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Post-fire overland flow generation and inter-rill erosion under simulated rainfall in two eucalypt stands in north-central Portugal ☆

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ABSTRACT

The aim of this study was to improve the existing knowledge of the runoff and inter-rill erosion response of forest stands following wildfire, focusing on commercial eucalypt plantations and employing field rainfall simulation experiments (RSE's). Repeated RSE's were carried out in two adjacent but contrasting eucalypt stands on steep hill slopes in north-central Portugal that suffered a moderate severity fire in July 2005. This was done at six occasions ranging from 3 to 24 months after the fire and using a paired-plot experimental design that comprised two pairs of RSE's at each site and occasion. Of the 46 RSE's: (i) 24 and 22 RSE's involved application rates of 45–50 and 80–85 mm h^{-1}, respectively; (ii) 22 took place in a stand that had been ploughed in down slope direction several years before the wildfire and 24 in an unploughed stand.

The results showed a clear tendency for extreme-intensity RSE's to produce higher runoff amounts and greater soil and organic matter losses than the simultaneous high-intensity RSE's on the neighbouring plots. However, there existed marked exceptions, both in space (for one of the plot pairs) and time (under intermediate soil water repellency conditions). Also, overland flow generation and erosion varied significantly between the various field campaigns. This temporal pattern markedly differed from a straightforward decline with time-after-fire and rather suggested a seasonal component, reflecting broad variations in topsoil water repellency. The ploughed site produced less runoff and erosion than the unploughed site, contrary to what would be expected if the down slope ploughing had occurred after the wildfire instead of several years before it. Finally, sediment losses at both study sites were noticeably lower than those reported by other studies involving repeat RSE's, i.e. in Australia and western Spain. This possibly reflected a history of intensive land use in the study region, including in more recent times after the widespread introduction of eucalypt plantations.

1. Introduction

As thoroughly discussed by Shakesby and Doerr (2006), through their effects on soil properties as well as on vegetation and litter cover, wildfires can lead to considerable changes in geomorphologic and hydrological processes. Previous studies in various parts of the world, including Portugal (e.g. Shakesby et al., 1993, 1996; Walsh et al., 1992, 1995; Ferreira et al., 2005b, 2008), have revealed strong and sometimes extreme responses in runoff generation and associated soil losses following wildfire, especially during the earlier stages of the so-called "window-of-disturbance". Besides wildfire itself, post-fire forestry practices can strongly influence overland flow and erosion in recently burnt areas (e.g. Shakesby et al., 1994; Walsh et al., 1995; Fernández et al., 2007). For example, rip-ploughing during the window-of-disturbance was far more damaging in terms of soil loss than fire (Shakesby et al., 1994).

The need for a model-based tool for assessing erosion risk following wildfire and, ultimately, for guiding post-fire land management, like the Erosion Risk Management Tool (ERMiT) for the Western USA (Robichaud et al., 2007), is overtly evident in the case of Portugal. Over the past decades, wildfires in Portugal have devastated on average around 100.000 ha each year, with dramatically higher figures for dry years like 2003 and 2005 (Pereira et al., 2005). Furthermore, the frequency of wildfires in Portugal is expected to remain the same or to increase in the future (Pereira et al., 2006). In relation to fire occurrence, the widespread introduction of commercial eucalypt plantations (principally of *Eucalyptus globulus* Ait.) in central Portugal (including in the study area) in combination with their proneness to fire deserves special reference. Furthermore, post-fire erosion risk is expectedly higher in eucalypt stands than, for example,

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Maritime Pine forest, another common and fire-prone forest type in central Portugal, namely, eucalypt stands are typically associated with pronounced soil water repellency (Doerr et al., 1996, 1998; Keizer et al., 2005b, 2008; Leighton-Boyce et al., 2005), on the one hand, and on the other, water repellency is widely considered one of the main factors in enhancing runoff generation and the associated soil losses following wildfire (e.g. Shakesby and Doerr, 2006; Leighton-Boyce et al., 2007; Sheridan et al., 2007).

Following the dramatic wildfire season of summer 2003, the EROSFIRE project (Keizer et al., 2006, 2007) set out to develop such an erosion prediction tool tailored to the specificities of post-fire conditions in Portugal's forests. Field rainfall simulation experiments (RSE's) were selected as principal method for gathering the data required for initial calibration of the process-based model MEFIDIS (Nunes et al., 2005) for post-fire conditions, much along the lines of the approach applied in Nunes et al. (2009a, 2009b). In spite of the well-know limitations of RSE's in terms of reproducing natural rainfall events and emulating runoff/ erosion processes beyond small spatial scales (e.g. Rickson, 2001), they have been widely used for studying hydrological and erosion processes in recently burnt woodland areas, especially at spatial scales of 1 m^2 and less (e.g. Imeson et al., 1992; Kutiel et al., 1995; Sevink et al., 1989; Benavides-Solorio and MacDonald, 2001; Johansen et al., 2001; Cerdà and Doerr, 2005; Coelho et al., 2005; Ferreira et al., 2005a; Rulli et al., 2006; Leighton-Boyce et al., 2007; Sheridan et al., 2007). However, the bulk of these studies concerned singular moments in time-after-fire, not addressing for example the seasonal component in post-fire runoff and erosion that is often observed in longer-term plot monitoring studies under natural rainfall conditions (e.g. Shakesby et al., 1993, 1994). Also, the individual studies generally involved a single rainfall intensity. As far Portugal is concerned, surprisingly few field RSE studies have been carried out in recently wildfire-burnt stands of eucalypt (Leighton-Boyce et al., 2007) or, for that matter, in other prevailing forest types (Walsh et al., 1998; Coelho et al., 2004; Ferreira et al., 2005a).

The main aim of the present work was to explore repeated field campaigns of RSE's for a better knowledge and understanding of overland flow generation and associated sediment losses in recently burnt commercial eucalypt plantations. To this end, RSE's were carried out in two eucalypt stands on four occasions during the first year following wildfire and on two additional occasions during the second year. Two adjacent sites were selected for expectedly representing contrasting risks of post-fire erosion, with the site that had been rip-ploughed presenting a greater risk than the neighbouring unploughed site.

The specific objectives were to determine how overland flow generation and sediment losses varied at the micro-plot scale with (i) high *vs.* extreme simulated rainfall intensity (45–50 and 80–85 mm h^{-1}); (ii) time since fire and associated changes in initial conditions, in particular soil water repellency; (iii) within- and between-site characteristics at a ploughed *vs.* unploughed slope.

2. Materials and methods

2.1. Study area and sites

The present study was carried out in two adjacent commercial eucalypt (*Eucalyptus globulus* Ait.) plantations in the Açores locality of the Albergaria-a-Velha municipality of north-central Portugal (Fig. 1). The two study sites were located at approximately 40°42′N, 8°29′W and 60–70 m elevation, and comprised steep but short slopes bounded by paths (Table 1).

The study sites burned during early July 2005 in a wildfire that affected a total area of about 16 km^2, which was largely covered by eucalypt plantations. The complete consumption of the litter and herb cover, together with the partial consumption of the shrub layer and tree crowns, suggested that fire severity at both sites had been moderate (Shakesby and Doerr, 2006; Table 1). Judging by remaining tree stumps, the two sites had undergone at least two eucalypt (re)growth cycles prior to the fire. The two sites were selected for their contrasting land management practices and, as mentioned above, expectedly distinct risks of post-fire soil erosion. At the unploughed Açores1 site, trees had been planted without apparent evidence of mechanical ground operations, resulting in an undisturbed soil profile. At the ploughed Açores2 site, a clear pattern of shallow ridges and furrows (up to 20 cm high) running down the slope was present. Rip-ploughing (i.e. mechanical ploughing using a ripper with one to three teeth that rupture the upper soil horizons in a vertical plane without altering their disposition) in preparation for planting is a common practice in this region and, judging by the stand age, would have taken place around 5 years prior to the fire.

The study area is situated at the transition of the region's two major physiographic units, the Littoral Platform dominated by Ceno-Mesozoic deposits and the Hesperic Massif dominated by pre-Ordovician schists and greywackes and Hercynian granites (Ferreira, 1978; Pereira and FitzPatrick, 1995). The soils are mapped – at a scale of 1:1,000,000 – as a complex of Humic Cambisols and, to a lesser extent, Dystric Litosols (Cardoso et al., 1971, 1973). At both the study sites, two soil profiles were excavated in the middle and at the bottom of the study slopes. The soils corresponded to Umbric or Dystric Leptosols (FAO, 1988), depending on the depth of their A horizons. They were shallow (5–40 cm depth) soils developed over schists and had sandy loam textures and high organic matter contents (8.8–10.4%). These soil characteristics differed little between the two sites, which also agreed with the fact that rip-ploughing supposedly does not alter the disposition of the soil layers. Even so, the observed soil differences were duly considered in the discussion of the RSE results.

The climate of the study area can be characterised as humid meso-thermal, with a prolonged dry and warm summer (Köppen Csb) DRA-Centro (1998). Fig. 1 shows the locations of the study sites as well as of the nearest climate station (Estarreja: 40°47′N, 8°35′W, 26 m; 17.5 km distance) and the nearest rainfall station (Albergaria-a-Velha: 40°42′N, 8°29′W, 131 m; 4 km distance). The long-term mean annual temperature at the Estarreja station is 13.9 °C and the mean monthly temperatures range from 8.8 °C in December to 19.1 °C in July (DRA-Centro, 1998). The annual rainfall at the Albergaria-a-Velha station is, on average, 1229 mm and varies between 750 and 2022 mm (DRA-Centro, 1998). Fig. 1 also depicts the stations' seasonal variations in average monthly temperature and rainfall, and the monthly rainfall amounts at the study sites during the first year following wildfire. These latter data were obtained with a tipping-bucket rainfall gauge (Pronamic Professional Rain Gauge) linked to a Hobo Event Logger of Onset Computer Corporation, and were verified using the data from two totaliser rainfall gauges. All three gauges were installed at the foot of the study sites on September 24, 2005. These data were used in this paper to calculate the antecedent daily rainfall for the different field sampling days.

2.2. Rainfall simulation experiments

Between September 2005 and July 2007, a total of 46 rainfall simulation experiments (RSE's) were carried out in the field using two portable simulators as originally designed by Calvo et al. (1988) and later improved by Cerdà et al. (1997). One simulator was equipped with the original nozzle and was calibrated in the laboratory to produce artificial rain with an intensity of approximately 45 mm h^{-1}. The second simulator was equipped with a modified nozzle, using cone nozzle HARDI-1553-14 instead of HARDI-1553-10, to produce intensities of around 80 mm h^{-1}. The former intensity is comparable to the maximum hourly rainfall for a 100-year return period of the Aveiro rainfall station (Brandão et al., 2001). The latter is similar to the maximum hourly rainfall ever recorded in Portugal (Brandão et al., 2001) but a prior RSE study in Portuguese eucalypt forests like Leighton-Boyce et al. (2007) applied still higher intensities (100 mm h^{-1}) and found infiltration capacities exceeding this value. Hereafter, the two intensities will be referred to as ''high'' and ''extreme'', respectively. Other modifications to the original simulator design involved the use of a battery-driven pump system with pressure vat and of an approximately square plot (consisting of a square area of 0.50 m × 0.50 m and an outlet area of 0.03 m^2), both of which were introduced by De Alba (1997).

The 46 RSE's were carried out during four separate field campaigns in the first year after the wildfire, and two more campaigns in the second year (Table 2). Before every campaign (with the exception of the second) the two standard and two spare nozzles were (re-)calibrated in the laboratory. Each campaign involved four RSE's on both the ploughed and unploughed site, except in the case of the October 2006 campaign when only the high-intensity RSE's were carried out at the unploughed site due to failure of the extreme-intensity pump system. The four RSE's at a particular site were in general performed on the same day and within less than a week of those carried out at the other study site. Exceptions were the first campaign on the ploughed site and the October 2006 campaign, which took place on September 20 and 22, 2005, and October 12 and 31, 2006, respectively.

The four RSE's at each site and date were carried out using a pair-wise sampling design. High- and extreme-intensity RSE's were run almost