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The differential response of surface runoff and sediment loss to wildfire events

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ABSTRACT

Wildfires are of primary importance in determining ecosystem function and geomorphological process in most of the forested landscapes across the globe. Following a fire event in a maquis forest located at the Carmel mountain range in northern Israel, we monitored the eco-geomorphic response of the system, in an attempt to explain runoff and sediment yield dynamics. Specifically, we assessed growth of vegetation cover, and monitored runoff and sediment yield in relation to three controlling factors: fire severity, slope aspect, and slope steepness. Fourteen 10 m^2 plots were constructed in different combinations of aspect, fire severity and steepness, which were monitored for a period of 24 months.

Analysis of vegetation cover indicated that initial growth was faster on the north aspects, but by the end of the study period vegetation cover was similar to that of pre-fire levels on both aspects. Runoff and soil loss amounts from the burnt sites were commonly significantly higher on the south slope, steep gradients and high fire severity, compared to the counterpart plots. Temporal analysis indicated that sediment yield from the plots significantly decreased between the first and second winter seasons, whereas no statistically significant decrease in runoff was observed. Applying regression analysis methods we investigated the response of sediment yield to runoff, vegetation cover, soil moisture, rain intensity and precipitation, with respect to each of the controlling factors. In all cases runoff appeared to be a significant variable, as was vegetation cover, with the exception of the moderate burnt plots.

We suggest that vegetation plays a complex role in determining the response of the geomorphic system to wildfire perturbations. While the mere presence of vegetation is sufficient to reduce soil loss, it is not sufficient to significantly affect runoff, most likely due to the different architecture of the newly regenerated vegetation. Additionally, vegetation seems to be an important factor in the harsher environments where more intensive soil movements occur, as the conditional effect of vegetation is more pronounced, and its contribution to the reduction of soil movements is higher.

1. Introduction

Forest fires play an important and prolonged role in structuring the complex eco-geomorphic systems of the Mediterranean basin. There is evidence that fires were frequent during the late Quaternary (Carrión et al., 2003), and probably even earlier, as many species have acquired adaptive mechanisms to endure and regenerate after recurrent fire events (Ne'eman et al., 2004; Pausas and Verdú, 2005). It is widely agreed that the immediate effects of wildfires on the chemical and physical properties of the soil–vegetation system (Certini, 2005; DeBano, 2000; González-Pérez et al., 2004; Wittenberg, 2012), coupled with reductions in biomass, facilitate erosive overland flow from the burnt sites, up to 5 orders of magnitudes higher than from natural, non-burnt rates (Inbar et al., 1998; Mayor et al., 2007; Rulli et al., 2006). The uppermost soil loss occurs mostly within the first years, followed by a sharp decrease in erosion rates and generally, within the first decade geomorphic processes rates return to their pre-disturbance conditions (Gimeno-Garcia et al., 2007; Shakesby, 2011; Wittenberg and Inbar, 2009).

Among the commonly considered factors in the literature determining post-fire hydrological and sedimentological dynamics, is the formation and destruction of hydrophobic layers (Debano, 2000; Doerr et al., 2000), fire-induced ash formation (Woods and Balfour, 2010), changes to the physical, chemical and biological soil properties (Mataix-Solera et al., 2011; Wittenberg, 2012), and damage to soil organic matter and the aboveground biomass (Doerr et al., 2009; Neary et al., 1999). Post-fire soil losses observed in the Mediterranean are relatively variable and depend on vegetation composition and soil type, post-fire weather conditions and fire severity (Shakesby, 2011).

Another key factor which plays a fundamental role affecting the hydrological processes is vegetation cover. The dominant mechanism by

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which vegetation affects these processes include 1) rain drops interception through the plant canopy and the litter, which reduces splash erosion (Domingo et al., 1998; Neary et al., 2005; Zuazo et al., 2004); 2) funneling the intercepted rain drops on to the stem of the plant to its base where the soil is more permeable, resulting in higher local infiltration rates and capacities (Martinez-Meza and Whitford, 1996; Zuazo et al., 2004); 3) increasing hydraulic roughness which decreases runoff flow velocity (Valentin and d'Herbes, 1999); and 4) organic matter produced by the vegetation increases soil aggregate stability (Neary et al., 2005).

These processes form a source-sink mosaic, in which bare soil functions as a source patch, providing sediments available for transport, and vegetation cover form sink patches, trapping sediments and enriching it with nutrients (Puigedefabregas, 2005). As a result, runoff rates from forested areas in the Mediterranean are generally negligible and the consequent soil loss is minimal.

Thus, the removal of vegetation cover following a fire event is an important factor dictating geomorphological response. Vegetation regeneration, however, may commence immediately depending on the species composition and timing of the fire. Several studies indicate that vegetation cover values are lower during the first wet season after the fire, characterized by 20%–45% vegetation cover, compared to a coverage of 50%–70% during the second rain season (Daly et al., 2004; Inbar et al., 1998; Mayor et al., 2007; Porporato et al., 2003). Runoff and soil loss yields significantly decrease after a threshold of vegetation cover is achieved. In the Mediterranean, a threshold of 30–40% vegetation cover is sufficient to significantly decrease soil loss and runoff yields (De Luis et al., 2001; Gimeno-Garcia et al., 2007; Loch, 2000; Puigedefabregas, 2005). The role of vegetation is also manifested via the physiographic properties of landscapes. Varying slope properties produce different runoff and soil loss yields, due to differences in aspect, steepness, lithology and vegetation type (Cerda et al., 1995; Mayor et al., 2007). Studies conducted in the Mediterranean basin found runoff values and soil loss yield after wildfires to be higher on the southern aspects than on northern ones (Cerda et al., 1995; Keizer et al., 2005; Wittenberg and Inbar, 2009), presumably due to higher vegetation regeneration rates on northern aspects. Fire severity also determines the abovementioned factors which affect geomorphic response, as it has been shown that 1) hydraulic roughness is lower in severely burnt areas compared to moderately burnt ones (Valentin and d'Herbes, 1999), 2) in severely burnt areas, the lack of litter exposes the soil to the effect of raindrops and the formation of a soil-sealed layer (Zuazo et al., 2004), and 3) the potential formation of the water-repellent hydrophobic layer may facilitate faster runoff generation and increasing soil loss rates (Doerr et al., 2000).

Following low-severity fires sediment loss is usually low due to the remaining foliage covering the soil (Pausas et al., 2008). In Mediterranean type ecosystems several studies indicated that as fire severity increases, the correlation between rainfall and erosion becomes stronger. Consequently, soil loss and runoff rates are higher in severity compared to moderately burnt sites (Campo et al., 2006; Gimeno-Garcia et al., 2007). In spite of the abundant literature pertaining to post-fire geomorphic processes, relatively little attention has been devoted to the intra- and inter-season revegetation properties and their influence on runoff and sediment yields. Herein, we analyze at a resolution of a single precipitation event the properties of these two phenomena following a fire event in a burnt Mediterranean maquis. Further, we analyze the dynamics of these variables with respect to the recovery of the vegetation cover, and their differential response in relation to fire intensity and different physiographic controlling factors.

2. Study site

Mt. Carmel is a distinctive mountain ridge steeply rising along the NW coast of Israel, with its highest peak at 546 m a.s.l. (Fig. 1). The permeable lithology is composed of upper Cretaceous carbonate rocks, mainly limestone, dolomite, chalk, marl and local exposures of volcanic tuff. The dominant soil type in the studied plots is brown rendzina (Lithic Haploxeroll), overlying soft limestone, chalk and marls (Soil Survey Staff, 2006). These soils have the following characteristics: total calcium carbonate content of 32%, pH of 7.4 and EC of 0.90 dS m^{-1}. Due to fire effects the upper top soil layer is highly disrupted and mixed with vegetation ash; the organic horizon (A), up to 5–7 cm grades downward into weakly structured C horizons (7–40 cm). The soil is clay-loamy from the surface (with 33–48% of clay in the first 7 cm) and clayey below down to 40 cm of depth (with 53–61% clay and 24–32% silt). Organic matter varies widely with fire severity (4.6–17.4%), exhibiting an average of 11.2% in the burnt plots, compared to 13.6% in the adjacent non-burnt soils.

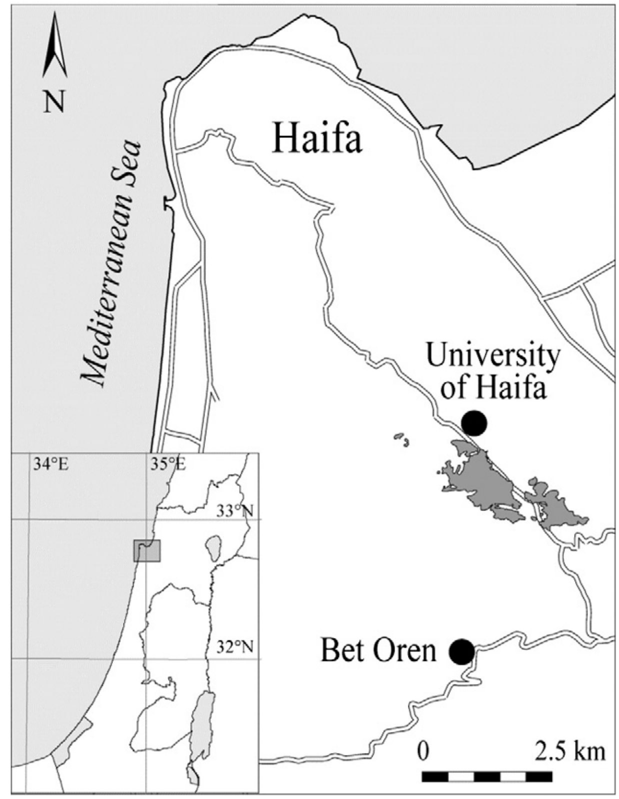

Fig. 1. The research area location, Mt. Carmel, Israel.

The vegetation of Mt. Carmel is a typical Mediterranean maquis (Malkinson and Wittenberg, 2007), ranges from dense mixed pine (*Pinus halepensis*) and oak (*Quercus calliprinos*) forests to more open and patchy mosaic-like tree-shrub formations (Kutiel and Naveh, 1987). The climate is characteristic Mediterranean, where a long hot and dry season prevails during May–October, and the precipitation is concentrated during the colder winter months, accounting for over 95% of the annual total. Mean annual precipitation in the region is 710 mm (Halfon, 2003). During April 2005 a wildfire consumed 154 ha of forest on the southern fringe of the city of Haifa, located in the northern part of the Carmel ridge. The fire was generally classified as a medium severity fire with some localities being consumed by high-severity fires (Tessler et al., 2008).

3. Methodology

One month after the fire event, runoff and sediment collecting plots were constructed. Plots were located after considering three physiographic controlling factors: slope gradient (steep > 15° vs. moderate < 15°), slope aspect (north vs. south) and fire severity