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Polyacrylamide application versus forest residue mulching for reducing post-fire runoff and soil erosion

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HIGHLIGHTS

- The effectiveness of two soil erosion control treatments was contrasted after a wildfire.
- Chopped bark mulch reduced runoff and soil erosion, whereas dry polyacrylamide did not.
- Rainfall amount and soil cover were key factors respectively for runoff and soil erosion.
- Fire intensity across the burnt slope also affected soil erosion and organic matter content on the eroded sediments.

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ABSTRACT

For several years now, forest fires have been known to increase overland flow and soil erosion. However, mitigation of these effects has been little studied, especially outside the USA. This study aimed to quantify the effectiveness of two so-called emergency treatments to reduce post-fire runoff and soil losses at the microplot scale in a eucalyptus plantation in north-central Portugal. The treatments involved the application of chopped eucalyptus bark mulch at a rate of 10–12 Mg ha^{-1}, and surface application of a dry, granular, anionic polyacrylamide (PAM) at a rate of 50 kg ha^{-1}. During the first year after a wildfire in 2010, 1419 mm of rainfall produced, on average, 785 mm of overland flow in the untreated plots and 8.4 Mg ha^{-1} of soil losses. Mulching reduced these two figures significantly, by an average 52 and 93%, respectively. In contrast, the PAM-treated plots did not differ from the control plots, despite slightly lower runoff but higher soil erosion figures. When compared to the control plots, mean key factors for runoff and soil erosion were different in the case of the mulched but not the PAM plots. Notably, the plots on the lower half of the slope registered bigger runoff and erosion figures than those on the upper half of the slope. This could be explained by differences in fire intensity and, ultimately, in pre-fire standing biomass.

1. Introduction

In the last few decades, wildfires have become a common and widespread phenomenon in Portugal (Pereira et al., 2005; Shakesby, 2011). One of the principal effects of wildfires is widely held to be a partial or total loss of vegetation and litter cover (e.g. Soto and Diaz-Fierros, 1997; Shakesby, 2011). The resulting reduction in both rainfall interception and plant transpiration enhances runoff generation as well as soil exposure to the direct impact of raindrops (Soto et al., 1998; Wagenbrenner et al., 2006; Ben-Hur et al., 2011; Fernández et al., 2011). Direct effects of wildfires due to soil heating, such as breakdown of aggregates and increased soil water repellency, are generally considered to be key factors in the strong and sometimes extreme hydrological and erosion responses of recently burnt areas (e.g. Coelho et al., 2004; Doerr et al., 2006; Ferreira et al., 2008; Keizer et al., 2008; Varela et al., 2010; Malvar et al., 2011). Fire-enhanced generation of runoff and the associated export of sediments, organic matter, nutrients and pollutants not only have negative consequences for on-site land-use sustainability, but also can endanger downstream aquatic and flood-zone habitats and associated human infrastructures (Shakesby and Doerr, 2006; Ferreira et al., 2008; Robichaud, 2009).

It is generally accepted that fire-enhanced erosion rates are maximal immediately after the wildfire (e.g. 35 Mg ha^{-1} during the first post-fire year in Fernández et al., 2011) and decrease with time to background levels at the end of the so-called window of disturbance (up to 10 years after the wildfire as reported in Swanson, 1981 and in Shakesby and Doerr, 2006). However, the intensity and extent of this period, which depends on fire severity and post-fire climate conditions,

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are still highly uncertain and difficult to quantify (Neary et al., 1999; Cerdà and Doerr, 2005; Cerdà and Lasanta, 2005; Robichaud, 2009).

A variety of measures have been identified that can effectively reduce post-fire soil erosion (e.g. Miles et al., 1989; MacDonald and Larsen, 2009; Robichaud et al., 2013). Arguably, the most widely accepted measure is mulching, i.e., the application of a cover of organic compounds on the soil surface to modify energy and water fluxes and to protect the soil from direct raindrop impact (Bautista et al., 2009). Mulching has been found to successfully control post-fire runoff and soil erosion in many field trials (e.g. Miles et al., 1989; Bautista et al., 1996; Wagenbrenner et al., 2006; Fernández et al., 2011; Prats et al., 2012). A mulch cover of 60% is widely considered the minimum threshold for a significant reduction in soil loss (Pannkuk and Robichaud, 2003; Cerdà and Doerr, 2008; Robichaud et al., 2010). In the case of straw mulch, this threshold cover is typically achieved by applying 2 Mg of straw per ha (Miles et al., 1989; Bautista et al., 1996; Badía and Martí, 2000; Wagenbrenner et al., 2006; Groen and Woods, 2008; Fernández et al., 2011), with costs ranging from 600 to 1200 USD ha^{-1} for aerial and manual application, respectively (Napper, 2006).

Although burnt areas are commonly mulched with straw, this has various disadvantages: high cost, potential introduction of non-native plants, and susceptibility to wind-scattering (Bautista et al., 2009). In recent years, there has been increasing interest in alternative mulch types derived from forest residues, using fibers of different shapes and sizes (Yanosek et al., 2006; Smets et al., 2008). In laboratory experiments, 6-cm long wood strands applied at rates of 4 to 8 Mg ha^{-1} were found to be highly effective, reducing erosion rates by 80% (Foltz and Copeland, 2009; Foltz and Dooley, 2003; Foltz and Wagenbrenner, 2010). In field trials, mulching with 10- to 15-cm long chopped eucalyptus bark fibers markedly reduced post-fire erosion during the first year after the fire (Prats et al., 2012), while mulching with wood chips did not (Fernández et al., 2011). The mulch employed by Prats et al. (2012) had the further advantages of being readily available in the study region (due to the widespread occurrence of eucalyptus plantations in north-central Portugal), not being susceptible to removal by wind, decaying more slowly than straw, and not introducing invasive weeds. The cost of applying the chopped bark mulch, however, differed little from that of applying straw, as the lower costs per Mg were offset by the higher application rates needed to achieve the 60% cover threshold.

A more recent measure to control post-fire erosion is the application of polyacrylamides (PAMs; Rough, 2007; Robichaud et al., 2010). PAMs refer to a family of flocculant agents, comprising a broad class of chemical compounds with different chain lengths, charge types and charge densities. Different PAM formulations have been developed to ensure effective binding with clay particles through direct ionic attractions or cation bridges (Theng, 1982; Vacher et al., 2003). The application of PAMs constitutes a remarkable soil- and water-management technique, due to their extremely low cost (~3 USD per kg), their safety, and their capacity to influence physicochemical processes (Sojka et al., 2007). During the last two decades, the use of PAMs has proven effective for erosion control in furrow irrigation in intensive agriculture (Ben-Hur, 2006; Sojka et al., 2007). Application rates as low as 1 to 50 kg ha^{-1} have been found to noticeably reduce soil losses from agricultural fields as well as from steep road embankments (Agassi and Ben-Hur, 1992; Ben-Hur, 2001; Ben-Hur and Keren, 1997; Ben-Hur and Letey, 1989; Lentz et al., 2002; Levy et al., 1991). The effectiveness of PAMs in reducing post-fire erosion, however, is poorly established. The few studies which have been carried out have produced inconsistent results. Davidson et al. (2009), Riechers et al. (2008) and Inbar (2011) found PAM to be effective, whereas Rough (2007) and Wohlgemuth and Robichaud (2007) did not.

The main objective of the present study was to evaluate the effectiveness of two erosion-mitigation techniques – mulching with forest residues (chopped bark) and surface application of a dry granular anionic PAM – during the first year after a wildfire in a eucalyptus plantation in north-central Portugal. The specific objectives were to: (i) assess the performance of both techniques at a high temporal resolution (monitoring every 1 or 2 weeks); (ii) determine the spatial variation in overland-flow generation and soil losses from the base to the top of a 40-m long slope; and (iii) determine the key factors explaining overland flow and soil losses for the treatments, together and separately.

2. Material and methods

2.1. Study area

The study area was located near the Ermida hamlet in the Sever do Vouga municipality of north-central Portugal. The area was affected by a wildfire that consumed 295 ha between 26 and 28 July 2010 (AFN, Autoridade Florestal Nacional, 2012). The burnt area not only consisted mainly of eucalyptus (*Eucalyptus globulus* Labill.) plantations, but also included some maritime pine (*Pinus pinaster* Ait.) plantations and a stand of cork oak (*Quercus suber* L.). The eucalyptus trees in the region are typically planted as monocultures for paper pulp production, and harvested every 7–14 years. After logging, the eucalyptus trees are left to regrow from the stumps two or three times, after which a new plantation cycle is begun (Ferreira et al., 1997; Leighton-Boyce et al., 2005; Prats et al., 2012).

The climate of the study area can be classified as humid mesothermal (Csb in the Köppen classification), with moderately dry but extended summers (DRA-Centro, Direcção Regional do Ambiente do Centro, 1998) when the bulk of the wildfires occurs. The mean annual temperature at the nearest weather station of "Castelo Burgães" (40°51′16″N, 8°22′55″W, 306 m a.s.l.; 1990–2010; SNIRH, Serviço Nacional de Informação dos Recursos Hídricos, 2011) was 14.9 °C, while mean monthly temperatures ranged from 9.0 °C in January to 21.1 °C in July. Annual rainfall at the nearest rainfall station of "Ribeiradio" (40°44′39″N, 8°18′05″W; 228 m a.s.l.; 1990–2010; SNIRH, Serviço Nacional de Informação dos Recursos Hídricos, 2011) varied between 960 and 2530 mm, with an average of 1609 mm.

The study area is situated in one of the region's major physiographic units, the Hespheric Massif. The area consists mainly of pre-Ordovician schists and graywackes, but includes Hercynian granites at several locations (Ferreira de Brum, 1978). Within the study area, a steep (25°) but short (40 m) slope with southwest aspect was selected for this study (40°44′05″N, 8°21′18″W, 200 m a.s.l.; Fig. 1). The eucalyptus trees in the study site had been cut just before the fire, as evidenced by the tree logs that were piled up at the base of the slope and were partially charred by the wildfire. Judging from the remaining tree stumps (with diameters of roughly 1 m), the stand had undergone three prior harvestings, and had originally been planted some three decades before the 2010 wildfire. The overall severity of the 2010 wildfire was estimated to be moderate, as inferred from the complete consumption of the logging slash residues, the understory vegetation and the litter layer, as well as from the prevalence of a 1- to 4-cm thick layer of black ash (Table 1). At the base of the slope, however, the presence of gray and white ashes suggested moderate to high severity.

2.2. Experimental setup

At the end of August 2010, before any significant rainfall events (Fig. 2), the study site was instrumented with two rainfall gauges (one tipping-bucket gauge with a resolution of 0.2 mm and one storage gauge for validation purposes), and 12 square erosion plots of approximately 0.28 m^2 were established (Fig. 1). The 12 plots were organized into four sets (blocks) that were located at about equal distances from the base to the top of the slope (Table 1), while the three plots of each block were placed at 1- to 3-m distance from each other. The plot outlets were connected to tanks with a storage capacity of 30 l for overland-flow collection. The spatial variation in soil properties across the study slope was examined in February 2011 by excavating a soil profile in each block, measuring soil depth, and collecting two samples from