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The effect of fire-induced surface heterogeneity on rainfall–runoff–erosion relationships in an eastern Mediterranean ecosystem, Israel

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Abstract

The effect of forest fire on rainfall–runoff–erosion relationships at the micro-scale (plot) and at the meso-scale (hillslope) were studied in a Mediterranean mountainous region near Haifa, Israel. Rainfall simulation experiments were carried out on several plots at different times since the fire. Runoff and sediment yield were collected during the experiments. Soil samples from the upper soil layer (0–4 cm) were collected for analysing physical and chemical properties. The results obtained show that the total runoff and sediment yield varied considerably in both space and time. High spatial variability, at the plot scale, together with relatively low fire intensities and a well-structured and stable soil, were considered to be the main reasons for the very low runoff and sediment yield at the meso-scale (hillslope).

1. Introduction

An act of arson in September 1989 on Mt. Carmel near Haifa devastated 400 ha of mature pine forest and oak shrubland within one of the most important nature reserves in Israel. One immediate question raised by the park managers was whether soil erosion would occur following the first rainfall events and, if so, to what extent? Studies conducted world-wide, but mainly in the Mediterranean region, have reached opposing conclusions. Some investigators stated that fire significantly decreased infiltration and increased runoff and soil loss (Arend, 1941; Krammes, 1960; White and Wells, 1979; Chartres and Mücher, 1989; Coelho et al., 1990; McNabb and Swanson, 1990; Inbar et al., 1992), while others asserted that runoff and erosion increased slightly immediately after fire but fell rapidly to the pre-fire level after only a few weeks (Diaz-Fierros et al.,

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1990), or that there were no significant changes in these processes as a consequence of fire (Kutiel and Inbar, 1993).

The main reasons for an increase in runoff and erosion following fire are the destruction of the vegetation and litter layer (Bohling and Gerold, 1991; Diaz-Fierros et al., 1990; Wells et al., 1979), the creation of a physical crust by ash deposits (Wells et al., 1979; Morin and Benyamini, 1977), and the development of a hydrophobic layer (Wells et al., 1979; Dunn and Debano, 1977; Debano, 1981; Coelho et al., 1990; McNabb and Swanson, 1990; Imeson et al., 1992). Therefore, the extent of damage to vegetation and the rate of regeneration determine the rate of change of runoff yield and soil loss. Giovannini and Lucchesi (1991), however, noted that vegetation cover following fire plays a limited role in controlling soil erosion because of striking modifications induced by heat to the soil physico-chemical characteristics. These changes affect aggregate and soil stability, which decrease significantly at temperatures above 460° C as a result of the total destruction of organic matter and clay minerals (Giovannini and Lucchesi, 1983; Giovannini et al., 1988).

The purpose of this paper is to elaborate on these contradictory findings by focusing on the spatial variability of surface roughness induced by fire.

2. Methods and area description

The study was carried out in 1990 on Mt. Carmel, a mountainous region in north-western Israel (Fig. 1). The climate is Mediterranean with wet cool winters and

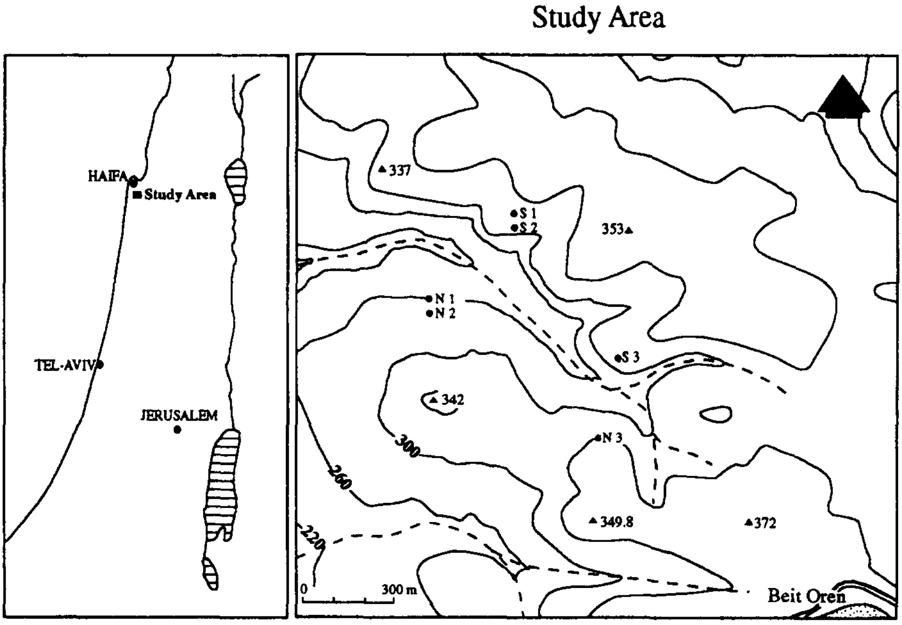

Fig. 1. Location map of research site and experimental plots (N1–3 and S1–3).

dry warm summers. The rainy season usually begins at the end of September and lasts until mid-May, with a mean annual rainfall of 690 mm. The topography is, in general, gentle and the soil type is Terra Rossa. The vegetation ranges from dense mixed Aleppo pine (*Pinus halepensis*)–oak (*Quercus calliprinos*) forests to more open and patchy mosaic-like tree–shrub formations (Kutiel and Naveh, 1987a). The area suffered from a wildfire in the summer of 1983 and experienced a second fire in 1989.

The study consisted of rainfall simulation experiments carried out on surfaces differing by the periods of time elapsed since a fire. Three observation sites were located on both north- and south-facing slopes. One site was at the area burned in 1989 (''one year after fire'': i.e. N3 and S3 in Fig. 1) and two sites were at the area which was not burned since 1983. One of these two sites was studied as is (''unburned'': N1 and S1 in Fig. 1), and in the second site a controlled fire was conducted just prior to the rainfall simulation experiments (''immediately after fire'': N2 and S2 in Fig. 1). The temperatures of the set fire were measured with thermocouples at the soil surface and at 2.5 cm depth during the fire. At N2 and S2 (''immediately after fire''), an additional set of rainfall simulation experiments were conducted two weeks after the set fire (''two weeks after fire'': N2.b and S2.b). The vegetation of the unburned site was removed in order to neutralise the dominant effect of vegetation cover on runoff generation and on soil loss, and to enable a comparison between burned and unburned exposed soil surfaces. In this way the fire effect on soil properties affecting soil erosion could be assessed, without including the effect of the fire on vegetation cover removal.

For each experiment, two adjacent runoff plots were established at each site. The size of each plot was 1 × 1 m and the gradient around 10°. In total, sixteen rainfall simulation experiments were conducted on twelve runoff plots (Table 1). Detailed descriptions of the soil surface before and after fire, such as stone cover, ash and remnants of burned and unburned plants (branches, twigs, leaves, cones and acorns), were made.

The rainfall simulation experiments were undertaken using the Morin rotational disk simulator (Morin et al., 1967). The simulator produces rainfall with a realistic drop-size distribution and velocity on a 4 m^2 area. The rainfall was applied at an intensity of about 30 mm/h with a total rainfall of 60 mm. Such intensities are considered to be very high and relatively rare in this area. The probability interval of such rain duration and intensity is about once in ten years (Fig. 2).

Table 1
Experimental plots, slope and orientation data

Site		Slope gradient (°)	Orientation (azimuth)
Unburned	N1	8.5	352
Immediately after fire	N2	8.5	352
Two weeks after fire	N2.b	8.5	352
One year after fire	N3	11.0	360
Unburned	S1	10.0	157
Immediately after fire	S2	10.0	157
Two weeks after fire	S2.b	10.0	157
One year after fire	S3	12.5	174

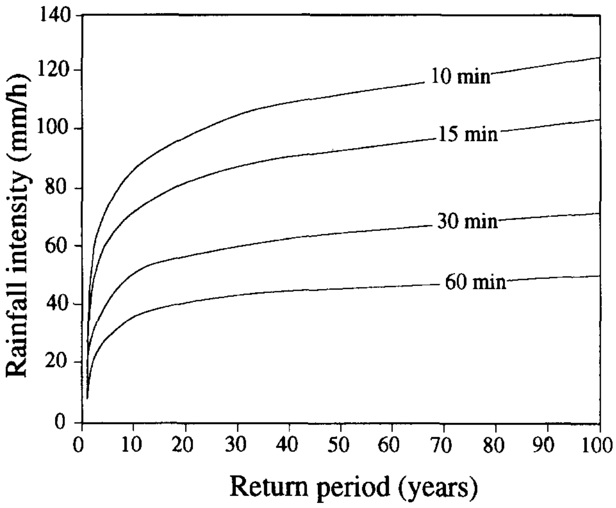

Fig. 2. Rainfall intensity–duration–freqency for Mt. Carmel.

Runoff and sediment yields were collected during the simulated rain from the centrally-located runoff plots, 1 m^2 in size, surrounded by a large buffer area (Lavee et al., 1991). From these measurements, parameter values were obtained for infiltration equations (Morin and Benyamini, 1977).

Table 2
Soil profile description of the unburned and burned one year after fire sites for the northern and southern aspects

	Depth (cm)	Colour	Texture	Structure
a. Northern aspect				
Unburned	0–15	2.5YR3/3 Reddish brown	clay	Strong fine subangular
	15–30	2.5YR3/4 Reddish brown	clay	Strong fine cubic
Burned	0–3	5YR3/3 Brown yellowish	clay	Crumb to granular
	3–10	5YR3/4 Brown yellowish	clay	Crumb to granular
b. Southern aspect				
Unburned	0–20	5YR3/3 Reddish brown	Clay	Granular to fine subangular
	20–30	5YR3/4 Reddish brown	Clay	Fine subangular
Burned	0–15	10YR2/1 Dark brown	Loamy clay	Weak granular
	15–35	7YR2/2 Dark brown	Loamy clay	Weak granular

Two soil profiles on each aspect were described; one in the "one year after fire" site and the other in the "unburned" site (Table 2). Soil samples were taken from the upper soil layer (0–4 cm) of the buffer area of each plot before each experiment in order to characterise the physical and chemical properties of the soil. Previous studies showed that the most significant changes induced by fire occur in the upper layer (Kutiel and Naveh, 1987a,b; Kutiel and Shaviv, 1989). It is precisely this layer that determines the infiltration rate of the soil and thus the runoff and erosion yield.

Several soil properties reflecting various responses of soils to fire and to wetting were analysed in the laboratory. These included changes in soil and aggregate stability, soil texture, organic matter content, cation concentration, and $CaCO_3$ content. Two tests were used to characterise structural stability and response to wetting; the single-drop aggregate stability test (Low, 1954; Imeson and Vis, 1984) and the C5-10 stability index (De Ploey and Mücher, 1981). Soil texture was analysed using the Sudan method (Beam, 1913). Cation concentrations (Ca, Mg, Na and K) in extract saturated pastes, pH, and electrical conductivity (EC) were also determined. $CaCO_3$ was determined by the amount of CO_2 released from soil samples mixed with 5% HCl solution. Organic carbon was determined using a potentiometric titration method (Raveh and Avnimelech, 1972).

3. Results and discussion

During the controlled fire soil temperatures were found to vary greatly from point to point. The temperature at the soil surface was, in general, 200–300° C for 23 minutes and 400–450° C for 31 minutes on the northern and southern aspects, respectively. However, at the beginning of the set fire the temperatures on the soil surface at the south-facing slope reached almost 900° C (Fig. 3), and a random measurement at the soil surface of the north-facing slope, 3 m from the measurement point, showed a value of 600° C. At 2.5 cm depth the maximum temperatures were 58° C and 82° C, respectively (Fig. 3).

Similar spatial and temporal differences were observed during another controlled fire set in a mature planted pine forest in this region (Kutiel, 1992a,1994; Zohar et al., 1992). These differences were considered due to variations in plant composition, fuel load, moisture content of the available fuel, and other factors such as topography and weather conditions (mainly wind velocity) during the fire (Kutiel, 1992a,b,1994; Zohar et al., 1992). The fresh fuel biomass (litter and branches on the forest floor) in a mature dense planted Aleppo pine forest was on average 1.2 kg m^{-2} and the fuel moisture content was around 14% (Zohar et al., 1992). The biomass amount in the present study was much lower before this mixed pine–oak forest was burned ten years ago.

The temperatures of the set fire are characteristic, according to Sampson (1944), of moderate-intensity fires. Accordingly, the striking modifications in soil properties at temperatures above 460° C persisting within the same spot for more than 2–3 minutes, and which significantly affect runoff and erosion after fire (Giovannini and Lucchesi, 1983; Giovannini et al., 1988), are not relevant to the present study. It should be taken into consideration that Giovannini and Lucchesi (1983) and Giovannini et al. (1988) conducted their studies in a laboratory in order to overcome the concomitant effects of

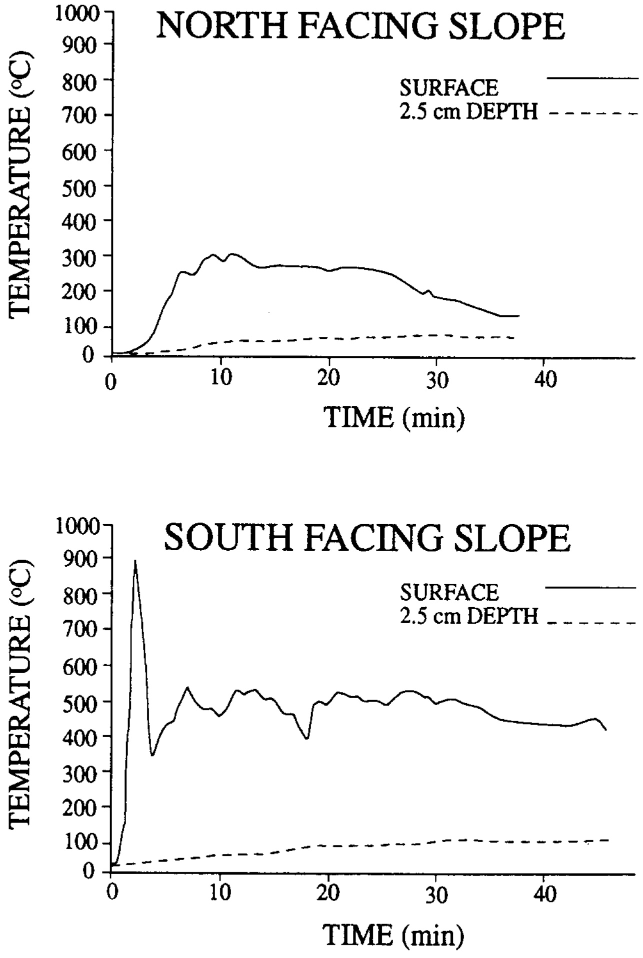

Fig. 3. Changes in fire temperature at the soil surface and at 2.5 cm depth for north and south aspects.

heat and ash inputs. Such experiments can shed light on processes but they do not always reflect the situation in the field.

The spatial variability of the fire temperature and the vegetation density, created "spatial heterogeneity" in soil surface microtopography. A patchy puzzle-like pattern, consisting of remnants of partly-burned trunks, branches, twigs, charcoal, black and white ash layers, Pyronema fungi, and depressions created at sites by tree roots when the trunks fell, developed at the soil surface.

Similar heterogeneous surfaces were observed at the sites which had suffered from fire in 1983 and 1989 (Lavee et al., 1995). We assume, therefore, that high spatial and temporal variability of fire temperature is also typical for wildfires in this region.

The chemical and physical properties of the soil also showed high spatial variability. Soil colour, texture and structure differed between the northern and southern aspects

Table 3
Chemical and physical properties of the upper soil layer (0–4 cm) for the different treatments and aspects (the drop test presents the percentage of the remaining aggregates after 400 drops; N, S = north and south aspects, respectively; 1, 2 = number of replica)

Time since fire (treatment)		Clay, %	Organic matter, %		Electrical conductivity, dS/cm		pH		$CaCO_3$, %		Aggregate stability (drop test), %		Soil stability C5-10 index	
			1	2	1	2	1	2	1	2	1	2	1	2
Unburned	N	68.3	5.4	4.3	0.86	1.19	7.6	7.6	0.0	0.0	100	42	5.00	6.96
	S	53.0	6.3	7.4	0.94	1.26	7.5	7.6	15.7	26.3	100	52	6.73	8.33
Immediately	N	66.1	6.5	6.0	1.22	1.17	7.5	7.5	1.1	1.0	19	100	5.61	8.75
after fire	S	62.2	7.0	7.9	1.00	1.63	7.6	7.6	12.4	14.2	50	50	7.50	10.00
Two weeks	N	66.1	6.5	6.0	1.47	1.56	7.5	7.7	1.1	1.0	100	100	3.94	6.25
after fire	S	62.2	7.0	7.9	1.26	0.63	7.9	7.9	12.4	14.2	100	100	5.92	8.75
One year	N	48.8	6.0	4.3	0.81	0.79	7.9	7.9	24.1	21.0	100	33	5.61	6.23
after fire	S	35.7	7.2	8.3	2.36	1.78	7.6	7.5	33.7	38.8	75	25	4.23	4.25

(Table 2). Likewise, organic matter, electrical conductivity, $CaCO_3$ content and aggregate stability differed considerably between aspects and even between adjacent plots (Table 3). Similar spatial variability was also observed in the unburned sites. This indicates that spatial heterogeneity is also affected by the original local differences in lithology and soil properties.

Very slight differences in soil texture between burned and unburned sites were observed (Table 3). These differences are due to the local variations in soil properties, rather than due to fire effect. Arias et al. (1991) noted that clay minerals do not seem to change significantly after fire where maximum temperatures recorded near the soil surface is 370° C. Organic matter, commonly associated with clay minerals, was also found not to be affected by fire (Table 3). These two components partly explain the stability of the soil before and after fire. Organic matter content above 3% and high amounts of clay contribute to the high aggregate and soil stability (Kamper and Koch, 1966). Alcaniz et al. (1991) also noted that the structural stability of the soil was not significantly modified by fire.

Infiltration rates and runoff and sediment yields also differed between the various plots. One plot produced relatively high amounts of runoff and erosion immediately after fire, while no runoff and sediment yield were observed in an adjacent plot intended to serve as a replica (Table 4). This was due to the different surface properties induced by the fire. In patches where a layer of white ash or a cover of Pyronema fungi produced a smooth and less permeable surface, overland flow and erosion occurred. At other patches, where partly-burned branches, twigs and cones, charcoal or depressions dominated the surface, the infiltration rate increased due to more surface roughness and the protecting effect of mulch.

This surface heterogeneity induced by fire was the dominant factor controlling runoff generation and erosion rate. The importance of spatial variability of soil surface properties in controlling geomorphic processes has been noted by Luk and Morgan (1981) and by Roels (1985).

Table 4
Simulated rainfall intensities, final infiltration and runoff rates, and total sediment yield for the different treatments and aspects (N, S = north and south aspect, respectively; 1, 2 = number of replica)

Time since fire (treatment)		Mean rain intensity, mm/h		Final infiltration rate, mm/h		Final runoff rate, mm/h		Total sediment yield, gr/m^2	
		1	2	1	2	1	2	1	2
Unburned	N	31.6	30.0	26	30	5	0	20	0
	S	29.2	41.4	29	40	1	2	14	20
Immediately after fire	N	32.8	30.5	23	30	11	0	50	0
	S	31.2	48.0	29	35	4	13	15	63
Two weeks after fire	N	32.4	34.4	16	29	18	5	70	20
	S	34.0	48.0	30	40	2	8	13	60
One year after fire	N	24.2	29.3	23	21	9	12	35	60
	S	30.8	29.6	29	21	9	2	50	12

The mosaic-like pattern of runoff generating and runoff accepting patches does not permit continuous overland flow and sediment movement at the meso-scale (hillslope). This is because overland flow generated on some patches will infiltrate after a short distance upon reaching a permeable patch. The probability of significant amounts of overland flow and sediments reaching the valley bottom is thus very low. This is confirmed by the results of other studies conducted at hillslope and watershed scales in the same region. Kutiel and Inbar (1993) observed very low runoff coefficients following a moderate wildfire in a planted mature Aleppo pine and *P. brutia* (red pine) forest on Mt. Carmel. Similar findings were reported by Zohar et al. (1992) in a study of prescribed fire effects in a mature *P. brutia* pine plantation on Mt. Carmel. Naveh (1973) also reported that after a hot fire of dense sclerophyll maquis shrubland in the Western Galilee, no traces of runoff, soil splashing, or soil movement were observed.

It is worthwhile noting that even when overland flow and erosion were observed in the experimental plots, the maximum runoff rate and total sediment yield were negligible (Table 4). This suggests that the relevant scale of surface heterogeneity induced by fire is in the order of several square centimetres or a few tens of square centimetres. In such a situation, even in the 1 m^2 experimental plots, a mosaic-like pattern of very small runoff generating and runoff accepting patches developed; overland flow that measured at the plot base was contributed only by the lower part of the experimental plot.

The infiltration values measured for the burned and unburned plots were rather high in spite of the fact that relatively rare, but moderate, rainfall intensities were used in the rain simulation experiments (Table 4). Under natural conditions, therefore, we may expect that most and perhaps all the rain will infiltrate into the soil.

4. Conclusions

Moderate intensity fires in Mediterranean forests, having relatively low vegetation biomass, are characterized by high temporal and spatial variations in fire temperatures. This causes a mosaic-like pattern of runoff generating and runoff accepting patches. The size of the patches ranges between several square centimetres to a few square meters. The outcome at the hillslope scale, is for discontinuous overland flow and for very low runoff and sediment yields contributed to the valley.

Runoff and sediment yields after forest fires are very difficult to predict due to the complexity of such a system. This complexity is due not only to the spatial and temporal distribution of the fire temperature, but also to the exact location of runoff generating and runoff accepting patches on the hillslope. An existance of runoff generating patches at the slope base will prevent overland flow and sediment deliverty to the valley. Rainfall intensity following fire compounds the complexity. For example, a rainfall event immediately following fire may leach the ash into the soil, while in the case of a dry period after fire the ash can be removed by wind. Such factors help to explain the different observations and conclusions reported by different investigators.

Acknowledgements

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