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Fire and aspect induced differences on the erodibility and hydrology of soils at La Costera, Valencia, southeast Spain

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Abstract

This paper presents measurements of soil aggregation parameters and rainfall simulation experiments from areas of Mediterranean scrubland vegetation in La Costera district, in the southern part of Valencia Province, Spain. Data were obtained using a portable rainfall simulator and from laboratory studies of aggregate stability, using the water-drop test and ultrasonic dispersion methods. Three locations were chosen to enable the influences of aspect and the post-fire recovery time of the vegetation on soil erosion and hydrology to be investigated. The slopes studied were (a) a north-facing slope burnt ten years before the experiment, (b) a south-facing slope burnt at the same time, and (c) a north facing slope, burnt two years before the experiment, similar to slope "a" in terms of its basic characteristics. The experiments demonstrate the importance of both wildfires and aspect on hydrological and erosional soil surface processes.

The north facing slope at La Costera (slope a) has a higher aggregate stability than the corresponding south facing slope (slope b). The recently burnt north facing slope (c) is intermediate in terms of aggregation, but has the most erodible soils because of the lower infiltration rates and the low vegetation and litter cover. Nevertheless, for the slopes burnt ten years previously, the south-facing slope is more erodible than the north-facing one.

The results suggest that the forest fire ten years ago did not produce a persistent degradation of the ecosystem, only higher soil and water losses during the first years following the fire. A southern aspect, where vegetation recovery rates are slower and the hydraulic stress is higher, favours the development of soils with a relatively low aggregate stability.

1. Introduction

Wildfires constitute a major environmental problem in parts of the Valencia Region (Spain). Post fire soil erosion can be severe because of the very high autumn rainfall

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intensities that occur after the summer fire season. Nowadays, the high fire frequency makes the risk of such erosion very high (Sala and Rubio, 1994). Furthermore, the repeated loss of the above ground vegetation and ecto-organic soil horizons with the nutrients that they contain will lead after several fire to the gradual development of a degraded landscape (Fantechi and Margaris, 1986). Wildfires are known to have occured in the Mediterranean region throughout historic and prehistoric times (Naveh, 1990) but the frequency with which they occurred was much lower than today. Although the association of land degradation with wildfires is generally acknowledged in the Valencia region, there are many unanswered research questions, two of which are raised in this paper.

The first research question concerns the way in which geomorphological processes are controlled by aspect. Soils on south facing slopes always appear to be far more eroded or degraded than those on more humid north-facing slopes (Churchill, 1982).

The second research question relates to the need to consider post-fire erosion in the context of the post-fire recovery of the vegetation. The post-fire cycle of initial increase and subsequent decrease of erosion to the same level as before the fire is indicative of the resilience and stability of the ecosystems that have been burnt (Westman, 1986; Calvo and Cerdà, 1994).

The general objective of this paper is to contribute to the knowledge of the influence of fire and aspect on the hydrological and erosional response of soils in a typical Mediterranean environment.

The data that have been collected to investigate the above research questions, consist of firstly, the results of rainfall simulation experiments. These data describe the condition of the soil surface with respect to its influence on regulating the balance between infiltration and overland flow. Secondly, they consist of soil erodibility and stability measurements. It is well known that the soil erodibility and hydrology are both sensitive to fire and other forms of environmental disturbance.

2. The field sites

Three slopes were selected for the research near Canals and Genovés, in a characteristic matorral (scrubland) landscape in the La Costera District, in the south of Valencia Province, Spain (Fig. 1). The slopes are on limestone, with similar land use and vegetation. Slope (a) is a north-facing slope burnt ten years before this study; slope (b) a south-facing slope burnt at the same time (August 1981) and slope (c) a north-facing slope burnt only two years before the experiment (August 1989). Measurement and sampling sites were located in the middle part of the slope just above the contact with the colluvial accumulation. The slopes of the nine experimental plots range from 12 to 21° due to the local influence of rock outcrops on slope morphology.

For all slopes, the lithology is formed by homogeneous limestone (IGME, 1976,1981) and the morphology is characterized by an upper convexity, a straight middle slope, and a concavity at the bottom, where colluvium is accumulating (Calvo, 1987).

At Genovés (slopes a and b), the vegetation is distributed in a patchy mosaic of shrubs, which constitute the typical garrigue or *matorral* vegetation of Southeast Spain,

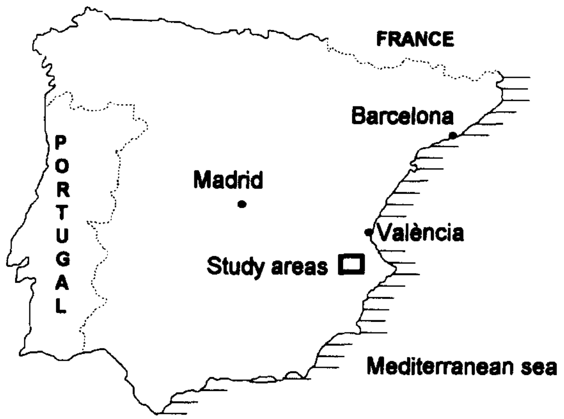

Fig. 1. Location map.

that is widely present in all types of dry scrubland and vegetation on uncultivated calcareous soils in the western part of the Mediterranean basin. Areas between the shrub patches are occupied by perennials (*Thymus vulgaris*, *Globularia alypum*, *Fumana ericoides*, etc.) and annuals (*Brachypodium retusum*). The *matorral* cover has regenerated after the fire and the north facing slope has a high plant cover of around 85–90%,

Fig. 2. View of the Genovés study areas. South-facing slope.

Fig. 3. View of the Canals study areas.

in which the dominant plants are *Quercus coccifera*, *Pistacia lentiscus*, *Rosmarinus officinalis*, *Brachypodium retusum* and *Ulex parviflorus*. On the south facing slope (slope b), the cover is less being around 60–65%. The vegetation here is characterized by *Thymus vulgaris*, *Erica multiflora*, *Chamaerops humilis*, *Rosmarinus officinalis*, *Quercus coccifera*, *Ulex parviflorus*, *Globularia alypum* and *Sedum sediforme* (Fig. 2).

In the Canals area (slope c, burnt in 1989), the vegetation is characterised by an important regeneration of *Ulex parviflorus*, *Rosmarinus officinalis* and *Anthyllis Cystisoides* in the first year after the wildfire, and by regrowth of *Pistacia lentiscus* and *Quercus coccifera* in the second year (Fig. 3). The revegetation process is dominated mainly by seed germination (herbs and swarf shrubs) on the interpatch surfaces and by sprouting on the shrub-patch surfaces. Two years after the fire, some ash is still found concentrated on the foot slope and the vegetation cover has reached 25–30%.

At both areas (9 km apart), the climate is characterized by a dry summer and a wet autumn, winter and spring. The average annual rainfall is 688 mm at the nearest meterological station (Xàtiva), 4.5 kms from both study areas, and October is the wettest month, usually with 20% of the annual rainfall. Before the forest fire, the vegetation was dominated by *Matorral* (*Quercus coccifera* and *Pistacea lentiscus*) and by a wood of *Pinus halepensis*. In the bottom of the valley abandoned terraces were built using large rock fragments, and they were abandoned twenty years ago (Cerdà, 1993a). The vegetation of the abandoned fields is characterized by *Cistus albidus*, *Ulex parviflorus*, *Anthyllis cystisoides*, *Cistus monpeliensis* and *Olea europaea*.

3. Methods

The sites for the rainfall simulation experiments and sampling were selected at middle slope positions. The slopes are here more homogeneous than elsewhere and less affected by intensive human activity.

The rainfall simulation experiments, used to obtain hydrological and erosional parameters, employed a sprinkler rainfall simulator described by Cerdà (1993a,1995). The rain was produced at an intensity of 55 mm h^{-1} over a 1 m^2 area. Runoff was measured from a 0.25 m^2 plot within the target area. The duration of the experiments was 60 minutes and deionised water was used. Discharge from the plots was measured at 1–2 minute intervals and the sediment was collected between five and seven times during the experiment. One sample was taken at the beginning of runoff, one at the end, and three or more in between.

Several authors have studied the frequency and duration of natural rainfall events in this region and they demonstrate that storms similar to the one simulated have a return period of 4–5 years (García Bartual, 1986). The 10 year return period rainfall event with one hour duration in the North of Betic Mountains ranges between 80 to 110 mm (Elías and Ruiz, 1977).

The experimental plots on the recently burnt *north-facing* slope (slope c) at Canals are numbered CN01, CN02 and CN03. In the area burnt ten years previously at Genovés, plots on the ***south-facing*** slope (slope b) are numbered GS01, GS02 and GS03, and the plots on the ***north-facing*** slope (slope a) GN01, GN02 and GN03. At each slope, the first plot (01) was selected to characterise the more stable surface; the second one (02) the average vegetation cover, and the third one (03) represents the least vegetated surface. The criteria for the selection of the second plot (02) include surface cover by vegetation characteristics, rock fragments and other surficial characteristics such as biogenic crusts, plant litter and moss.

Soil samples for determining the moisture content were taken before the experiments at the surface (0–2 cm) and at depths of (4–6 cm) and (10–12 cm). As the experiments were carried out during the summer (1991) the soil moisture content was very low.

The soil water content was measured gravimetrically, and the sediment concentration in the runoff by evaporation. The organic matter content (Walkley–Black method), grain-size distribution (USDA classification), and calcium carbonate content (Bernard calcimetry) for nine soils was also determined. One profile was selected per plot, and sampling at 0–2, 4–6 and 10–12 cm depth was done at each one for measuring aggregate stability.

Aggregate stability tests were performed following a standard treatment that consisted of sieving and selecting the 4–4.8 mm fraction, and then moistening this at pF1 for 24 hours with distilled water. The estimation of aggregate stability by ultrasound (Genrich and Bremner, 1972) has been discussed by North (1976). For the ultrasonic dispersion test a Sanfier 1312 cell destructor (Branson Sonic Power Company, Danbury, Connecticut) was used. The procedure used (UD, Ultrasonic Disruption) involved immersing 10 aggregates (4–4.8 mm) in 40 ml of distilled water, and then subjecting these to the probe output for 10 or 5 seconds with the probe tip placed 10 mm under the water surface and the energy output set was increased from 30 to 115 Watts. After the treatment the surviving aggregates (> 2.8 mm) and the aggregate fragments (< 2.8 mm) were weighed after sieving.

For the water-drop test, a burette nozzle with silicon tubing was used, together with a supply system with a constant head. The drops produced (distilled water) had a weight of 0.1 g. The water-drops were allowed to fall through a polythene pipe (15 cm diameter), from a height of 1 m onto the aggregates placed on a 2.8 mm metal mesh.

The water-drop test is a very old technique and there are many procedures (Low, 1954). The procedure adopted followed that of Imeson and Vis (1984):

1. CND: *Counting the Number of Drop impacts* required to disrupt the aggregate sufficiently for it to pass through the 2.8 mm sieve. In this case the experiment was repeateded for at least twenty aggregates.
2. TDI: Ten Drop Impacts. This consisted of measuring the weight of different aggregate fractions ater 10 drop impacts.

The various fractions are expressed as percentages of the air-dry weight of the tested aggregates. The manner in which the aggregates broke down under this treatment was also recorded (Imeson and Vis, 1984).

4. Results

4.1. Soil characteristics

The main surface characteristics of the plots are shown in Table 1. The plots from the south facing slope (slope b) have an average slope of 13.3° and an orientation of 187°. The plots on the north-facing slope (slope a) are steeper (17°) and the aspect is 346°. The plots selected on the recently burnt slope (c) have a slighty NNW aspect (319°) and the

Table 1
Study areas, plot name, aspect, slope and surface cover distinguishing between mosses, plants and stones

Study slopes	Plot	Aspect (°)	Slope (°)	Moss (%)	Plants (%)	Stones (%)
Slope a						
Genovés	GN01	340	21	10	100	15
North	GN02	351	12	14	80	30
Burnt-10	GN03	346	18	9	22	40
Slope b						
Genovés	GS01	200	10	3	94	12
South	GS02	185	12	5	65	20
Burnt-10	GS03	176	18	0	15	45
Slope c						
Canals	CN01	302	14	5	90	30
North	CN02	356	14	0	25	60
Burnt-2	CN03	300	15	2	10	20

Table 2
Soil characteristics. Organic matter, texture, $CaCO_3$ and water content before the experiments on the south slope (b) of Genovés, burnt 10 years before the measurements

Plot	Depth (cm)	Org. mat. (%)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	Moisture (%)
GS01	0–2	4.65	66.43	20.06	13.51	3.54	3.02
	6–8	1.54	55.04	20.13	24.83	2.65	4.65
	14–16	0.78	49.43	18.99	31.58	2.21	6.43
GS02	0–2	3.94	65.02	21.90	13.08	4.82	2.43
	6–8	1.03	50.19	21.71	28.10	3.21	4.54
	14–16	0.98	55.04	19.16	25.80	3.09	5.67
GS03	0–2	1.42	54.32	23.43	22.25	4.56	1.43
	6–8	0.87	50.58	20.65	28.77	4.32	3.24
	14–16	0.65	49.65	19.16	31.19	2.32	4.30

average slope is 14.3°. The presence of rock outcrops results in a locally high level of variability. Most soil is located in the hollows produced by the dissolution of the limestone. Both with respect to aspect and slope angle, the within site variability is higher than the variability between sites. This is reflected by the sampling strategy of selecting extreme sites: the 01 and 03 plots. The most common site (02) is used for comparing slopes.

The plant and moss cover is higher on average on the north facing slope (a) than on the south (b) or more recently burnt slope (c) (see Table 1). This is obviously as a consequence of the effect of aspect in the first case and on fire in the second. Moss is quite abundant on the north facing slope (a) (11%); it is not found on the recently burnt slope (c) and it is very scarce on the south-facing one (b) (5%). The same trend is found in the plant cover (80% on slope a; 65% on slope b and 25% on slope c). The stone cover is highest on the recently burnt area (37%), and quite similar at the other two sites (26 and 28%).

Laboratory data for the three sites, three plots per site and one profile pit per plot, is summarised in Tables 2–4. The soil organic matter content shows a decrease with depth on slope a and b, both of them burnt ten years ago. At the recently burnt site, there is little difference between the uppermost horizons, presumably because the organic surface horizons with the highest organic matter content were lost in the fire, although the differences are vague. The calcium carbonate content is very low at all sites, everywhere being less than 6%. There is no concentration of carbonates on the surface, not even in the crusts.

The mechanical composition of all of the soils is characterised by a high percentage of sand, particularly at Canals, although the differences are small. And by a clay content which increases with the depth. The clay content is sometimes very high, reaching a maximum of 47% on the north-facing slope (a).

The high spatial variability at each study area is due to the patchy distribution of plants and the influence of vegetation on soil properties.

Table 3
Soil characteristics. Organic matter, texture, $CaCO_3$ and water content before the experiments on the north slope (a) of Genovés, burnt 10 years before the measurements

Plot	Depth (cm)	Org. mat. (%)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	Moisture (%)
GN01	0–2	8.14	63.45	20.91	15.64	3.02	4.54
	6–8	3.21	50.70	21.43	27.87	2.43	6.54
	14–16	1.23	29.76	22.43	47.81	2.30	8.65
GN02	0–2	6.78	54.55	26.54	18.91	3.20	3.21
	6–8	0.97	45.44	23.24	31.32	3.20	4.56
	14–16	2.10	57.33	17.12	25.55	2.12	6.87
GN03	0–2	4.32	60.32	24.21	15.47	3.24	1.14
	6–8	1.20	51.43	20.23	28.34	2.54	3.43
	14–16	0.67	53.21	20.32	26.47	1.23	5.65

4.2. Rainfall simulation experiments: hydrological response

A summary of the results of the rainfall simulation experiments is shown in Table 5. The time to ponding (t_p, min), time to runoff (t_q, min) average runoff (Q_m, mm h^{-1}) and runoff coefficient (k) are shown separately for each plot at the three sites. The value t_q indicates the time after the start of rainfall that surface water was observed to begin moving on the plot. The parameter t_Q (min) is the time at which runoff was first collected leaving the plot. Q_{end} (min) is the duration of after flow; that is the number of minutes runoff was recorded after the rainfall simulator was turned off. The final infiltration rate (f_{end}) is the average infiltration during the last five minutes of the experiment. The results of the individual experiments show the high spatial variability as mentioned above for the soil chemical and physical properties (Tables 2–4).

Table 4
Soil characteristics. Organic matter, texture, $CaCO_3$ and water content before the experiments on the north slope (c) of Canals, burnt 2 years before the measurements

Plot	Depth (cm)	Org. Mat. (%)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	Moisture (%)
CN01	0–2	6.65	70.32	15.03	14.65	2.43	2.34
	6–8	4.34	73.85	7.65	18.50	2.54	4.32
	14–16	2.43	75.43	7.03	17.54	3.21	5.43
CN02	0–2	4.87	69.32	14.23	16.45	5.32	2.10
	6–8	2.13	56.56	13.54	29.90	2.10	2.78
	14–16	1.23	54.64	14.76	30.60	2.09	4.65
CN03	0–2	2.01	54.24	20.32	25.44	5.32	0.99
	6–8	2.32	56.25	15.87	27.88	4.60	2.12
	14–16	1.02	58.98	18.54	22.48	2.80	4.02

Table 5
Hydrological response. Time to ponding (t_p), time to surface runoff (t_q), time to plot runoff contribution (t_Q), time to the end of runoff after the end of the rainfall (Q_{end}), average runoff (Q_m), runoff coefficient (K) and steady state infiltration capacity (f_{end}). Ponding and runoff times in minutes. Average runoff and infiltration rates in mm h^{-1} (WR = without runoff)

Study slopes	Plot	t_p (min)	t_q (min)	t_Q (min)	Q_{end} (min)	Q_m (mm h^{-1})	K (min^{-1})	f_{end} (mm h^{-1})
Slope b								
South	GS01	8.43	14.54	21.02	0.3	3.39	0.04	50.28
Genovés	GS02	5.87	9.14	14.35	1.03	7.87	0.11	42.30
Burnt-10	GS03	2.43	3.5	5.3	1.43	21.20	0.35	25.63
Slope a								
North	GN01	WR	WR	WR	WR	0.00	0.00	> 55
Genovés	GN02	12.43	20.32	28.05	0.15	2.81	0.03	50.32
Burnt-10	GN03	5.43	9.32	14	0.45	14.89	0.21	30.61
Slope c								
North	CN01	13	17.45	21.3	1.4	3.69	0.04	49.41
Canals	CN02	1.5	3	4.55	1.2	27.64	0.46	18.31
Burnt-2	CN03	1.3	2.3	3.25	2.3	36.67	0.63	14.95

The recently burnt soils (c) has a t_p that is shorter that at the other areas except for one run (CN01) where the grass *Brachypodium retusum* was prevalent and where ash was still present. The t_p is shorter on the south-facing slope than on the north-facing one.

With respect to t_Q and t_q, on average, the soils of the burnt slope (c) produce surface runoff first, followed by the south (b) and north-facing slope (a). The values of Q_m and k indicate differences between slopes, and emphasize the effect of the large variability in site condition due to the distribution of the shrubs.

The value of Q_{end} indicates that the duration of the after flow is short when the volume of the runoff is low, due to the effect of storage. The duration and volume of afterflow is higher for the burnt soils (c) followed by the south (b) and north facing slope (a) respectively. The recently burnt soils also have lower infiltration capacities.

Even though the variability at each area is very high, both the average values, and the value of the most representative plot (02 at all cases) show clear differences between the sites. At the soils having a postfire recovery time of ten years, infitration is always very high. The influence of aspect is in this case small. On the north-facing slope 92% (97% for the plot GN02) of the rain was infiltrated, compared to 88% on the south-facing slope. On the burnt slope, the infiltration rate is still low two years after the fire amounting to only 62% of the rainfall (54% for the plot CN02). The extremes also show clear trends: north-facing (a), south-facing (b) and burnt (c) slopes have in this order the maximum, medium and minimum infiltration rate.

The sediment concentrations measured in the runoff were used to calculate sediment discharges. The total weight of sediment eroded and transported from the plot during the experiment is reported as the sediment yield in Table 6. The average rate of erosion

Table 6
Erosional response. y_S, sediment yield (g), c_S, sediment concentration (g l^{-1}) and r_E, erosion rates (g m^2 h^{-1})

Study slopes	Plot	y_S (g)	c_S (g l^{-1})	r_E (g m^2 h^{-1})
Slope b				
South	GS01	0.39	0.68	1.49
Genovés	GS02	0.96	0.69	4.10
Burnt-10	GS03	5.80	1.32	25.41
Slope a				
North	GN01	0.00	0.00	0.00
Genovés	GN02	0.32	0.81	1.21
Burnt-10	GN03	2.26	0.87	9.91
Slope c				
North	CN01	0.90	1.63	3.87
Canals	CN02	61.32	10.38	263.34
Burnt-2	CN03	79.70	10.84	375.05

(g m^{-2} h^{-1}) and the runoff sediment concentration (g l^{-1}) are also given. The differences are extremely large with values at the burnt sites (c) being several hundred times higher than at the other sites, except for the special case of CN01, with the higher grass cover mentioned above.

The sediment concentration in the runoff is more than seven times higher at the burnt site (c) than elsewhere. The differences between the north and south facing slopes are not very large (0.56 g l^{-1} in the north and 0.89 g l^{-1} in the south) when compared with the soils on the burnt slope. The large differences in erosion rates between the burnt and other sites are due both to the higher runoff volumes and the higher sediment concentrations.

The south-facing slope (b) has erosion rates three times higher than the north-facing slope, mostly due to the higher runoff rates.

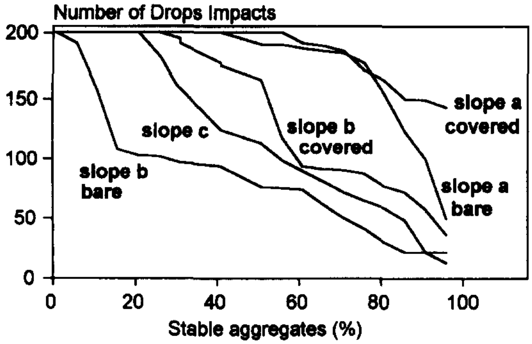

Fig. 4. Water-drop test (CND) at different slopes. North slope burnt two years (slope c) and South and North slope burnt ten years before the experiments (slope b and a, respectively) distinguishing between the shrub (covered) and inter-shrub (bare) locations.

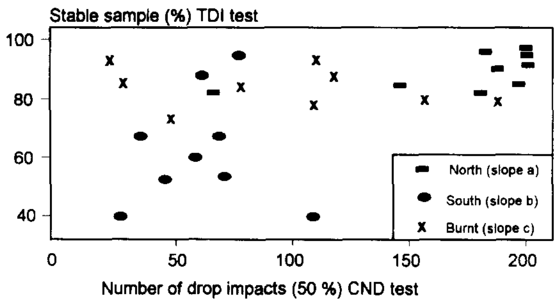

Fig. 5. Relationship between CND and TDI tests comparing the number of drops necessary to broke 50% of the aggregates (CND) and the amount of stable sample (TDI) at the different situations.

4.3. Aggregate stability

The aggregate stability determinations for top soil samples are shown in Figs. 4–7. For soils located in the interpatch areas, the water drop test results (Fig. 4) indicate clear differences. South-facing slope (slope b) has the most erodible aggregates, followed by the burnt slope (slope c) and north-facing slope (slope a).

With respect to soils from beneath plants at the slopes burnt ten years prior to the fire (slopes a and b covered) refer to sites colonised by *Quercus coccifera* and *Pistacia lentiscus*. The other samples are from bare soils or beneath a cover of *Brachypodium retusum* and other herbs or swarf shrubs *like Thymus vulgaris* or *Globularia Alypum* (slopes a and b bare). Of these aggregates, those from the soil with the shrub type of vegetation are much more stable. It can be seen that, the type of vegetation is as important with respect to aggregate stability as the location on a north or south facing slope, or the effect of fire.

The TDI method of the water drop test showed that all of the samples were quite stable, the aggregates surviving the treatment ranging from 81.4% on the south facing slope to 96.5% on the north facing *matorral* (shrubland) covered slope. The burnt soil

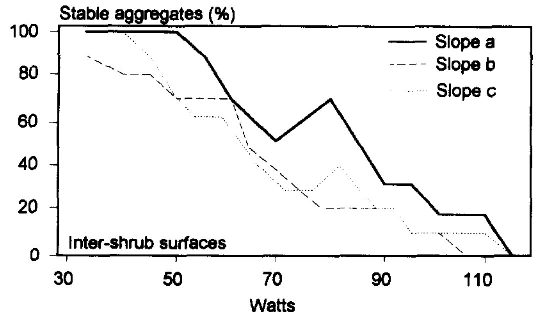

Fig. 6. Ultrasonic disruption test (UD) at the bare areas (interpatch surfaces) on different slopes. North and South slopes burnt ten years before the experiments, and Burnt slope, burnt 2 years before the experiments. Test performed during five seconds.

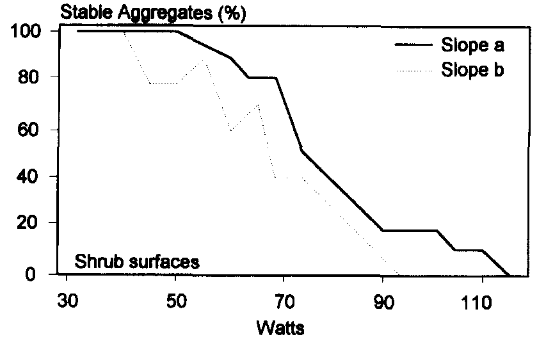

Fig. 7. Ultrasonic disruption test (UD) at the vegetated patches of *Matorral* on the north and south slopes. Both of them burnt 10 years before the experiments. Test performed during five seconds.

had an intermediate value of 90.4%. The relationship between TDI and CND show that the less stable soils are located on the south-facing slope (b), the more stable aggregates on the north-facing slope (a) and in an intermediate position the recently burnt slope (c) (Fig. 5).

The results of the ultrasonic dispersion test (Figs. 6 and 7) illustrate several characteristics of the different soils. A threshold energy of 55 Watts was needed before the aggregates on the north facing slope were destroyed. This compares to 45 Watts on the burnt slope and 30 Watts on the south facing slope. The trend is similar to that in water drop test results. The cumulative graph for the south facing slope (Fig. 6) indicates that the aggregates have a wide range of stabilities. The results are not only determined by the strength of the organic matter-clay material bonds that have to be broken but also by the calcium carbonate cementation. On the south and the burnt slope, the results are rather similar for energy levels above 55 Watts.

In conclusion, the results of the aggregate stability tests all indicate that the soils from the north-facing slope are more stable than those from the south-facing one. Furthermore, soils under matorral are more stable that the soils from the interpatch areas covered by herbs and dwarf shrubs (Fig. 7).

5. Discussion

There are several factors that make fires important as a hydrogeomorphological agent in Mediterranean ecosystems. One factor is the high fire frequency and consequently the length of time that an area has its soil surface exposed to direct radiation (higher temperatures) and rainfall, thus allowing erosion and runoff processes to be more active (Calvo and Cerdà, 1994). Furthermore, the rainy season occurs immediately after the fire season, during which rainfall intensities are extremely high (Sala and Rubio, 1994).

The results of the experiments described above enable some conclusions to be drawn on the recovery of burnt soils on north and south facing slopes, 10 years after a fire. Also the differences between north-facing slopes burnt 2 and 10 years ago provide some indication of the rate at which this recovery takes place, both for the vegetation and soil erodibility characteristics.

It is clear from the data, that the recently burnt soil on the north facing slope (c) has a relatively low aggregate stability and low vegetation and litter cover, which results in surface crusting in the bare surfaces. This results in low infiltration rates, a rapid runoff production and very high erosion rates. These findings confirm the negative relationship between aggregate stability and soil erosion and hydrology that have been found by different authors (Basak, 1972; Egashira et al., 1983; Farres, 1987; Cerdà, 1993b).

The south facing slope (burnt ten years before, slope b) has an even lower aggregate stability but the infiltration capacity is higher than in the burnt area. This is due to the higher vegetation cover, which favour macropore fluxes and higher soil hydraulic conductivity (Cerdà, 1993a). The rate of erosion, although very low compared to the burnt slope, is nevertheless considerably higher than on the north facing slope due to the vegetation cover. On this north facing slope burnt ten years before the experiments, the runoff and erosion produced by the rainfall simulation experiments was extremely low. Runoff can not be generated by Horton overland flow because of the very high infiltration rates (Horton, 1940), and if runoff does occur this will be by saturated overland flow (Betson, 1964). Immediately after the fire, Horton overland flow could possibly occur (Calvo and Cerdà, 1994; Soto et al., 1994).

The importance of soil surface sealing by raindrop impact can be seen at Canals (slope burnt two years previously). The low calcium carbonate contents at the surface point to a physical or biological origin of the crusts. Differences in the soil organic matter are pronounced. The surface horizons of the south facing slope plots have a lower organic matter content than those on the north facing slope. The burnt soils have organic matter contents intermediate between those at the other sites (Tables 2–4).

At all three sites the vegetation cover and its pattern play an important role. On the burnt site vegetation is sparse or absent so that runoff is produced almost immediately after the start of the rainfall. On south facing slopes, the high spatial variability means that any runoff from poorly covered areas infiltrates under shrubs. On the north facing slopes infiltration rates are so high almost everywhere that runoff is very low.

Comparable differences between soils on south and north facing slopes in Catalonia have been described elsewhere in an area where forest fires are frequent (Imeson et al., 1992). Also it was found that the effects of fire were far greater on nutrient poor soils derived from granodiorite than on more nutrient rich materials, possibly also due to the low rate of forest regeneration (Sevink, 1988). But in general, the soil aggregate stability after the forest fire is the complex result of many processes in which cementing agents, fire temperature and organic matter play an important role (Giovannini and Lucchesi, 1983; Sanroque et al., 1985; Giovannini et al., 1988; Ubeda et al., 1990; Imeson et al., 1992).

The relations between fire and aspect described in this study demonstrate that both need to be considered together in terms of their effect on erosion (see the scheme of the Fig. 8). Differences between soil aggregate stability on north and south facing slopes with the same fire history are greater than between two north slopes burnt ten and two years before the measurements. Obviously, aggregate stability is affected by the fire (Cerdà, 1993b), but aspect has a greater effect on this soil characteristic. The recently

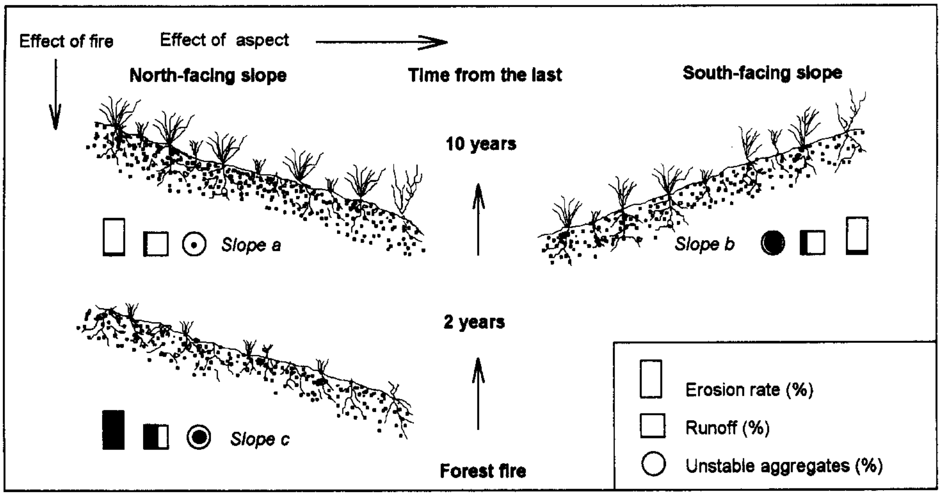

Fig. 8. Scheme of the effect of aspect and fire on the erosion rate, runoff and the amount of breakeable aggregates.

burnt slope is the more erodible because of lower infiltration rates and the low vegetation and litter cover. Crust formation is an important factor as in other semiarid environments (Morin et al., 1989).

According to the results, fire provokes an increase in water and soil loss, and a decrease in aggregate stability, although the second is not as important as the first. Aspect favour soils with less stable aggregates and lower infiltration rates, although the quality of the aggregation is more affected than in the recently burnt soils.

The results indicate that individual forest fires do no produce a persistent degradation of the ecosystem, but higher soil and water losses for a few years following the fire. On the south-facing slope, where post-fire revegetation rates are lower, soil aggregates are less stable and the water stress is higher. Perhaps there are long term effects.

An important consideration is that normally under Mediterranean conditions, burnt areas except on south-facing slopes, are soon covered by vegetation as it quickly regenerates after fire (Cerdà, 1995). Only south-facing slopes can have surfaces still free of vegetation or with a low shrub cover ten years after the fire. Nevertheless, the degradation and erosion of north facing slopes can still occur if there is a high fire frequency because these slopes are then also free of a vegetation cover for a longer period of time. Regenerating vegetation on north facing slopes relatively quickly covers the surface, although the first years after the fire show high soil and water losses.

6. Conclusion

Runoff, erosion and infiltration are greatly affect by fire. Aggregate stability is a synthetic ecological parameter that is affected by different factors, some of which are related to aspect. Forest fires provoke a slight immediate reduction on the aggregation strength. Long term differences related to aspect are more significant.

The clear influence of fire and aspect on soil hydrology is one of the main conclusions of this study. Another is the rapid regeneration of the soil, particularly where there is a vegetation cover. Probably, often recurring fire can provoke long-term degradation of the soil and lead to a definitive reduction in infiltration rates and a lower ecosystem productivity.

The high diversity of Mediterranean ecosystems means that the spatial variability of soil characteristics at one particular slope can be almost as large as it is when different slopes are compared. Nevertheless, average values show a slight reduction of the aggregate stability and an increase in runoff and soil loss after fire. On the contrary, south aspects favour a slight increase on runoff and soil loss in comparison with the low aggregate stability that was measured there.

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References

Basak, P., 1972. Soil structure and its effects on hydraulic conductivity. Soil Sci., 114(6): 417–423.

Betson, R.P., 1964. What is watershed runoff? J. Geophys. Res., 69(8): 1541–1551.

Calvo, A., 1987. Geomorfología de laderas en la montaña del País Valenciano. I.V.E.I., Col. Politécnica, Valencia, 301 pp.

Calvo, A. and Cerdà, A., 1994. An example of the changes in the hydrological and erosional response of soil after a forest fire, Pedralba (Valencia) Spain. In: M. Sala and J.L. Rubio (Editors), Soil Erosion as a Consequence of Forest Fires. Ediciones Geoforma, Logroño, pp. 99–110.

Cerdà, A., 1993a. La infiltración en los suelos del País Valenciano. Factores y variaciones espacio–temporales. Unpublished Ph.D. Thesis, Universitat de València, 357 pp. + appendix.

Cerdà, A., 1993b. Incendios forestales y estabilidad de agregados. Cuad. Geogr., 53: 1–16.

Cerdà, A., 1995. Factores y Variaciones Espacio–Temporales de la Infiltración en los Ecosistemas Mediterráneos. Geoforma Ediciones, Logroño, 151 pp.

Churchill, R.R., 1982. Aspect-induced differences in hillslopes processes. Earth Surf. Process. Landforms, 7: 171–182.

Egashira, K., Kaetzu, Y. and Takuma, K., 1983. Aggregate stability as an index of erodibility of Ando soils. Soil Sci. Plant Nutr., 29(4): 473–481.

Elías, J. and Ruiz, L., 1977. Precipitationes Máximas en España. Ministerio de Agricultura, Madrid, 545 pp.

Fantechi, R. and Margaris, N.S., 1986. Desertification in Europe. Commission of the European Communities, Reidel, Dordrecht.

Farres, P.J., 1987. The dynamics of rainsplash erosion and the role of soil aggregate stability. Catena, 14: 119–130.

García Bartual, R., 1986. Estructura estocástica de los hietogramas correspondientes a precipitaciones extremas. Proyecto final de carrera, Universidad Politécnica de Valéncia, 252 pp.

Genrich, D.A. and Bremner, J.M., 1972. A reevaluation of the Ultrasonic-Vibration method of dispersing soils. Soil Sci. Soc. Am. Proc., 36: 944–947.

Giovannini, G. and Lucchesi, S., 1983. Effect of fire on hydrophobic and cementing substances of soil aggregates. Soil Sci., 136: 231–236.

Giovannini, G., Lucchesi, S. and Giachetti, M., 1988. Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Sci., 143: 220–226.

Horton, R.E., 1940. An approach toward a physical interpretation of infiltration capacity. Proc. Soil Sci. Soc. Am., 5: 399–417.

IGME, 1976. Mapa Geológico de España (E: 1/50.000). CANALS (Hoja 794).

IGME, 1981. Mapa Geológico de España (E: 1/50.000). JATIVA (Hoja 795).

Imeson, A.C. and Vis, M., 1984. Assessing soil aggregate stability by water-drop impact and ultrasonic dispersion. Geoderma, 34: 185–200.

Imeson, A.C., Verstraten, J.M., Van Mulligen, E.J. and Sevink, J., 1992. The effect of fire and water repellency on infiltration and runoff under Mediterranean type forest. Catena, 19: 345–361.

Low, A.J., 1954. The study of soil structure in the field and the laboratory. J. Soil Sci., 5(1): 57–75.

Morin, J., Keren, R., Benyamini, Y., Ben-Hur, M. and Shainberg, I., 1989. Water infiltration as affected by soil crust and moisture profile. Soil Sci., 148(1): 53–59.

Naveh, Z., 1990. Fire in the Mediterranean — a landscape ecological perspective. In: J.G. Goldammer and M.J. Jenkins (Editors), Fire in Ecosystems Dynamics. Mediterranean and Northern Perspective. SPB Academic Publishing, The Hague, pp. 1–20.

North, P.F., 1976. Towards an absolute measurement of soil structural stability using ultrasound. J. Soil Sci., 27: 451–459.

Sala, M. and Rubio, J.L. (Editors), 1994. Soil Erosion as a Consequence of Forest Fires. Ediciones Geoforma, Logroño, 275 pp.

Sanroque, P., Rubio, J.L. and Mansanet, J., 1985. Efectos de los incendios forestales en las propiedades del suelo en la composición florística y en la erosión hídrica de las zonas forestales de Valencia (España). Rev. Ecol. Biol. Sol., 22: 131–147.

Sevink, J., 1988. Soil organic horizons of Mediterranean Forest soils in NE-Catalonia (Spain): their characteristics and significance for hillslope runoff and effects of management and fire. Catena Suppl., 12: 31–45.

Soto, B., Basanta, R., Benito, E., Pérez, R. and Díaz-Fierros, F., 1994. Runoff and erosion from burnt soils in Northwest Spain. In: M. Sala and J.L. Rubio (Editors), Soil Erosion as a Consequence of Forest Fires. Ediciones Geoforma, Logroño, pp. 91–98.

Ubeda, X., Sala, M. and Imeson, A.C., 1990. Variaciones en la estabilidad y consistencia de un suelo forestal antes y despues de ser sometido a un incendio. In: Proceedings of the 1st Reunión Nacional de Geomorfología, Teruel, pp. 677–685.

Westman, W.E., 1986. Resilience, concepts and measures. In: B. Dell, A.J.M. Hopkins and B.B. Lamont (Editors), Resilience in Mediterranean Types Ecosystems. Dr. W. Junk Publishers, Dordrecht, pp. 5–19.