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Modelling runoff and erosion, and their mitigation, in burned Portuguese forest using the revised Morgan–Morgan–Finney model

D.C.S. Vieira [a,*], S.A. Prats [a], J.P. Nunes [a], R.A. Shakesby [b], C.O.A. Coelho [a], J.J. Keizer [a]

[a] Centre for Environmental and Marine Studies (CESAM), Dpt. Environment and Planning, U. Aveiro, Aveiro 3810-193, Portugal
[b] Department of Geography, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP, UK

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ABSTRACT

The revised Morgan–Morgan–Finney (MMF) model was used as a modelling approach, which has performed reasonably well to estimate soil losses for burned areas in humid Mediterranean forests in Portugal, and NW Spain. Simple model enhancement approaches are applied to recently burned pine and eucalypt forested areas in north-central Portugal and to subsequent post-wildfire rehabilitation treatments. Model enhancement is validated by applying it to another similar burned area to evaluate model calibration robustness and wider applicability. Model modifications involved: (1) focusing on intra-annual changes in parameters to incorporate seasonal differences in runoff and erosion; and (2) inclusion of soil water repellency in runoff predictions. The main results were that following wildfire and mulching in the plantations: (1) the revised model was able to predict first-year post-fire plot-scale runoff and erosion rates ($NS_{(Runoff)} = 0.54$ and $NS_{(Erosion)} = 0.55$) for both forest types, and (2) first year predictions were improved both by the seasonal changes in the model parameters ($NS_{(Runoff)} = 0.70$ and $NS_{(Erosion)} = 0.83$); and by considering the effect of soil water repellency on the runoff ($NS_{(Runoff)} = 0.81$ and $NS_{(Erosion)} = 0.89$), (3) the individual seasonal predictions were considered accurate ($NS_{(Runoff)} = 0.53$ and $NS_{(Erosion)} = 0.71$), and the inclusion of the soil water repellency in the model also improved the model at this base ($NS_{(Runoff)} = 0.72$ and $NS_{(Erosion)} = 0.74$). The revised MMF model proved capable of providing a simple set of criteria for management decisions about runoff and erosion mitigation measures in burned areas. The erosion predictions at the validation sites attested both to the robustness of the model and of the calibration parameters, suggesting a potential wider application.

1. Introduction

Wildfires are a natural phenomenon in regions with a Mediterranean-type climate (Naveh, 1990). However, the present-day widespread occurrence of fires in southern Europe is unprecedented and strongly reflects human activity, not only directly through ignition (Veléz, 2009) but also indirectly through land-use changes such as land abandonment and widespread introduction of highly flammable pine and eucalypt plantations (Moreira et al., 2009; Shakesby, 2011). On average, wildfires consume each year 500,000 ha in southern Europe (San-Miguel and Cami, 2009), 100,000 ha of which in Portugal (Pereira et al., 2006a). Wildfire occurrence in Portugal is also not expected to decline markedly in the foreseeable future, both because of the economic importance of the country's forestry activities using flammable species and of the likely increase in meteorological conditions conducive to wildfires (Carvalho et al., 2010; Pereira et al., 2006b; Harding et al., 2009).

Wildfires are widely regarded as an important cause of increased runoff and soil erosion, and hence, land degradation in Mediterranean forests and woodlands, even though there remains considerable uncertainty about the long-term and landscape-scale impacts (e.g. Cerdà and Doerr, 2007; Shakesby and Doerr, 2006; Shakesby, 2011). This also applies to Portugal, where the degradational effects of post-fire land-use practices have equally been highlighted (Shakesby et al., 1993, 1996; Walsh et al., 1992, 1995; Ferreira et al., 2005, 2008; Malvar et al., 2011, 2013; Martins et al., 2013; Prats et al., 2012, 2013). Fire-enhanced runoff and erosion are commonly attributed to the (partial) removal of the protective soil cover of vegetation and litter, in combination with heating-induced changes in soil properties such as aggregate stability (e.g. Varela et al., 2010; Mataix-Solera et al., 2011) and soil water repellency (SWR) (e.g. Scott et al., 1998). SWR is widely reported in burned forest soils (e.g. Wells, 1981; Vega and Díaz-Fierros, 1987; Prosser, 1990; Walsh et al., 1994; Keizer et al., 2008a) but is also commonly found in unburned soils (e.g. Imeson et al., 1992; Arcenegui et al., 2007; Martínez-Zavala and Jordán-López, 2009; Jordán et al., 2010; Keizer et al., 2005a). Although SWR can be induced and enhanced by wildfire (DeBano, 2000; Doerr et al., 2000; Doerr and

* Corresponding author. Tel.: +351 914233748.
E-mail address: dianac.s.vieira@ua.pt (D.C.S. Vieira).

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Moody, 2004), the principal consequence of fire seems to be that SWR becomes geomorphologically 'activated' (Doerr et al., 1996; Doerr, 1998; Shakesby et al., 2000; Keizer et al., 2005b).

Many authors have investigated the relationships between SWR and soil moisture content and/or antecedent rainfall and overland flow response (Doerr and Thomas, 2000; Doerr et al., 2003; Ferreira et al., 2005; Keizer et al., 2005a; Malvar et al., 2011; Santos et al., 2013). Apparently, the predominant runoff generating process can shift from saturation-excess to Hortonian overland flow when pre-storm soil conditions change from moist and wettable to dry and repellent (Doerr et al., 2003). In water repellent soils, the common assumption that infiltration capacity is inversely related to soil moisture content does not apply. Depending on the degree of water repellency, infiltration capacity is reduced for soil moisture contents below a critical threshold (Dekker and Ritsema, 1996) and often increases as soils become wet (Burch et al., 1989; Imeson et al., 1992; Doerr et al., 2003).

The effect of wildfires of increasing runoff and erosion has created a strong demand for a model-based tool for post-fire sediment loss prediction. Post-fire erosion prediction has been a research target by a number of authors (Benavides-Solorio and MacDonald, 2005; Díaz-Fierros et al., 1987; Fernández et al., 2010a; Larsen and MacDonald, 2007; Moody et al., 2008; Soto and Díaz-Fierros, 1998), and, in the case of Portugal, by the EROSFIRE-I and -II projects (Keizer et al., 2008b; Vieira et al., 2010). A variety of erosion models originally developed for agricultural areas have been applied to burnt areas. They range from simple empirical models such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) and the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997), to semi-empirical models such as the revised Morgan–Morgan–Finney (MMF) model (Morgan, 2001) and the WEPP-based Erosion Risk Management Tool (ERMiT; Robichaud et al., 2007), and to process-based models such as the Water Erosion Prediction Project (WEPP; Nearing et al., 1989) and the Pan-European Soil Erosion Risk Assessment (PESERA; Kirkby et al., 2008). Besides for evaluating post-fire erosion risk, soil erosion models have elevated potential for assessing the medium- to long-term impacts of fire as a landscape-disturbance and soil degradation agent, providing a welcome complement to the field studies that typically involve monitoring at small spatial scales and over short periods (Esteves et al., 2012; Shakesby, 2011).

The ERMiT tool deserves special mention as it has been developed as an operational tool for decision support in post-fire land management in (parts of) the USA (Robichaud et al., 2007). It allows predicting erosion risk during the early stages of the window-of-disturbance and, at the same time, the reduction of this risk by selected erosion control measures. This complementary information enables forest managers to evaluate the impact of fire on site productivity and the potential benefits of rehabilitation treatments (Larsen and MacDonald, 2007), and helps to formulate scenarios of erosion mitigation treatments to reduce the probabilities of high sediment yields (Robichaud et al., 2007). The ERMiT tool, however, has not been tested for post-fire conditions in Portuguese or the Mediterranean in general. The need for testing and, in many cases adjusting existing models to local conditions is generally accepted (Shakesby, 2011). For example, Esteves et al. (2012) applied PESERA to post-fire conditions in central Portugal, and recommended that future applications would highlight factors such as SWR, the (temporary) presence of an ash layer and stone content (which is often high in the mountain soils in north-central Portugal).

The authors have been focusing their post-fire erosion modelling efforts on the revised MMF model (Morgan, 2001), as a relevant development compared to (R)USLE while maintaining much of (R)USLE's ease-of-application, especially in comparison to process-based models with their elevated model input requirements. Furthermore, the revised MMF model has shown considerable promise for predicting soil losses in recently burnt woodlands in the humid Mediterranean climate region of the Western Iberian Peninsula (Fernández et al., 2010a; Vieira et al., 2010). It is a semi-empirical model that was originally developed for predicting annual soil loss from field-sized areas on hillslopes (Morgan, 2001). While MMF inherited many concepts of USLE (Wischmeier and Smith, 1978), its conceptualisation aimed at improving USLE physical basis by separating the soil erosion process into a water phase and a sediment phase (Fig. 1). The water phase determines the energy of the rainfall available to detach soil particles from the soil mass as well as the volume of runoff; the sediment phase determines the rates of soil particle detachment by rain splash and runoff as well as the transporting capacity of the runoff volume. Runoff in MMF is estimated based on the method proposed by Kirkby (1976) which assumes that runoff occurs when the daily rainfall exceeds the soil moisture storage capacity and that daily rainfall amounts approximate an exponential frequency distribution (Morgan, 2001, 2005). The transport capacity of this runoff is then determined through a simplification of the scheme described by Meyer and Wischmeier (1969). MMF can easily accommodate soil conservation practices in its different phases. For example, agronomic measures can be simulated through the changes they produce in evapotranspiration, interception and crop management, which, in turn, affect the volume of runoff, the rate of detachment and the transport capacity, respectively (Morgan, 2005).

The overall aim of this study was to apply the revised MMF, testing simple enhancements of the model for recently burned pine and eucalypt forest in north-central Portugal. These model enhancements involved: (1) implementing seasonal changes in model parameters, in order to accommodate seasonal patterns in runoff and erosion as had been measured in the field trail; and (2) incorporating the role of SWR in overland flow generation, taking into account the findings of various post-fire hydrological/erosion studies in (north-) central Portugal (Walsh et al., 1994, 1995; Ferreira et al., 2005, 2008; Esteves et al., 2012; Prats et al., 2012; Malvar et al., 2011, 2013). Worth stressing is that SWR has rarely (if ever) been incorporated explicitly in the modelling of post-fire runoff and erosion. These model enhancements were applied to two independent data sets collected by Shakesby et al. (1996) and Prats et al. (2012) at comparable sites at nearby locations but burnt and studied more than two decades apart. The data set of Prats et al. (2012) was used to calibrate the enhanced model, whilst the data set of Shakesby et al. (1996) was then used to validate it. The enhanced MMF model was evaluated to predict runoff and erosion following fire as well as following the application of mulching, a post-fire emergency treatment that both studies found to be highly effective.

2. Materials and methods

2.1. Study areas and sites

The two study areas in north-central Portugal where Shakesby et al. (1996) and Prats et al. (2012) collected their data sets were located near the villages of Falgarosa (40° 32′ N, 8° 22′ W) and Lourizela (40° 38′ N, 8° 19′ W), in the Águeda municipality, and near the village of Pessegueiro do Vouga 40° 43′05″N; 8°21′15″W), in the Sever do Vouga municipality, respectively. The former, validation data set concerned two sites covered by a pine plantation and a eucalypt plantation that burnt in 1991 and 1992, respectively; the latter, calibration data set concerned two nearby sites planted with pine and eucalypt that both burnt in 2007, in a single wildfire. A characterisation of wildfire severity at the four sites is given in Table 1.