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Effect of fire frequency on runoff, soil erosion, and loss of organic matter at the micro-plot scale in north-central Portugal

Mohammadreza Hosseini [a,*], Jan Jacob Keizer [b], Oscar Gonzalez Pelayo [b], Sergio Alegre Prats [b], Coen Ritsema [a], Violette Geissen [a]

[a] SLM Group Wageningen University (WUR), P.O. Box 47, 6700 AA Wageningen, The Netherlands
[b] Earth surface processes team, Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal

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ABSTRACT

Wildfire is a natural phenomenon that is a common ecological factor in Mediterranean ecosystems. The increase in occurrence in recent decades has raised widespread concern about the impact of repeated wildfires on runoff and erosion, a topic that has not been widely studied. We addressed these concerns in an area of north-central Portugal by comparing runoff at the micro-plot scale and the associated transport of sediments and organic matter (OM) in unburnt, once burnt, and repeatedly burnt plantations of Maritime Pine. We selected nine sites following a large wildfire in September 2012 that affected roughly 3000 ha of the Viseu municipality. Three of the sites had not been burnt since 1975 and acted as controls, with covers of pine trees, shrubs, and annual vegetation; three sites had burnt only in 2012 and contained burnt pines but no shrubs or annual vegetation; and three degraded sites had suffered from three wildfires prior to 2012 and contained no vegetation. We established nine micro-plots (0.25 m^2) at each site and collected runoff, eroded soil, and OM losses in tanks after each rain from October 2012 to September 2014. The repeated wildfires strongly increased the runoff coefficient and the risk of downstream flooding after heavy rains. OM losses were nearly half the volume of the eroded soil in the degraded sites due to the transport of ash in the runoff. Runoff and soil losses occurred not only after erosive rainstorms following a fire but also after a subsequent period of drought. Soil cover, rain intensity, and soil moisture were key factors in the amount of runoff and erosion. The insights provided by this study can contribute to pre- and post-fire activities and management in protect areas and can thus improve post-fire recovery.

1. Introduction

Fire is a serious and frequent disturbance in forest ecosystems, especially in Mediterranean regions due to their dry, hot summers followed by frequent and high-intensity rain in the autumn immediately after the summer wildfires (Shakesby, 2011; Bento-Gonçalves et al., 2012; Pausas and Fernández-Muñoz, 2012; Shakesby et al., 2013; Badía et al., 2015). Wildfires regularly occur in north-central Portugal and are thought to be a serious contributor to erosion and land degradation (A. Elwood Willey, 2004; Shakesby, 2011; Bento-Gonçalves et al., 2012; Prats et al., 2014). Changes in land use, forest plantations, and human activities have increased the flammable biomass. These changes have rendered our research area in Portugal increasingly susceptible to both wildfire and the accompanying ecosystemic degradation (Carreiras et al., 2014). New areas prone to wildfires have concurrently increased in number (Nunes et al., 2005), therefore, improving forest management to decrease soil losses has become increasingly important (Pausas and Fernández-Muñoz, 2012; Badía et al., 2015).

Repeated fires reduced vegetation cover followed by a higher exposure of the soil surface which is leading to higher runoff rates, and cause more soil erosion (Wittenberg and Inbar, 2009a; Malkisnon et al., 2011). Therefore, the present study is focused on and contributes to a better understanding of the impact of repeated wildfires on runoff and physical soil properties such as erodibility and OM losses in plantations of Maritime Pine (*Pinus pinaster* Ait.).

Heat, which is a direct effect of fire on soil, can change the physio-chemical properties of the soil, depending on the temperature reached during a fire and the duration of the fire (Keeley, 2009; Mataix-Solera et al., 2011; Stoof, 2011; Caon et al., 2014; Stoof et al., 2015). Some of the physical change that occurred can cause a decrease in soil porosity and increase in bulk density (Alauzis et al., 2004; García-Corona et al., 2004; Stoof et al., 2010, 2015; Aznar et al., 2013) and can decrease the retention of soil water (Stoof et al., 2010, 2015; Shakesby, 2011; Stoof, 2011; Ebel, 2012) and infiltration (Martin and Moody, 2001; García-Corona et al., 2004; Stoof et al., 2015). Soil structure is consequently affected by fire (Coote et al., 1988; Léonard and Richard,

* Corresponding author.
E-mail address: mohammadreza.hosseini@wur.nl (M. Hosseini).

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2004; Stoof et al., 2015) and burnt organic matter (OM) and ash form a hydrophobic coating on soil surface (Ritsema and Dekker, 1994; DeBano, 2000; González-Pelayo et al., 2010; Stoof et al., 2015), which reduces infiltration, increases runoff and soil erodibility (Nunes et al., 2005; Onda et al., 2008; Moody and Ebel, 2014; Stoof et al., 2015).

Also, chemical changes can occur by fire, such as decrease in calcium content that would lead to change of the pH on the top soil horizons, nutrients leaching caused by precipitation after the fire and also, a decrease in cation exchange capacity and an increase in the electrolyte concentration. Fire also causes a decrease in sodium adsorption ratio, which prevents clay dispersion and strong micro aggregate formation to reduce infiltration rate and an increase in runoff and soil erosion (Giovannini et al., 1990; Inbar et al., 2014). Fire decreases ground cover, which changes soil roughness so that water can flow more easily and runoff increases (García-Corona et al., 2004; Sheridan et al., 2007; Mataix-Solera et al., 2011; Martín et al., 2012; Stoof et al., 2015). The depth of soil organic matter changes after fires due to volatilization and/or due to the transport of surface ash and sediments (Caon et al., 2014). The intensity of this change depends on soil-moisture (SM) content, soil type, surface cover, and the type, duration, and intensity of a fire (Caon et al., 2014).

Post-fire runoff, sediment transport, and OM losses have been studied (Stoof et al., 2010, 2015; Shakesby, 2011; Stoof, 2011; Ebel, 2012). But, much less attention has been paid to the consequences of repeated fires on these processes. Repeated forest fires, effect on eco-geomorphic processes and also, decrease ecosystem resilience. Observations after fire in the field bring the conclusion that; vegetation recovery was significantly lower after the repeated fire than after one fire. As pointed before, much less attention has been paid to the consequences of repeated fires on runoff, soil erosion, and loss of organic matter. Therefore, our main objective was to assess the effect of fire frequency on runoff and associated sediment and OM losses at the micro-plot scale by comparing pine plantations those have experienced single vs. recurrent wildfires. Specific objectives were to assess the effect of frequent recurrence of fire on generation of i) runoff and related sediment and OM losses at micro-plot scale, ii) the effect of both temporal and spatial variations on the runoff and erosive response at micro-plot scale, and iii) the effect of ground cover, soil moisture content, and soil water repellency (SWR) on runoff and associated sediment and OM losses at micro-plot scale.

2. Materials and methods

2.1. Study site

The study area was in the basin of the Vouga River, which drains into the Ria de Aveiro coastal lagoon, in north-central Portugal (Fig. 1). The climate is classified in Köppen's system as temperate Csb, humid meso-thermal with prolonged dry and warm summers. Annual rainfall ranges from 1200 to >2000 mm y^{-1}, and mean monthly temperatures range from 9 °C in January to 23 °C in July (SNIRH, 2014). The soils, classified in 2012 as loam and sandy loam, are shallow Epileptic Umbrisols and Umbric Cambisols with a depth <30 cm developed on schist parental material (WRB, 2014) and susceptible to degradation by erosion due to the land use and lack of vegetation. 5000 m^2 of fire occurrence area was selected for this study. The study area was mainly covered by stands of *P. pinaster*, which is a highly flammable tree species with a rotation cycle of 40 years (Moreira et al., 2013; Maia et al., 2014), and with *Pterospartum tridentatum* as the predominant shrub species (Cunningham et al., 1914). Ash cover in the burnt sites averaged approximately 10 cm, and the depth of the O horizon in the unburnt sites was 7–10 cm. Repeated fires reduced tree and shrub cover, the soil cover of the burnt and unburnt sites at the beginning of the experiment are shown in Fig. 2. There were no vegetation that remained in the repeatedly (4×) burnt sites, and the shrub layer and some pine trees were eliminated in the sites which burnt only once. Annual vegetation, pine trees, and shrub layers covered the unburnt sites.

2.2. Experimental set-up

The study was conducted in a forested area that had burnt in September 2012. Nine slopes (Table 1) of similar gradients and covered with Maritime Pine were selected. Three were in 4× burnt sites that had burnt four times between 1975 and 2012 (1978, 1985, 2005, and 2012). Three were in 1× burnt sites, which had only burnt in September 2012. Three sites that had not been burnt since 1975 but were near the burnt area acted as long unburnt. In this research we used the terms of degraded (D) for 4× burnt, semi-degraded (SD) for 1× burnt and control (C) for long unburnt sites. Small plots can help to understand the connectivity of sediment and water transport (Baartman et al., 2013). Therefore, samples of runoff and eroded sediments were collected from 0.25 m^2 micro-plots at the lower, middle, and upper sections of the slopes, using the same design as various prior studies in the region (Martins Martinho et al., 2013; Malvar et al., 2015) (Fig. 1). Plots were installed immediately after the fire of 2012, in areas without vegetation. This methodology is specially applied in areas where the generation of runoff is fast (Cerdà, 1999). On the control slopes, two micro-plots were established at the lower and upper sections, because the pine trees, litters and shrubs protected the soil from runoff and sediment losses and low variability was expected. Each plot was protected from upslope runoff by iron plates and was connected to a hose that carried the surface runoff to a 70-L tank.

3. Data collection

3.1. Soil characteristics

We determined soil pH (H_2O), texture, and bulk density to a depth of 10 cm for each micro-plot. Soil pH (H_2O) was measured using a potentiometer with an accuracy of ±0.01. Texture was analysed by sedimentation (Stokes' Law) with the Robinson pipet method (Guitián-Ojea and Carballas, 1976). Bulk density was determined by the cylindrical-core method (Blake and Hartge, 1986). Details of the average soil parameters at each site are presented in Table 2. The soils of the study site were described as an association of Epileptic Umbrisol and Umbric Cambisol developed on schist as parent material (WRB, 2014) and classified as loam and sandy loam. (See Table 2.)

3.2. Soil cover

The soil cover were assessed eight times from October 2012 to June 2014. A 10 × 10 cm gridded quadrat was laid over each plot, and the cover at each crossing point of the gridlines was determined and recorded as, stone (bedrock and fragments >2 mm), bare soil, ash, litter, or vegetation. Soil cover were included as factors affecting runoff and related sediment and OM losses.

3.3. Soil moisture and soil water repellency

Soil moisture sensors (Decagon EC5) were installed at a depth of 5–10 cm and connected to Em5b data loggers monitoring soil moisture variation in D2 and SD2 (as a random selection from the fire frequency sites). In the C plots the rainfall mainly influenced the moisture of the O horizon and with a strong time lag the mineral soil. Therefore, we decided to use comparable data sets and only compare soil moisture in D and SD. Data were recorded at 10-min intervals from October 2012 to September 2014.

Soil water repellency was determined by testing the molarity of ethanol droplets (Doerr et al., 1996; Doerr, 1998), and the samples were categorised into surface-tension classes from 1 (Very hydrophilic) to 7 (Extremely hydrophobic) (Doerr, 1998). Three drops of aqueous