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Predicting the effectiveness of different mulching techniques in reducing post-fire runoff and erosion at plot scale with the RUSLE, MMF and PESERA models

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ABSTRACT

Wildfires have become a recurrent threat for many Mediterranean forest ecosystems. The characteristics of the Mediterranean climate, with its warm and dry summers and mild and wet winters, make this a region prone to wildfire occurrence as well as to post-fire soil erosion. This threat is expected to be aggravated in the future due to climate change and land management practices and planning.

The wide recognition of wildfires as a driver for runoff and erosion in burnt forest areas has created a strong demand for model-based tools for predicting the post-fire hydrological and erosion response and, in particular, for predicting the effectiveness of post-fire management operations to mitigate these responses.

In this study, the effectiveness of two post-fire treatments (hydromulch and natural pine needle mulch) in reducing post-fire runoff and soil erosion was evaluated against control conditions (i.e. untreated conditions), at different spatial scales.

The main objective of this study was to use field data to evaluate the ability of different erosion models: (i) empirical (RUSLE), (ii) semi-empirical (MMF), and (iii) physically-based (PESERA), to predict the hydrological and erosive response as well as the effectiveness of different mulching techniques in fire-affected areas.

The results of this study showed that all three models were reasonably able to reproduce the hydrological and erosive processes occurring in burned forest areas. In addition, it was demonstrated that the models can be calibrated at a small spatial scale ($0.5\,m^2$) but provide accurate results at greater spatial scales ($10\,m^2$).

From this work, the RUSLE model seems to be ideal for fast and simple applications (i.e. prioritization of areas-at-risk) mainly due to its simplicity and reduced data requirements. On the other hand, the more complex MMF and PESERA models would be valuable as a base of a possible tool for assessing the risk of water contamination in fire-affected water bodies and for testing different land management scenarios.

1. Introduction

Wildfires have become a persistent threat in the Mediterranean, especially in the Iberian Peninsula where, on average, more than $100,000\,ha\,y^{-1}$ land burned in the past decade (San-Miguel-Ayanz et al., 2017). Fire activity is foreseen to increase in Mediterranean countries throughout the 21st century, as a result of shifts in climate and socio-economic conditions (Nunes et al., 2017; Turco et al., 2014, 2016; Viedma et al., 2015).

From the commonly reported environmental disturbances associated to wildfires, soil erosion by water is probably the one raising most concern (Esteves et al., 2012; Moody et al., 2013; Santín and Doerr, 2016; Shakesby, 2011; Shakesby et al., 2016). By reducing or eliminating the vegetation and ground cover, wildfires make the soil more susceptible to raindrop impact, reducing aggregate stability and promoting sediment detachment (e.g. Certini, 2005; Prats et al., 2014; Shakesby and Doerr, 2006). Fire-induced soil water repellency, often reported following wildfires (Keizer et al., 2008; Shakesby, 2011), can also contribute to an enhancement in runoff and soil erosion in burned forest areas (Fernández et al., 2010; Vieira et al., 2016). Fire-induced changes on forest hydrology and geomorphology are likely to negatively affect forest ecosystem services, including raw material and water provisioning, erosion and flood control, and biodiversity maintenance (Carvalho-Santos et al., 2016; Nunes et al., 2017; Smith et al., 2011;

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Verkaik et al., 2013).

Mitigation measures can be applied to help reduce the on-site and off-site negative effects of post-fire water erosion (Robichaud et al., 2010). Mulch treatments (e.g. straw mulch, chopped-bark mulch, pine needle mulch and hydromulch) are considered the most effective in minimizing post-fire soil erosion (Férnandez and Vega, 2016; Neary et al., 2005; Prats et al., 2014, 2016; Robichaud et al., 2013). This is mainly because mulch provides surface cover to soils prior to vegetation regrowth, thereby minimizing rain splash detachment while improving soil stabilization (Robichaud et al., 2007; Wohlgemuth et al., 2009).

As the hydrological and erosive response of burned areas is extremely complex, depending on an interplay of factors such as, vegetation, fire severity, climate, geology, soil type, topography, and land management (Certini, 2005; Shakesby and Doerr, 2006), post-fire treatments must be adapted to local conditions (Shakesby, 2011). Models are valuable tools for guiding management decisions mitigating post-fire soil erosion and for planning the rehabilitation of burned areas (Fernández et al., 2010; Fernández and Vega, 2016; Hyde et al., 2012; Robichaud and Ashmun, 2012), as they have been reported to accurately predict post-fire runoff and sediment yields in a multiplicity of forest catchments. However, in order to be realistic and accurate, models should be parameterized using field data to reduce uncertainties (Férnandez et al., 2010, Fernández and Vega, 2016; Larsen and MacDonald, 2007; Rulli et al., 2013; Shakesby, 2011).

Most of the models that have been used to simulate post-fire conditions were originally developed for unburned conditions. The adaptation of these models to burned conditions was typically achieved by introducing an empirical "fire factor" or by adjusting input parameters such as ground cover, surface roughness, soil hydraulic properties (Chen et al., 2013).

The existing post-fire erosion modelling studies include applications and adaptations of simple empirical models, such as the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) and its revised version, the RUSLE model (Renard et al., 1997), but also semi-empirical models, such as the revised Morgan–Morgan–Finney model (MMF, Morgan, 2001), and physically-based models, the Water Erosion Prediction Project (WEPP,), the Pan-European Soil Erosion Risk Assessment (PESERA, Kirkby et al., 2003) and the Soil and Water Assessment Tool – SWAT model (Arnold et al., 1998).

In the Mediterranean region, post-fire erosion predictions were performed using the RUSLE (Fernández et al., 2010, 2016; Karamesouti et al., 2016; Rulli et al., 2013; Terranova et al., 2009); MMF (Fernández et al., 2010; Vieira et al., 2014), WEPP (Soto and Díaz-Fierros, 1998), PESERA (Esteves et al., 2012; Fernández et al., 2016; Karamesouti et al., 2016) and SWAT models (Nunes et al., 2017). These model applications however, often yield different erosion rates (Fernández et al., 2010, Fernández and Vega, 2016; Karamesouti et al., 2016) and only few from these studies present results validation with field data (Fernández et al., 2010, Fernández and Vega, 2016; Nunes et al., 2017; Soto and Díaz-Fierros, 1998; Vieira et al., 2014).

As regards to post-fire rehabilitation, in general, there is a lack of model applications to simulate post-fire runoff and erosion in mitigated areas (Fernández et al., 2010; Robichaud et al., 2007). In the USA, the ERMiT tool has been widely used as an operational tool for decision support in post-fire land management (Robichaud et al., 2007). In the Mediterranean region, the RUSLE (Fernández et al., 2010; Rulli et al., 2013) and MMF models (Fernández et al., 2010; Vieira et al., 2014) have been applied and both models showed their ability to be used as operational tools to help land managers prioritize treatment areas and therefore, to optimize the limited resources that are typically available for post-fire land management.

The main objective of this study was to compare the ability of an empirical (RUSLE), semi-empirical (MMF) and physically-based (PESERA) model to predict the hydrological and erosive response and the effectiveness of different mulching techniques, namely hydromulching and natural mulching with pine needle, following a moderate severity wildfire in North-Central Portugal (Colmeal, Coimbra district). The ultimate goal of this work is to identify the best model to be used as base for a post-fire management tool, which aims for planning erosion mitigation and rehabilitation measures for this region, so that land managers can prioritize resources and evaluate trade-offs between different management strategies.

2. Materials and methods

2.1. Study area and study sites

On August 27, 2008, a wildfire ravaged and consumed almost 68 ha of forest lands, located near the Colmeal village, in the municipality of Góis, north-central Portugal (40°08′42″ N, 7°59′16″ W; 490 m a.s.l.). Prior to the fire, the Colmeal study area was predominantly dominated by maritime pine (*Pinus pinaster* Ait.) stands but also included some eucalypt (*Eucalyptus globulus* Labill.) stands (Vieira et al., 2016).

The climate of the study area can be characterized as humid mesothermal (Köppen, Csb), with prolonged dry and warm summers. Mean annual temperature and precipitation at the nearest meteorological station (GÓIS (13I/01 G); 10 km) are, respectively12 °C and 1133 mm (SNIRH, 2012).

The study area lies over pre-Ordovician schists and greywackes (Ferreira, 1978; Pimentel, 1994), which have given rise to shallow soils typically mapped as Humic Cambisols (Cardoso et al., 1971, 1973).

Within the burned area, 2 pine-dominated hillslopes were selected for testing two post-fire treatments, i.e. hydromulch and natural pine-needle mulch (Fig. 1). This study site had already been previously selected for several other studies concerning post-fire vegetation recovery (Maia et al., 2012a, 2012b), modelling post-fire hydrological response at catchment scale (van Eck et al., 2016), the effectiveness of hydromulch to reduce runoff and erosion after the wildfire (Prats et al., 2016), and also the effect of pre-fire plowing in the post-fire response (Vieira et al., 2016).

According to simple field indicators (i.e. tree canopy and woody debris consumption, litter combustion, ash colour and mineral soil), the two hillslopes appeared to have experienced a low-to-moderate burn severity since tree canopies and most of the logs were only partially consumed, the litter layer was fully consumed, the ash was black and the mineral soil was unaffected (DeBano et al., 1998; Hungerford, 1996). The 'Twig Diameter Index' (TDI), calculated based on the diameter of the 3 thinnest remaining twigs of each measured shrub (10 per site), also confirmed the existence of a moderate severity fire since an intermediate value (0.5) was found for an index that typically varies from 0 (unburned) to 1 (severely burned) (Maia et al., 2012a, 2012b; Vieira et al., 2016).

2.2. Model description and parameterization

The RUSLE, the revised MMF and the PESERA models, were applied to predict the hydrological and erosive response, and the effectiveness of different mulching techniques in reducing post-fire runoff and erosion at the Colmeal study area. A brief description of the three models is given below.

2.2.1. RUSLE

RUSLE (Renard et al., 1997) is an erosion model designed to predict long-term annual average soil losses induced by runoff, at slope scale. According to Wischmeier and Smith (1978), soil losses (A, Mg ha^{-1} y^{-1}) can be calculated as a product of five factors (Eq. (1)): rainfall erosivity (R, MJ mm h^{-1} ha-1 y^{-1}), soil erodibility (K, Mg h MJ^{-1} mm^{-1}), topography (LS, non-dimensional), crop (C, non-dimensional) and soil conservation practices (P, non-dimensional).

$$A = R \times K \times LS \times C \times P \quad (1)$$