (Robichaud *et al*., 2000). Straw application can also introduce invasive weeds and inhibit native species recovery (Kruse *et al*., 2004). Despite the increased application costs, other mulches of higher specific weight have also been tested. Forest residues, at application rates of 8 Mg ha^{-1} in Prats *et al*. (2012) and 46 Mg ha^{-1} in Shakesby *et al*. (1996), or wood strands mulch, at rates of 4–12 Mg ha $^{-1}$ in Robichaud *et al*. (2013a), were found to be as effective as straw mulch, whereas wood chips mulch was found to be much less effective (Kim *et al*., 2008; Fernández *et al*., 2011).

Mulching is effective against erosion because it reduces runoff and erosion rates by two mechanisms. First, it increases interception storage capacity, which reduces the amount of rain available for producing runoff, it reduces runoff velocity, and it increases soil moisture (Bautista *et al*., 2009). Second, mulch protects the soil surface against the kinetic energy of rainfall drops and decreases the hydrodynamic power of flowing water (Smets *et al*., 2008).

A recent variant of mulching is that of hydromulching, which refers to the application of a water-based mixture of organic fibers, seeds and a green colorant. It is easily applied because it can be sprayed onto slopes by a jet hose (Naveh, 1975). It also tends to bind strongly to the soil surface by the action of the soil-binding agent, so it is particularly useful on steep slopes and strongly modified areas such as quarries, construction sites, and cut and fill slopes along roads (Emanual, 1976; Benik *et al*., 2003; Robichaud *et al*., 2010). Runoff and soil erosion will be reduced because the hydromulch increases interception storage and protects the soil surface. Additionally, the introduced seeds are intended to increase the vegetative cover, especially when the mulch starts decompose. In burnt areas, seeding requires careful selection of species that are adapted to the target environment, both to guarantee that the seeding produces an adequate cover and to avoid that the introduced species come to behave as invasive weed (Kruse *et al*., 2004). An important disadvantage of hydromulching is its elevated costs, which can range from $3,700.00 to $10,300.00 per ha for aerial application (Hubbert *et al*., 2012). By contrast, the costs for straw mulching are on the order of $600.00 and $1,200.00 per ha for application by helicopter and by hand-spreading, respectively (Napper, 2006). Despite this greater expense, hydromulching has been used especially in the USA after some fires when access was difficult, the slopes were too steep or subject to wind to use straw mulch and when there were particularly important ‘values at risk’, such as water reservoirs, cultural or natural heritage sites, or industrial plants.

The effectiveness of hydromulching in reducing post-fire runoff and erosion has not yet been fully established. Although Robichaud *et al*. (2013b) found no marked decrease in post-fire runoff, Hubbert *et al*. (2012), Rough (2007), and Robichaud *et al*. (2010, 2013a) did report substantial reductions in erosion rates (with 65–95%). However, these reductions were restricted to the first year after hydromulching, which the authors attributed to the rapid breakdown of the mulch layer. Wohlgemuth *et al*. (2011) also found hydromulching to markedly reduce overall erosion rates (by 60–80%) but not the sediment losses produced by high-intensity storms. Robichaud *et al*. (2010) suggested that hydromulching would be most effective on short slopes (10–20 m), where interrill erosion is the dominant process and the hydromulch mat is less likely to be detached by rill incision. However, Rough (2007) found aerial hydromulching to be highly effective on long hillslopes with elevated rill densities (0·1 rill m^{-2}).

Given the elevated potential of hydromulching for post-fire rehabilitation, there is a clear need to test its effectiveness in geographical regions outside the USA. Although hydromulch can include surfactants, the effectiveness of hydromulching has been poorly assessed for vegetation types associated with strong or extreme SWR, such as the eucalypt and pine plantations that dominate in north-central Portugal (Ferreira *et al*., 2008, Keizer *et al*., 2008; Prats *et al*., 2012). Also, the effectiveness of hydromulching after post-fire salvage logging is poorly known in spite of being perhaps the most common practice following wildfires in north-central Portugal. Salvage logging was typically being used to recover timber values and reduce the risk of insect infestation (McIver & Starr, 2000), but it can trigger runoff and soil erosion through soil alteration and forest floor disturbances (Rab, 1994; Castillo *et al*., 1997; Edeso *et al*., 1999; Fernández *et al*., 2004, 2007).

The overall aim of the present research was to study the effectiveness of hydromulching to reduce runoff and erosion over a three-year period in a recently burnt and logged pine plantation in north-central Portugal. The specific objectives were to (i) assess the effectiveness of hydromulching in reducing runoff volumes and sediment yields at the plot scale; (ii) analyze the changes in runoff and soil erosion over time and across plot size (0·25, 0·5, and 10 m^2 plots); and (iii) determine the effect of hydromulching on key soil properties, surface cover, and vegetative recovery, and the extent to which these mulching-induced changes can explain the observed differences in runoff and erosion between the hydromulched and untreated plots.

MATERIAL AND METHODS

Study Area and Site

This study was conducted near the village of Colmeal in the Góis municipality of north-central Portugal (N 40º08′42″, W 7º59′16″; 490 m asl). On 27 August 2008, a wildfire burnt 68 ha of forest lands. A west-facing 25 degree steep hillslope was selected to study post-fire vegetation recovery (Maia *et al*., 2012a, 2012b), and, at a later stage, also for this study. The hillslope had been planted with maritime pine (*Pinus pinaster* Ait.) some 25 years before the wildfire, at a density of 2,600 saplings per ha. The undergrowth was composed of a mixture of Mediterranean and Atlantic shrubs and was dominated by *Calluna vulgaris* I. and *Arbutus unedo* L. (Maia *et al*., 2012b). The study area has a Mediterranean climate with a mean annual temperature of 10–12·5°C (according to Köppen; APA, 2011). The annual precipitation as recorded by the nearest weather station (Cadafaz, N 40º08′02″, W 8º32′40″; 12 km W^{-1} from the study area; 25 years of data) was, on average, 1,130 mm but varied from 717 mm to 1,872 mm (SNIRH, 2012). The soils were shallow, 30- to 35-cm deep Humic Cambisols (WRB, 2007), overlying schist, as was observed from four soil pits dug during November 2008 (Table I). A soil sample was collected at 0–5 cm depth in each pit, and later analyzed, using standard laboratory methods, for bulk density (Porta *et al*., 2003), porosity, and grain-size distribution (Guitian & Carballas, 1976). Percent organic carbon was determined by a carbon analyzer (Flash EA 1112 series by Thermo Finnigan, USA) and multiplied by the van Bemmelen factor (1·724) in order to obtain the organic matter content on the soil (Jackson, 1958).

Experimental Design, Field Data Collection, and Laboratory Analyses

At the location selected for this experiment, the 2008 wildfire had completely consumed the pine crowns, so there was basically no needle cast after the fire (Table I). On 11 December 2008, 106 days after the fire, more than half of the soil surface corresponded to black ashes, a third to stones, and less than 10% to bare soil. The fire severity was classified as moderate according to various severity indices described in Maia *et al*. (2012b) at locations some 5–10 m distance from the present experiment. For example, the maximum temperature reached (Guerrero *et al*., 2007) by the soil at 0–3 cm depth, estimated with near-infrared spectroscopy, was, on average, 78°C; the twig diameter index (Maia *et al*., 2012a), which ranged between 0 (unburnt) and 1 (very intense wildfire) was, on average, 0·4 (Table I).

Table I. Indicators of fire severity, ground cover, and mean soil properties from 0- to 5-cm depth ($n = 4$)

Site characteristics	Average	±	SD
Overall fire severity		Moderate	
Tree canopy consumption		Total	
TDI	0·4	±	0·1
MTR (°C)	78	±	30
Ground cover in December 2008 (%)			
Litter	2	±	1·3
Black ashes	56·6	±	9·7
Bare soil	7·2	±	3·7
Stones (>2 mm)	34·2	±	8·3
Soil properties			
Soil depth (cm)	35·3	±	4·3
Slope (º)	24·5	±	3·4
Bulk density (g cm^{-3})	0·8	±	0·1
Porosity ($cm^3 cm^{-3}$)	0·5	±	0·1
Organic matter (%)	16·4	±	1·6
Soil texture			
Clay (%)	8·4	±	1·9
Silt (%)	35·8	±	9·0
Sand (%)	55·8	±	12·8
Stoniness (>2 mm) (%)	36	±	15·0
USDA soil texture class		Sandy loam	

TDI, twig diameter index; MTR, maximum temperature reached, following Maia *et al*. (2012a, 2012b); SD, standard deviation; USDA, United States Department of Agriculture.

Because the National Forestry Authority had decided to log the stand as soon as possible because of the risk of nematode infestation, the experimental set up of this study involved four phases. The first phase comprised the installation of a tipping-bucket rain gage (Pronamic professional rain gauge with an event logger) in combination with a storage gage for validation purposes. This was carried out on 15 September 2008, prior to any rainfall following the wildfire. After that, the rainfall was measured weekly from the storage gage, and the maximum weekly or monthly 30-min rainfall intensity ('I30', in mm h^{-1}) was calculated for each period from the tipping-bucket rain gage data series.

On 5 November 2008, the pretreatment period started with the installation of four plots bounded with metal sheets. Two were micro-plots of approximately 0·5 × 0·5 m, whereas the other two were small plots of approximately 0·5 m wide and 1·0 m long. The outlets of each plot were connected, using garden hose, to 30 L tanks, where the runoff was collected. The runoff volume in each tank was measured at 1- to 2-weekly intervals, depending on rainfall, from 5 November 2008 to 12 October 2010, except during March 2008 when the runoff measurements had to be interrupted because of the logging activities. This 23-month period was divided in a pretreatment and posttreatment period, as further specified in Table II. Whenever runoff exceeded 250 ml, a sample was collected for determination of sediment and organic matter contents by using standard laboratory methods (filtration at 14 μm, drying for 24 h at 105°C and loss-on-ignition for 4 h at 550°C; APHA, 1998).

The third phase began on 30 March 2009, after the logging had been completed, when two more micro-plots and two more small plots were installed at close distances from the previous micro-plots (<5 m) along with six sediment fences (Robichaud & Brown, 2002) that had been set up at some 10–20 m distance in the upslope direction. Following the design by Fernández *et al*. (2011), these sediment fence plots ('SF plots') of roughly 2-m wide and 5-m long were bounded by means of a geotextile fabric and delimited by metal sheets to avoid run-on into the plots. The geotextile fabric filtered the runoff, and only the sediments accumulated at the bottom of the SF plots were collected at monthly intervals from 31 March 2009 to 12 October 2010. Afterwards, the SF plots were emptied

Table II. Overall figures of rainfall, overland flow, soil losses, and effectiveness of hydromulching during the first 3 years after a wildfire in a maritime pine plantation

		Year 1		Year 2	Year 3
Period		Pre	Post	Post	Post
Start date		5 November 2008	31 March 2009	21 September 2009	12 October 2010
End date		11 February 2009	21 September 2009	12 October 2010	28 November 2011
Rainfall (mm)		609	282	1464	1527
Overland flow					
Number of plots (C/Hm)		*4/0*	*4/4*	*4/4*	—
Runoff (mm)	C	363	140	691	—
	Hm	—	61	152	—
Runoff coefficient (%)	C	60	50	47	—
	Hm	—	22	10	—
Erosion					
Number of plots (C/Hm)		*4/0*	*7/7*	*7/7*	*3/3*
Soil loss ($g\,m^{-2}$)	C	86	217	361	247
	Hm	—	36	63	109
Specific soil loss	C	0·14	0·77	0·25	0·16
($g\,m^{-2}\,mm\ rain^{-1}$)	Hm	—	0·13	0·04	0·07
Organic matter content (%)	C	48	50	52	—
	Hm	—	57	57	—
Effectiveness of	Runoff	—	−56	−78	—
hydromulching (% change)	Soil losses	—	−83	−83	−56
	OM %	—	15	10	—

C, control; Hm, hydromulching; OM, organic matter.

on a single occasion, on 28 November 2011, comprising the fourth phase of this study. The collected sediments were later analyzed for their moisture and organic matter contents by using standard laboratory methods (drying for 24 h at 105°C and loss-on-ignition for 4 h at 550°C; APHA, 1998).

On 31 March 2009, the hydromulch was applied to two of the four micro-plots, two of the four small plots, and three of the six SF plots, all of which were selected randomly. In addition, it was applied to one of two adjacent soil strips of 5-m wide and 10-m long, which had been delineated for monitoring of selected soil properties by using destructive techniques. The hydromulch was provided and applied by Serraic, Lda. by using a jet hose operated by a person on foot. It consisted of an aqueous mixture of wood fibers, seeds, a surfactant, nutrients, a natural bio-stimulant and a green colorant applied at a nominal ratio of 3.5 Mg ha^{-1}. The formulation is confidential, but the company guaranteed that the components are nontoxic for humans or the environment. The seed composition was also confidential, but detailed descriptions of the floristic composition in the SF plots suggested that it included grass (e.g., *Lolium perenne* L.) as well as shrub species [*Cytisus striatus* (Hill), *Ulex minor* Roth.].

Ground cover was measured at seven occasions between 31 March 2009 and 12 October 2010 and finally on 11 November 2011. The ground cover was recorded at each intersection point of a 5 × 5-cm grid in the case of the micro-plots and small plots, and of a 10 × 10-cm grid in the case of the SF plots, that is, at 100, 200, and 400 points, respectively. Each recording involved classifying the ground cover according to seven categories: stones bigger than 2 mm ('Stone'), bare soil ('Bare'), ashes ('Ash'), litter ('Litter'), hydromulch ('Hm'), native vegetation ('Natveg'), and vegetation introduced by hydromulch ('Introveg'). The data also were grouped into two lumped categories: total vegetation ('Tveg') and total protective ground cover ('Hlv'), with the latter being the sum of hydromulch, litter, and vegetation.

The soil strips were sampled at monthly intervals from 22 April 2009 to 11 August 2010 for a total of 17 occasions. Sampling involved destructive measurements of soil shear strength, using a torvane (vane tester, Eijkelkamp), and of SWR, using the molarity ethanol drop (Doerr, 1998). At the bottom of each 50 m^2-strip, 15 equally spaced measurements were made along a horizontal transect, and this transect was then shifted approximately 0·5 m upslope for the next sampling occasion. Before measuring shear strength or repellency, any hydromulch, stones, litter, or ashes were removed. The molarity ethanol drop test was slightly modified in accordance with our prior studies (e.g., Keizer *et al*., 2005a, 2005b, 2008). In this study, three drops of pure water were applied to the soil surface, and, if two of the three drops did not infiltrate within 5 s, three drops with successively higher ethanol concentrations were applied until two of the three drops infiltrated within 5 s. The nine ethanol concentrations used were 0, 1, 3, 5, 8·5, 13, 18, 24, and 36%. In data analysis, the overall median of the relative frequency of any ethanol concentrations higher than 0%, calculated over the total measurements in each strip, was called SWR frequency.

Volumetric soil moisture content was monitored at a depth of 0–5 cm at eight locations: four within the untreated SF plots and four within the hydromulched SF plots. This was carried out using eight EC-5 sensors linked to two Em5b data loggers (Decagon Devices, Inc.) and recording data at 10 min intervals. For each read-out period, initial soil moisture content ('Sm') was calculated as the soil moisture at the start of the largest rainfall event during that 1- to 2-weekly period by using the data of the automatic rainfall gage to identify this event.

Data Analysis

For the statistical analyses described in the succeeding text, runoff volumes and (specific) soil losses were fourth-root transformed so that the residuals did not fail the assumption of normality according to the Kolmogorov–Smirnov test at $\alpha \leq 0{\cdot}05$, whereas runoff coefficients were square-root transformed for the same reason. Furthermore, 16 read-outs with low rainfall amounts (less than 6 mm) had to be removed from the data set to prevent non-normality of the residuals.

The effects of hydromulching, plot size, and time-since-hydromulching on the dependent variables (runoff volume, runoff coefficient, soil losses, specific soil losses, and organic matter content of the eroded sediments) were assessed by means of a three-way repeated measures analysis of variance (ANOVA) (Ott & Longnecker, 2001). The variance–covariance structure of each dependent variable was selected according to the lowest values of the Akaike information criterion and the restricted maximum likelihood (REML) fit (Littell *et al*., 2006). The heterogeneous first-order auto-regressive variance–covariance structure was selected for all dependent variables except runoff coefficient, for which a spatial power structure was selected. In addition, specific contrasts between the treated and control plots, for each individual read-out as well as between the three plot sizes, were tested by means of the least squares means and adjusted by the Tukey–Kramer method (Kramer, 1956). Repeated measures ANOVA was also used to test the treatment and time effects on the seven ground cover categories and the initial soil moisture content. In the case of soil resistance and SWR frequency, however, the treatment effect could only be tested using a nonparametric test, that is, the Mann–Whitney *U*-test ($\alpha \leq 0{\cdot}05$).

Stepwise multiple linear regressions using the REG procedure in SAS (Littell *et al*., 1996) were used to determine how well the weekly runoff volumes ($n = 35$) and the monthly soil losses ($n = 17$) could be explained by a set of independent variables. These variables were selected sequentially in a forward selection procedure, in order of decreasing significance by using a minimum p value of 0·05. The 16 independent variables were plot size ('Plotsz'), rainfall amount ('Rain'), 30-min maximum rainfall intensity ('I30'), days since the last rainy day ('Drain'), the seven individual ('Stone', 'Bare', 'Ash', 'Litter', 'Hm', 'Natveg', and 'Introveg'), the two lumped categories ('Tveg' and 'Hlv'), soil shear strength ('Storv'), SWR frequency, and initial soil moisture content ('Sm'). Especially because the various cover categories can be expected to reveal strong correlations, collinearly tests were included in the stepwise procedure, removing independent variables with a condition index higher than 30 (Belsley *et al*. 1980) from the regression models.

RESULTS

Rainfall Amount and Intensity

Rainfall was considerably lower during the first year after the wildfire (1,014 mm) than during the two subsequent years (1,464 and 1,527 mm, respectively; Table II). Even though this study did not commence until 8 December 2008 and had to be interrupted, because of the salvage logging, during March 2009, the present analysis covered almost 90% of the rainfall during the first post-fire year (891 mm; Figure 1). From these 891 mm, 609 mm fell before the logging and the hydromulch application (designated here as 'pretreatment period'), and 282 were measured until the end of post-fire year 1. The highest rainfall amounts were measured during winter, in January 2009 and 2010 with 244 and 262 mm, respectively. The highest rainfall intensities, however, occurred during different times of the first

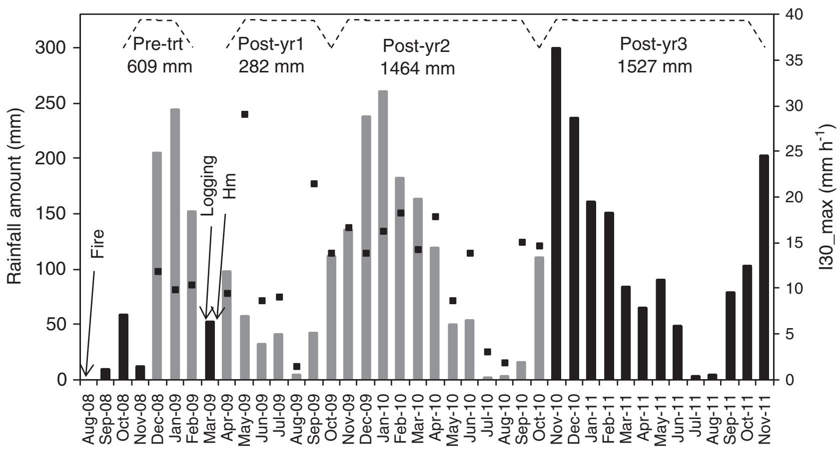

Figure 1. Monthly rainfall (mm) and maximum monthly 30-min rainfall intensity over the study period. Black columns represent total rainfall where no rainfall intensity data were collected. Arrows indicate the date of the fire, logging, and the hydromulch application (Hm), respectively.

post-fire year, during May 2009 and September 2009 with maximum I30 of $29\,mm\,h^{-1}$ and $21\,mm\,h^{-1}$. During the second post-fire year, I30s of $15\,mm\,h^{-1}$ occurred at least once a month from October 2009 to April 2010.

Ground Cover

At the start of this study, in December 2008, half of the soil surface was covered by ashes, and less than 10% was bare (Figure 2; Table I). By 26 March 2009, after the logging had been completed, ash cover had decreased to 28%, the bare soil cover had increased to 17%, and the stones had become the predominant cover category with, on average, 42%. The recovery of the vegetation was very slow on the control plots, as vegetative cover continued to be near zero 1 year after the fire (August 2009), but reached 30% after the second year (October 2010) and a mere 36% at the beginning of the fourth post-fire year (November 2011). Immediately after its application, on 31 March 2009, the hydromulch provided a cover of 80% on average, but this cover was significantly higher at the two micro-plots and two small plots (90% ± 4%) than at the three SF plots (64% ± 2) (ANOVA, $p < 0{\cdot}05$). This difference was no longer significant after five months (August 2009), even though the hydromulch cover continued higher at the four runoff plots (64% ± 12) than at the three SF plots (47% ± 7; ANOVA, $p = 0{\cdot}06$). There was a marked decrease (5·3% per month) in the average of the hydromulch cover during the first 5 months after its application. After 1 year from the application (1 April 2010), the hydromulch cover decreased to 27% on average (an annual decay rate of 4·6% per month). This decrease in hydromulch cover was, by and large, compensated by an increase in protective soil cover due to the native and introduced vegetation (including the litter it produced). The cover of the introduced vegetation was at its maximum (22%) in June 2010 and became practically zero by November 2011. The native vegetation recovered slowly on the hydromulched plots as well but by November 2011 did attain a clearly higher cover than at the control plots (52% vs. 36%). The total protective ground cover (lumped into the 'hlv' category) was around 75% through all the post-treatment period. When the stone cover is included, a protective layer consistently covered 90% of the surface.

Soil Properties

The monthly values of soil shear strength, frequency of SWR, as well as the soil moisture content over the post-treatment period are depicted in Figure 3. The three variables oscillated across the monitoring period according to the rainfall amounts. Soil shear strength and soil moisture varied in the wake of the rainfall variations. By contrast, SWR showed the lowest values during the rainiest months.

Overall, soil resistance to detachment was lower at the untreated than treated strip ($2{\cdot}4 \pm 0{\cdot}7\,kg\,cm^{-2}$ vs. $2{\cdot}8 \pm 0{\cdot}5\,kg\,cm^{-2}$; *U*-test: $Z = -5{\cdot}04$; $p < 0{\cdot}01$). Shear strength was clearly lowest at the control strip during 12 out of 17 months as opposed to 2 months at the hydromulched strip, when shear strength was also greater than during the remaining months.

The hydromulched strip, overall, was less repellent than the control (15% vs. 35% SWR frequency; *U*-test: $Z = -6{\cdot}07$; $p < 0{\cdot}01$) and consequently had higher soil moisture (18·1% volume ± 9·7 vs. 14·3% ± 6·7; ANOVA: $F = 7$; $p < 0{\cdot}05$). In certain periods, however, the opposite was true, as is well-illustrated by Figure 3. In the case of soil moisture content, these periods were confined to the dry season of summer 2009; in the case of SWR, it also happened during summer 2010.

Overall Runoff and Soil Losses

Roughly half of the rainfall was converted into runoff on the control plots (Table II). This corresponded to 360 mm of runoff [runoff coefficient (rc) = 60%] during the pre-treatment period, 140 mm during the post-treatment

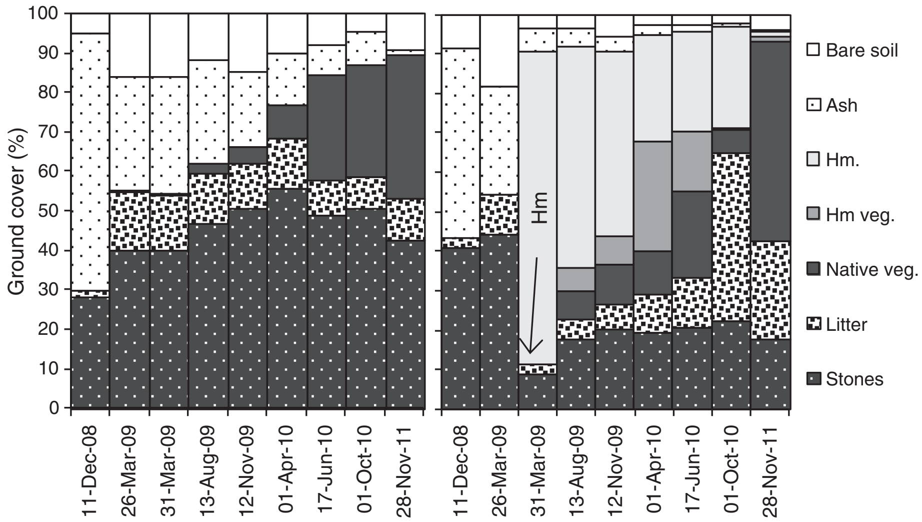

Figure 2. Mean ground cover (%) of the seven categories analyzed in the seven control plots (left) and seven hydromulched plots (right). The arrow indicates the date of the hydromulch application (Hm).

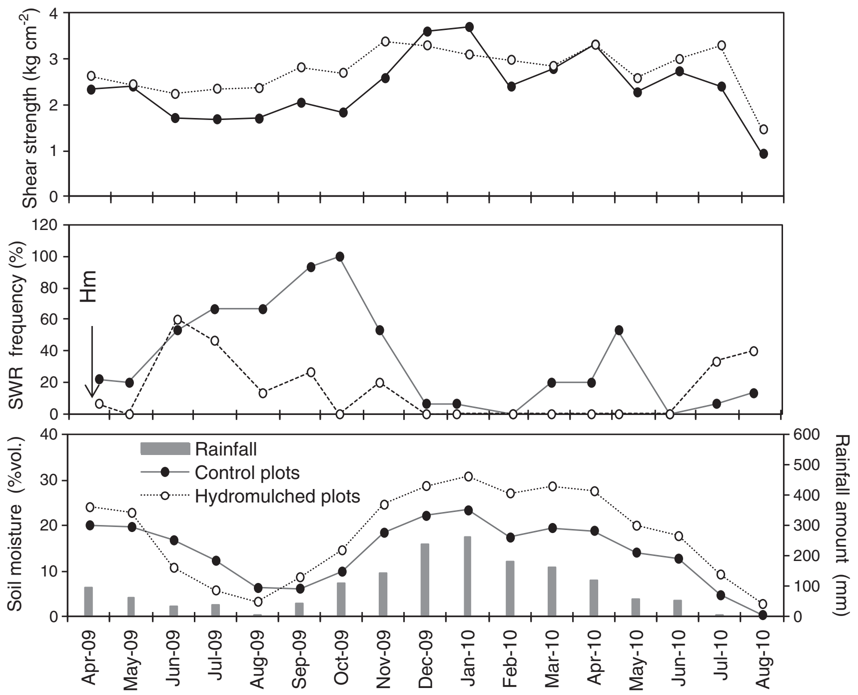

Figure 3. Monthly average values of soil shear strength (top), frequency of soil water repellency (middle) and initial soil moisture content (i.e., prior to rainfall events) and rainfall (bottom) for the control and hydromulched strips.

period of the first post-fire year (rc = 50%), and 691 mm during the second post-fire year (rc = 47%). These differences coincided with the variations in rainfall amount. However, the same was not true in the case of soil losses. The control plots produced, on average, 86 g m^{-2} during the pre-treatment period, 217 g m^{-2} during the post-treatment period of the first post-fire year, and 361 g m^{-2} during the second post-fire year. There was a fivefold increase in the specific soil losses between the pre-treatment and post-treatment periods (from 0·14 to 0·77 g m^{-2} mm rain^{-1}), and after that, the specific soil losses decreased progressively until reaching values similar to those prior to the logging during the third year (0·16 g m^{-2} mm rain^{-1}; Table II).

Hydromulching was highly effective in reducing overland flow, with, on average, 56% during the first post-fire year and even 78% during the subsequent year (Table II). Hydromulching effectiveness in decreasing soil losses exceeded the effectiveness at reducing overland flow to a marked extent, amounting to 83% during both years. During the third post-fire year, however, the effectiveness in mitigating erosion reduced to 56%. Hydromulching did, however, increase somewhat the relative amounts of organic matter in the eroded sediments to 57% as opposed to 50% and 52%.

The ANOVA analysis of Table III showed that the treatment effect strongly influenced all the variables, especially

Table III. Summary of the three-way repeated measures analysis of variance of the 1- to 2-weekly runoff amounts (fourth-root transformed), runoff coefficients (square-root transformed), as well as of the monthly soil losses, specific soil losses (fourth-root transformed) and organic matter contents of the eroded sediments during the posttreatment period (31 March 2009–12 October 2010)

Variable Unit *n*	Df num, den	Runoff amount mm 35	Runoff coeffient % 35	Df num, den	Soil losses g m^{-2} 17	Specific soil losses g m^{-2} mm^{-1} rain 17	Organic matter content % 17
Treatment	1,4	**80·2**	**176·3**	1,8	**71·7**	**63·7**	**9·3**
Size	1,4	1·0	0·0	2,8	3·3	2·6	2·7
Size*treatment	1,4	3·2	3·9	2,8	1·7	1·4	0·3
Time	34,136	**116·6**	**17·3**	16,124	**27·8**	**21·2**	**3·0**
Treatment*time	34,136	**8·4**	**3·2**	16,124	**5·0**	**4·5**	**1·9**
Size*time	34,136	**2·1**	0·7	30,124	**3·8**	**3·6**	**1·7**
Size*treatment*time	34,136	**2·1**	1·1	30,124	**3·1**	**3·0**	1·5

Df, degrees of freedom; num, numerator; den, denominator.
The *F* values in bold, or both in bold, and underlined were statistically significant at $\alpha = 0{\cdot}05$ and 0·01, respectively.

in the case of runoff coefficient (F value of 176) and less important in the case of the organic matter content ($F = 9$). The strong treatment effect, especially in the case of runoff coefficient as highlighted by the big F value (176), contrasted with the lack of effect of the plot size.

In Figure 4 it can be observed that the differences in runoff between plot sizes were very low (in the order of 12–20%, for micro-plots and small plots, respectively). The runoff on the control plots decreased with increasing plot size mainly because of the low runoff amount of one of the small plots (684 mm), whereas the same was true but in the opposite sense in the case of one small hydromulched plot (309 mm). These opposite tendencies resulted in a higher hydrological effectiveness of hydromulching for the micro-plots compared with the small plots (on average, 80% vs. 68%). Plot size also did not play a clear-cut role in soil losses, but the variance increased, especially in the case of the control SF plots (up to 70%). Consequently, the overall reduction in soil losses on the micro-plots and small plots was somewhat higher compared with the SF plots (90%, 89%, and 76%, respectively).

Temporal Patterns in Overland Flow and Soil Losses

The average monthly runoff amounts produced by the untreated plots revealed a marked seasonal pattern in which peak runoff values appeared to antecede the maximum monthly rainfall values during the winter season (Figure 5a). As a result, runoff coefficients were highest during the autumn months, varying between about 80% to 90% in December 2008, November 2009, and October 2010. High runoff coefficients were also observed during late spring and early summer, when rainfall amounts were comparatively small (<53 mm), attaining 62% in July 2009 and 81% in June 2010. The average monthly soil losses at the untreated plots revealed a less obvious temporal pattern (Figure 5b). The four peak losses of 50 $g\,m^{-2}\,month^{-1}$ or more occurred during autumn (December 2008, September and November 2009) and spring (May 2009). Apparently, the latter peak was associated with the elevated maximum rainfall intensity ($I30 = 29\,mm\,h^{-1}$), whereas the December 2008 and November 2009 ones were rather related to runoff peaks. The average specific soil losses suggested a contrast between the two months with the highest maximum rainfall intensities—that is, May and September 2009—and the remaining months. The specific losses during these two months amounted to 0·8 and 1·2 $g\,m^{-2}\,mm\,rain^{-1}$, respectively, as opposed to the baseline monthly average of 0·25 $g\,m^{-2}\,mm\,rain^{-1}$ for the rest of the study period.

The hydromulched plots produced, on average, consistently lower amounts of monthly runoff as well as monthly soil losses than the untreated plots (Figure 5a and 5b). In the case of runoff, these monthly differences were statistically significant from July 2009 onwards, with the exception of the summer 2009 and 2010 months with little to no rainfall. In the case of soil losses, however, the monthly differences were also statistically significant for the first 2 months following hydromulching and, thus, for basically all of the 19 months with noticeable rainfall. Even so, the three-way ANOVA results indicated that hydromulching did not have an unequivocal statistically significant effect on monthly soil losses, as the triple interaction term of treatment x time-since-mulching x plot size was statistically significant (Table III). The same applied to the corresponding specific soil losses as well as to the 1- to 2-weekly runoff volumes and *mutatis mutandis* (i.e., because of a significant treatment x time-since-mulching interaction) to the runoff coefficients and the organic matter content of the eroded sediments.

Hydromulching failed to produce significant reductions in overland flow generation (average 1- to 2-weekly values) across the whole range of maximum rainfall intensities (Figure 6). There was, however, a tendency for the hydrological effectiveness of hydromulching to decrease with maximum rainfall intensity, reflecting first and foremost the comparatively low effectiveness (<50%) for the two more intense measurement periods that happened in May and September 2009. Also, the effectiveness of hydromulching to reduce average monthly soil losses was comparatively low for these two highest maximum rainfall intensities, albeit it still amounted to some 80% and corresponded to a statistically significant difference between the hydromulched and untreated plots. In overall terms, however, the reduction in soil losses lacked an obvious relationship with rainfall intensity.

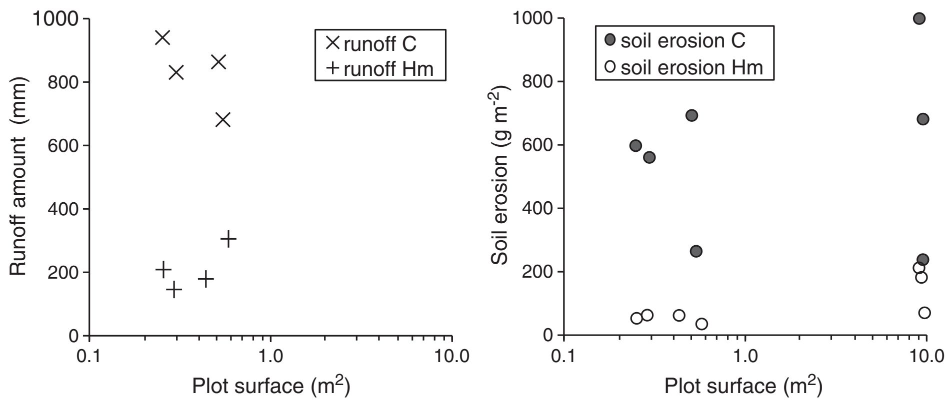

Figure 4. Total overland flow (mm) and total soil losses ($g\,m^{-2}$) of the individual untreated and hydromulched plots over the first and second year of the posttreatment period (31 March 2009 to 12 October 2010).

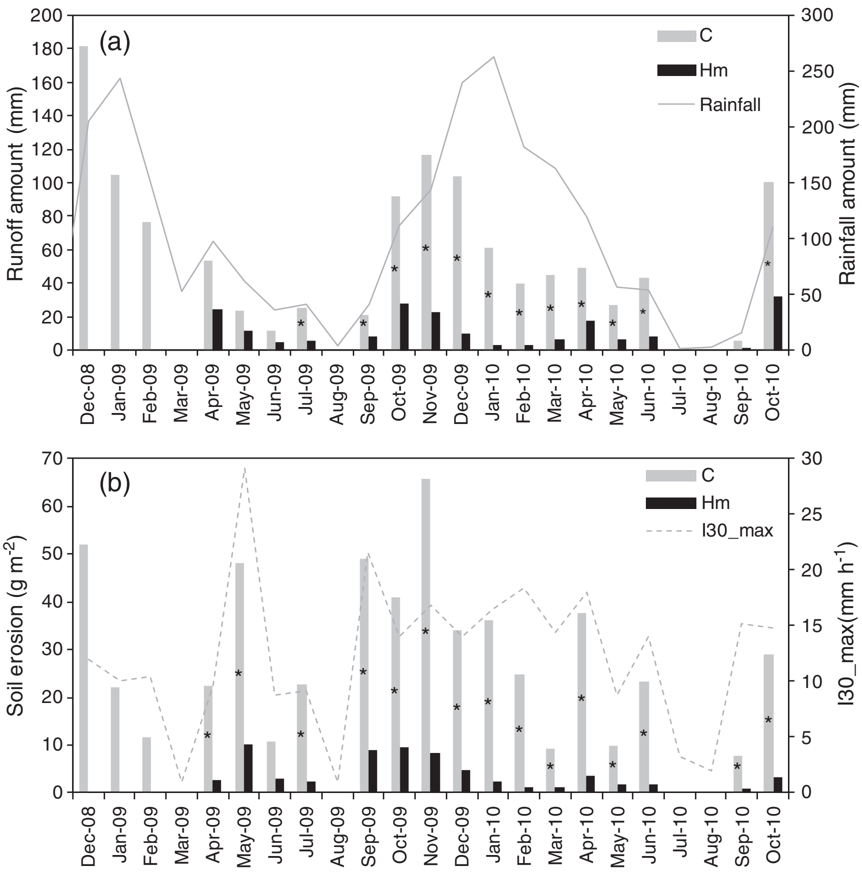

Figure 5. Average monthly values of rainfall (mm) and overland flow (mm) (5a) and of 30-min maximum rainfall intensity (I30; $mm\,h^{-1}$) and soil losses ($g\,m^{-2}$) (5b) for the untreated and hydromulched plots from the fourth through the twenty-sixth month after the wildfire. Asterisks denote significant least squares mean differences between hydromulched and control plots ($p < 0{\cdot}05$).

Key Factors Explaining Runoff and Soil Losses

Stepwise multiple linear regression with all eight hydromulched and untreated runoff plots together ('global model') revealed that the total protective ground cover ('hlv') stood out as the principal factor in overland flow generation, explaining more than twice as much of the variation in fourth-root transformed runoff amount than the second factor, I30 (31% vs. 13%; Table IV). The hydrological response of the untreated plots alone, however, could clearly be explained best by rainfall amount (41% of variance), whereas that of the hydromulched plots alone was mainly controlled by maximum rainfall intensity, albeit to a lesser degree (19% of variance). Initial soil moisture content was the second most important (and significant) explanatory variable of the runoff produced by the untreated but not the hydromulched plots. The negative sign of its coefficient suggested that the role of initial soil moisture was indirect, with SWR increasingly enhancing overland flow generation as soils dry out. Figure 7 illustrated well that the hydrological response of the untreated plots was stronger under drier than wetter soil conditions. A similar tendency was suggested for the hydromulched plots but just for rainfall amounts below 60 mm, as higher rainfall amounts were associated with wetter soils at the hydromulched than untreated strips.

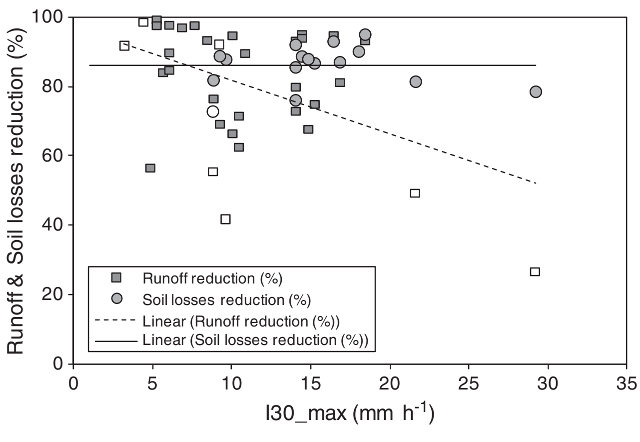

Figure 6. Weekly runoff (squares) and monthly soil losses (circles) reductions at the hydromulched plots compared with untreated plots in relation to 30-min maximum rainfall intensity for the posttreatment period (31 March 2009 to 12 October 2010). Gray-filled/white-filled symbols correspond to significant/not significant least squares mean differences between control and hydromulched plots (at $\alpha = 0{\cdot}05$). Dotted and continuous lines correspond to linear regression equations fitted to runoff and soil loss reductions, respectively.

The predominant role of total protective ground cover ('hlv') was even more pronounced in the case of the global model for soil losses than that for runoff volumes, explaining over half of the variation (55%; Table IV). The most conspicuous contrast between the erosion and runoff

Table IV. Multiple regression models for 1- to 2-weekly runoff amounts ($n = 35$) and monthly soil losses ($n = 17$) for all plots together ('Global') and for the untreated ('Control') and hydromulched plots separately

Selected variable		Global models: Parameter estimate	Global models: Variable name	Global models: Partial r^2	Control models: Parameter estimate	Control models: Variable name	Control models: Partial r^2	Hydromulching models: Parameter estimate	Hydromulching models: Variable name	Hydromulching models: Partial r^2
Runoff amount (mm; 4th root transformed)	Intercept	1·86			1·97			0·40		
	1st variable	−0·01	Hlv	0·31	0·01	Rain	0·41	0·05	I30	0·19
	2nd variable	0·02	I30	0·13	−0·03	Sm	0·11	0·01	Hm	0·05
	3rd variable	−0·02	Sm	0·06	−0·01	Tveg	0·03			
	4th variable	0·01	Rain	0·03						
	Cumulative r^2			0·53			0·54			0·24
Soil losses ($g\,m^{-2}$; 4th root transformed)	Intercept	1·65			1·58			0·76		
	1st variable	−0·01	Hlv	0·55	0·03	Bare	0·26	0·08	Bare	0·35
	2nd variable	0·03	Bare	0·07	0·03	I30	0·11	0·02	I30	0·08
	3rd variable	0·03	I30	0·05	−0·01	Hlv	0·06			
	Cumulative r^2			0·68			0·43			0·43

The independent variables selected (statistically significant at $\alpha = 0{\cdot}05$) were: Rain, rainfall amount; I30, 30-min rainfall intensity, total protective ground cover; Hlv, the sum of hydromulch, litter, and vegetation cover; Hm, hydromulch cover; Tveg, total vegetation cover; Bare, bare soil cover; Sm, initial soil moisture.

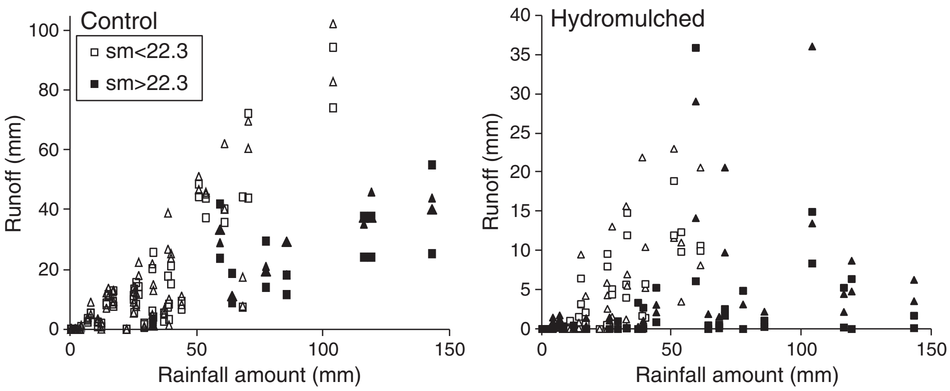

Figure 7. Runoff versus rainfall amounts for the untreated (left) and hydromulched (right) micro-plots (triangles) and small plots (squares) under contrasting initial soil moisture conditions, of less versus greater than 22·3% (open and filled symbols, respectively). Note the different scales of the two Y axes.

results, however, was evidenced by the treatment-specific models. Bare soil cover clearly outranked rainfall amount/intensity as the prime factor explaining soil losses, not only at the untreated plots (26% vs. 11% of variance) but also at the hydromulched plots (35% vs. 8% of variance).

DISCUSSION

Post-Fire Hydrological and Erosion Response in Pine Sites of Central Portugal

Post-fire runoff coefficients as high as observed here were also reported by previous studies in north-central Portugal, such as Ferreira *et al*. (2008) and Malvar *et al*. (2011) by using rainfall simulation experiments. Both prior studies related their strong hydrological response to extreme SWR. In the present study, however, the role of SWR would be limited to the first year after the wildfire, when repellency was moderate, and mostly hydrophilic after November 2009. This reduced importance of SWR was also suggested by the multivariate linear regression model that was fitted to the runoff data from the control plots. The global regression model attested that it was rather ground cover that played a key role in overland flow generation. Pierson *et al*. (2009) likewise argued that ground cover exerted a greater influence on post-fire hydrological response than SWR. Various studies in Portugal (Shakesby *et al*., 1996; Ferreira *et al*., 2008; Prats *et al*., 2012) have furthermore attributed low post-fire runoff coefficients in pine stands to needle cast from scorched tree crowns (Shakesby *et al*., 1996; Cerdà & Doerr, 2008; Ferreira *et al*., 2008; Prats *et al*., 2012).

The soil losses from the control plots during the first post-fire year (302 $g\,m^{-2}$) were higher than the range of 80–220 $g\,m^{-2}\,year^{-1}$ reported by other studies in burnt pine plantations (Shakesby *et al*., 1996; Fernández *et al*., 2007; Ferreira *et al*., 2008; Prats *et al*., 2012). This could be due to the salvage logging activities that took place during late winter/early spring 2009, as was also suggested by the markedly higher specific soil losses immediately after logging than during the pretreatment period. Logging-enhanced erosion rates were also reported by Inbar *et al*. (1997) and suggested by Malvar *et al*. (2013) but not by Fernández *et al*. (2007). The latter authors attributed their findings to the low severity of the fire, the low rainfall erosivity, and the reduced perturbations of the soil by the machinery employed. To minimize the erosion effects of post-fire logging, it is widely recommended to delay the logging activities until litter fall from scorched tree canopies has provided a 'natural' mulching (Rab, 1994; Castillo *et al*., 1997; Edeso *et al*., 1999; Fernández *et al*., 2004, 2007; Cerdà & Doerr, 2008).

The soil losses during the first post-fire year fitted in well with the low values that were reported by Shakesby (2011) for moderate severity on field plots in the Mediterranean region (321 $g\,m^{-2}\,year^{-1}$), which was attributed to an intensive land-use history. By contrast, in regions of lower forest interventions such as North America, post-fire erosion rates can be one order of magnitude higher, amounting to 2,500 $g\,m^{-2}\,year^{-1}$ (Spigel & Robichaud, 2007). The discrepancy between these two geographical regions seems to be much smaller for organic matter losses, with values of 200 and 150 $g\,m^{-2}\,year^{-1}$. High losses of organic matter are of particular relevance as they can easily compromise soil fertility and, thus, on-site land-use sustainability and downstream surface water quality through pollution with toxic pyrogenic organic compounds (Vila-Escalé *et al*., 2007; Campos *et al*., 2012).

A protective ground cover was also the most important factor explaining the monthly soil losses observed in this study and the differences therein between the treated and untreated plots. This agreed well with the bulk of post-fire soil erosion studies (e.g., Benavides-Solorio & MacDonald, 2001; Pannkuk & Roubichaud, 2003; Benavides-Solorio & MacDonald, 2005; Fernández *et al*., 2008; Larsen *et al*., 2009). At the same time, bare soil cover played a key role in the differences in soil losses among the hydromulched plots, as well as among the control plots. Pietraszek (2006) equally attested to the relevance of bare soil cover for soil losses from untreated areas. It could explain 50% of the variability in soil erosion produced by ten sites that had burnt from less than one up to 10 years earlier.

Effectiveness of Hydromulching in Reducing Runoff and Soil Losses

The hydromulch was a complex mixture which contained water, wood fibers, seeds, surfactants, seed-growing biostimulants, nutrients and a green colorant. It is intended that each component affected some of the pieces of the post-fire runoff erosion process.

Runoff was highly reduced at the treated plots, between 56% and 73%, which is higher than in other post-fire mulching experiments, both with straw (Bautista *et al*., 1996; Groen & Woods, 2008) and forest residues (Shakesby *et al*., 1996; Prats *et al*., 2012). Probably, this high effectiveness could be related to the effect of the wood fibers, because it increases the surface water storage capacity, but also due to the effect of the surfactants, a wetting agent that reduces SWR and increases soil infiltration (Leighton-Boyce *et al*., 2007; Madsen *et al*., 2012).

Soil losses were highly reduced in the hydromulch plots during the 3 years after the wildfire. Ground cover was pointed out as the main factor controlling soil losses, but the hydromulch mat showed a rapid decay during the first year after the application. This was identified as one of the disadvantages of hydromulchings (MacDonald & Robichaud, 2007). In the present study, the decayment rates of the hydromulch ranged between 4% and 6% per month, very similar to other research with hydromulch (Hubbert *et al*., 2012; Robichaud *et al*., 2013a). In contrast to those sites, our hydromulch was highly conducive to germination and growth of plants from seeds. Thus, the introduced seeds compensated for the loss of hydromulch with progressively more plant and litter cover, which resulted in more than 70% protective ground cover since the hydromulch application until the third post-fire year (Figure 2).

Besides the composition, the application technique can influence the hydromulch effectiveness. In this study, the area was already logged and the plots were small, which a priori will facilitate the spread of the hydromulch from a jet hose operated on foot. However, the hydromulch cover was significantly lower on the SF plots despite being sufficient to reduce soil erosion. Rough (2007) and Robichaud *et al*. (2010) reported that the hydromulch sprayed from vehicles was intercepted by the standing trees, and they recommended special caution when applying the mixture in areas with a high density of dead trees and from long distances. Aerial hydromulch can be a better and less expensive option, but Hubbert *et al*. (2012) checked that the intended application rates of 50% and 100% hydromulch cover resulted in only 20–26% and 56%.

Unsuccessful hydromulch experiences were first attributed to extreme rainfall events (Wohlgemuth *et al*., 2011) or to the long length of the plots (Napper, 2006). Robichaud *et al*. (2010) pointed out that hydromulch effectiveness depended on slope length, only being effective at slopes shorter than 10–20 m, when interrill erosion was the dominant process instead of rill erosion. The former authors hypothesized that in their long slope sections, the smooth and dense hydromulch mat had little resistance against the sheer force of concentrated flow. But on the other hand, the research of Rough (2007) showed that aerial hydromulching was highly effective and was carried out at the hillslope scale (2,500 m^{-2}, on average), where rills were frequent (0·1 rills m^{-2}) and after extreme rainfall events (I30 = 40 mm h^{-1}). Many other hydromulch formulations are available and are being evaluated for their capacity to reduce soil losses. As concluded by Robichaud *et al*. (2013a), the differences in hydromulch components, application techniques, and application rates can greatly impact hydromulch effectiveness. However, Napper (2006) referred that one of the major problems is the difficulty in knowing the specific chemical composition that was applied in a given situation because most of the hydromulch formulations are kept confidential.

Hydromulching Effects in Soil Properties

Soil properties in agriculture had been typically improved by mulching (Smets *et al*., 2008) by materials such as manure, stones, straw, forest residue, and wood shreds (Harris & Yao, 1923; Mulumba & Lal, 2008; Foltz & Copeland, 2009). Regarding post-fire soil shear strength, the results are not conclusive. Bautista *et al*. (1996) and Fernández *et al*. (2011) found no differences between control and straw mulch plots. Fernández *et al*. (2007) found lower figures in logged compared to unlogged plots. They related these lower values to the absence of roots, once that the logged plots showed a much lower vegetation cover. Agreeing with them, the statistically higher soil shear strength measured on the hydromulch strip could be related to a higher vegetation cover compared to the control strip. Regarding soil water properties, our results are consistent with other mulch experiments (Smets *et al*., 2008; Bautista *et al*., 2009; Prats *et al*., 2012) in which higher soil moistures were found on the mulched areas. The hydromulching layer acted as a water adsorbent dense mat, which effectively increased the soil water retention capacity. It prevented sunlight from reaching the soil surface and thereby decreased soil temperatures. Still, the surfactants included on the hydromulch could have a role in increasing soil infiltration and improve the seed germination (Madsen *et al*., 2012). Besides the positive impacts over plant recovery and soil microbial activity (Bautista *et al*., 2009), a major insight suggested by Prats *et al*. (2012) supported the fact that mulching affected the SWR regime of the burnt forest, promoting the hydrophilic soil conditions. However, this was not true during the dry seasons. Probably, the higher plant cover of the hydromulch (13% vs. 3% during the first post-fire summer) could increase the transpiration and thus lowering soil moisture and increasing SWR. Brainard *et al*. (2012) reported a higher water demand of plants during water stress periods in agriculture, and Soto & Diaz-Fierros (1997) found lower soil moisture on the vegetated areas as compared with bare and burnt plots during the first post-fire summer.

CONCLUSIONS

The main conclusions of this study in the effectiveness of hydromulching to reduce runoff and erosion in a recently burnt and logged pine plantation were as follows: (i) hydromulching, providing coverage of 80%, produced marked changes in SWR and soil moisture, especially in the soil cover. Despite a decrease of up to 30% after 1 year from the application, the treatment induced a highly protective ground cover because of an increase of both vegetative and litter cover; (ii) 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, reducing erosion by 56%; (iii) hydromulching was less effective in reducing runoff (around 30%) but not in reducing soil losses (80%) for the more intense storms (I30 higher to 20 mm h^{-1}); (iv) the protective soil cover provided by hydromulch, in combination with litter and vegetation, explained runoff and soil losses better than any other variable, however, rainfall intensity and soil moisture explained a considerable portion of the variation in runoff generation; (v) the application of hydromulch was lower than expected on the larger plots (only a 64% hydromulch cover as compared with 90% in the smaller plots), despite both applications having significantly reduced soil losses. Further research will be needed to determine the effective ground cover in order to match hydromulch decayment rate and vegetative cover increase over time, especially to minimize application costs; and (vi) soil losses were similar across the range of plot sizes studied here (0·25–10 m ^{2}). This, plus the small size of the plots, indicates that interrill erosion was the dominant erosion process. Further research is needed to determine how the effectiveness of hydromulching may vary with increasing slope length when rill erosion is more likely to occur.

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