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The evolution and significance of soil–vegetation patterns following land abandonment and fire in Spain

L.H. Cammeraat *, A.C. Imeson

Landscape and Environmental Research Group, University of Amsterdam, Nieuwe Pinsengracht 130, 1018 VZ Amsterdam, Netherlands

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Abstract

Examples are presented from two locations in SE and NE Spain where patterned or banded vegetation are found on semi-natural and abandoned land or where vegetation is recovering from wildfire. In both cases patterns are being investigated as process-pattern phenomena with the aim of understanding how different kinds of environmental gradients influence pattern evolution. On abandoned land, patterns occur at different scales. At the patch scale there are areas where *Plantago albicans* germinates in cracks and influences the accumulation of silty material. At the slope scale these form elongated steps that create a characteristic micro-topography. At the patch and slope scale *Stipa tenacissima* tussocks form an hexagonal pattern on level areas where water infiltrates in and around the tussocks. On sloping areas the *S. tenacissima* tussocks form parallel ovoid bands. They intercept fine and coarse material being eroded on the slopes by both overland flow and the hooves of sheep and goats. This also creates a distinctive micro-topography. Rainfall simulation experiments were undertaken in combination with monitoring activities in order to investigate the effects that key-processes of sediment and water movement have on the patterns. Other methods include controlled experiments and modelling. Biologically driven erosion processes are very important as key processes. Positive feedback mechanisms are important at various stages in the evolution of the pattern. The patterns studied play an important role in creating more favourable micro-environments where vegetation recovers first after disturbances. This is particularly the case following wildfire. The first post-fire rain produces patterns in ash and litter around sites, concentrating these at locations where shrubby vegetation subsequently resprouts or becomes

* Corresponding author

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seeded. On abandoned land, the evolution of patterns reflects the parent material, grazing and the climate.

Keywords: Vegetation patterns; Runoff; Upscaling; Land degradation; Water repellency

1. Introduction

In Mediterranean areas semi-natural vegetation is often structured in a spotted or banded spatial configuration and these patterns are of importance for understanding runoff and erosion processes. The interaction between vegetation development, soil surface properties and water movement must be responsible for the patterns observed. The patterns found resemble features described for semi-arid regions such as in Australia (Tongway and Hindley, 1995), the Sahel zone of Africa (Thiéry et al., 1995), and the western USA (Pierson et al., 1994). Most of such patterns indicate a very sensitive relationship between the amount of available water and the vegetation. This invariably reflects positive feedback mechanisms between water movement and the vegetation (Imeson et al., 1995; Tongway and Hindley, 1995). The spatial patterning of the vegetation can used as an expression of soil properties important for water reallocation in and over the soil.

Under the plants often higher organic matter contents are found, favouring soil aggregation and soil faunal activity, both increasing macroporosity. A special micro-climate is present under plants and vegetated zones, with much smaller temperature amplitudes, more shading and often better soil moisture conditions than for bare soil conditions. This results in higher infiltration rates under the plants (runoff absorption) and lower infiltration rates on bare crusted soil surface (runoff generating areas). In water limited geo-ecological zones, such as the sub-humid and semi-arid Mediterranean areas, the spatial configuration of vegetated and bare areas is therefore very important and often indicates the spatial distribution of higher infiltration rates (Morin and Kosovsky, 1995).

Understanding the positive feed-back mechanisms that link water and vegetation has been an aim of recent research in Central and SE Spain undertaken on the context land degradation research (Imeson et al., 1995, 1996a; Bergkamp, 1996). This research has emphasised the importance of scale dependent linkages and has followed an hierarchical approach whereby processes at the fine scale are seen as important driving forces at the next hillslope level. Processes at this level operate under the constraints of the next higher level of scale (O'Neill et al., 1986). This means that the upscaling of small plots results, using for instance infiltration rates, cannot be done unless the spatial configuring of soil–plant phenomena is incorporated.

Land degradation and erosion processes are perceived to be important problems in many Mediterranean and semi-arid areas (Fantechi and Margaris, 1986; Thornes, 1995). In the northern Mediterranean much effort has been made to understand the effects of land use change and practices, fire and climatic change on land degradation. One of the most important aspects of this problem concerns the resilience of perturbed systems. The objective of this paper is to illustrate the potential significance of patterns in promoting the resilience, stability and inertia of landscape systems subject to various stresses. One example is from a semi-arid area in SE Spain where matorral vegetation was taken into cultivation during the 1960s and subsequently abandoned in 1983. Under conditions of drought and grazing pressure, different process-pattern features have evolved at different scales when the area was colonised by vegetation. The second example from NE Spain describes the infiltration patterns that exist in forested areas and how, following fire, these and other patterns emerge to concentrate water resources for seedlings and resprouting trees. It is suggested that process-pattern phenomena can be used as indicators of ecosystem functioning.

2. The study areas

2.1. The Cañada Cazorla / Maestra Oliva site in SE Spain

The field location in SE Spain is located in the upper Guadalentín basin (Fig. 1) (37°50′00″NL; 1°48′40″WL). It is situated in the driest part of Europe, and has a semi-arid climate with an average precipitation of 277 mm yr^{-1} (Embalse de Puentes, 1951–1980). Precipitation falls mainly in autumn and spring and there is a high inter-annual variability. Average temperatures in the region range between 9.3 (January) and 26.0°C (July/August) with an average annual temperature of 16.8°C (Navarro-

Fig. 1. Location map indicating both research areas in Spain.

Hervás, 1991). The investigated site constitutes one of seven reference locations of the MEDALUS Project in the Upper Guadalentín region (MEDALUS, 1996; Imeson et al., 1996b). The field area has a flat to gentle rolling topography and is part of an almost flat planation surface, developed in horizontally bedded Pliocene marls, conglomerates and limestones. It consists of a plateau bounded in all directions by concave slopes on which erosion processes are active. On the lower gently sloping areas calcareous marls of Upper Cretaceous–Lower Tertiary age (I.G.M.E., 1981) are found. The large variation in soil types reflects a combination of lithological differences, topographic position and aspect. Some characteristics of the most frequently occurring soils are shown in Table 1.

The soils, with a silt loam texture, are shallow and highly calcareous with low to very low organic matter contents, depending on the vegetation cover. Under the plants, in semi-natural conditions, organic carbon levels are higher and soil aggregation is better. The bare areas between the plants are crusted and the soil aggregation is very weak. Both structural and depositional crusts are found (Valentin and Bresson, 1992), whereas under the plants the soil surface is more open due to soil aggregation and soil animal activity, permitting higher infiltration rates. Some aspects of microbial biomass and aggregate stability in relation to surface cover type or land use are discussed in Cerdà et al. (1994, 1995) and in Cammeraat and Imeson (1998).

Land use varies throughout the area and has changed considerably over the last 40 years. Only 37% of the land use is the same today (1995) as in 1957, as interpreted from aerial photography analysis. On the plateau, open semi-natural *Stipa tenacissima* L. (Esparto grass) matorral occurs as well as fallow agricultural lands, the latter being used for rain-fed cereal production. The steep upper and middle hillslopes are covered with open *S. tenacissima* matorral. The lower hillslope was abandoned in 1983 and shows bare and strongly crusted soils alternating with bands of *Plantago albicans*. However, one small area under *S. tenacissima* still remains on the foot slope. The valley bottom itself is still under cultivation, for growing rain fed cereals, and was tilled just before sampling. The talweg is terraced to reduce gully development and for water harvesting.

2.2. The Vilobí d'Onyar site in NE Spain

The field area is located in the Selva region near the village of Vilobí d'Onyar in the south of the Gerona Province, Catalonia (41°53′02″NL; 2°44′30″EL), which has a sub-humid Mediterranean climate receiving between 700 and 800 mm of rainfall and which is covered by extensive Mediterranean oak forests. It is located on sandy and gravely Pleistocene and Pliocene fan deposits that occupy a large roughly north–south running graben that separates two major parallel mountain ranges, with mainly acid igneous and metamorphic rocks. The mean summer and winter temperatures range from about 24°C in the summer to 8°C in the winter. Most of the precipitation falls in the spring and autumn. The research site forms one of the reference locations established to investigate relationships between soil characteristics, hydrology and forest fires (Sevink et al., 1989; Imeson et al., 1992). The morphology of the field site, located on a fan which slopes gently eastward, is rather simple reflecting the incision by shallow but rather steep sided valleys that also drain eastward. The maximum altitude difference is about 15 m. Basic information on soils and land use is given in Table 2. The soils at non

Table 1
Main surface characteristics of the soils of the Cañada Cazorla site

Position	Slope (°)	Soil type after F.A.O. (1989)	Horizon	Depth (cm)	Land use	Texture			Org. C (%)	$CaCO_3$ (%)
						Sand, %	Silt, %	Clay,%		
Plateau	0–1	Petric Calcisol	(crust)	0–3	Semi-nat.(St)	26.6	60.1	13.4	2.3	53.9
			(Ah)	3–18		27.0	68.0	5.0	2.9	59.7
Plateau	0–1	Petric Calcisol	(crust)	0–2	Fallow (C)	27.6	67.8	4.6	3.4	53.4
			(Ap1)	2–19		34.4	60.9	4.7	3.2	53.7
Upslope	12–25	Eutric Leptosol	(crust)	0–3	Semi-nat.(St)	36.7	51.7	11.0	1.8	78.4
			(Ah)	3–12		21.1	62.7	16.2	1.8	78.5
Mid slope	12–3	Eutric Leptosol	(crust)	0–3	Semi-nat.(St)	38.4	52.6	7.9	1.6	71.2
			(Ah)	3–9		32.4	55.2	10.3	2.0	68.8
Downslope	6–3	Haplic Calcisol	(crust)	0–2	Abandoned (Pl)	26.5	66.6	6.5	2.1	64.4
			(Ap1)	4–21		23.3	68.4	6.2	1.8	64.4
			(Bw)	21– > 40		14.9	64.5	9.6	1.2	52.6
Valley	3–0	Calcaric Regosol	(Ap1)	0–20	Fallow (C)	19.6	65.4	14.5	1.4	61.1
			(Ap2)	20–40		13.3	66.6	17.2	0.7	40.7

St: *S. tenacissima* dominated; Pl: *P. albicans* dominated; C: Rain fed cereals.

Table 2
Main characteristics of the soils in the Vilobí d'Onyar region

Horizon	Depth (cm)	pH-$CaCl_2$	Org. C (%)	Sand (%)	Silt (%)	Clay (%)
Ah	0–5	4.8	2.4	61	29	10
E	5–20	4.5	0.4	60	32	8
Bt1	20–70	5.0	0.5	25	31	44
Bt2	70–120	5.4	0.2	32	33	35
BC	120–170	6.2	0	52	28	20

Slope segment soil surface characteristics

Position	Slope (°)	Soil surface type	Land-use	Vegetation	Cover (%)
Footslope	5	colluvium	burned	*Cistus* sp.	> 25
Midslope	30	Bt horizon	burned	no cover	0
Plateau	3	E horizon	burned	*Cistus* sp.	
Upperslope	20	E horizon	burned	*Cistus* sp.	5

Soil profile characteristics (Albic Luvisol) after F.A.O. (1989).

eroded sites at the top of the fan consist of albic luvisols characterised by a strong texture contrast at the base of the albic horizon. On the slopes the underlying Bt and BC horizons are exposed on the surface according to the local incision and erosion. In most places a Bt horizon is only covered by a thin remnant of the E horizon. Large contrasts in the soil structure and hydrology occur according to the truncation. When the Bt horizon is exposed it is frequently subjected to rill erosion. The lower slope positions are characterised by accumulations of colluvium which was in places more than a metre deep. The field site was almost completely burnt in the summer of 1986, a small part of the forest being protected by a road. The forest is characterised by *Quercus suber*, *Arbutus unedo* and *Erica arborea*, as well as by pines that could not be identified after the fire. From 1987 until 1993, field investigations were undertaken to study the post fire evolution of infiltration and runoff patterns in relation to the recovery of the vegetation.

3. Methods

Soil description and classification were carried out following the guidelines for soil description (F.A.O., 1977; F.A.O., 1989). Laboratory analysis was carried out on samples taken from the soil of beneath the plant canopies and between the plants. Both the soil crust (if present), and the upper soil horizons were sampled, as described in Tables 1 and 2. Chemical analysis was carried out to determine pH, $CaCO_3$ (dissolution in HCl) and Organic Carbon (Allison method) using standard analytical techniques. Textural analysis was carried out by standard sieving procedure for the sand fractions and with a X-ray particle sizer (Microscan II) for the fractions smaller than 63 μm for the Guadalentín samples and with the pipette method for the other samples. Due to the very high $CaCO_3$ contents of the samples from the Guadalentín these were not decalcified before laboratory analysis. Rainfall simulations were carried out at two scales: At the 0.5 m^2 plot scale, a portable dripping plate simulator (Bowyer-Bower and Burt, 1989) was used to apply three rainfall intensities. At the intermediate scale a large sprinkling rainfall simulator was used, covering 5×2.5 m^2 (SE Spain) or 10×2.5 m^2 (NE Spain). The experiments in SE Spain were designed in the following way: a rainfall intensity of 40 mm h^{-1} was applied for all experiments. An experiment of 2 days consisted of 5 consecutive storms, the first three of 10 min evenly spread over the first day of the experiment, and on the second day a storm of 10 min, after 1 h followed by a final storm of 30 min duration. In all cases demineralised water was used to prevent problems related to flocculation of suspended material and swelling of the topsoil, as these soils are very susceptible to dispersion. Time to ponding and overland flow was visually determined. Runoff was sampled at regular intervals and sediment load was determined by drying the runoff samples. The wetting front was studied by excavating a soil profile over 2 m width, after the experiments. The depth and lateral extension of the wetting front was recorded with measurement tapes and plotted on paper. Vegetation cover and structure were mapped in the field by using a grid counting method for small areas (< 1 m^2). Vegetation patterns on the hillslope scale were mapped at a scale of 1:100 or 1:50 using a grid system over 30 m length. Mapping also allowed for the identification of runoff, erosion, and deposition areas and patterns at the hillslope scale.

4. Results and analysis

4.1. Patterned phenomena in SE Spain

The plateau soil surface is flat and soil depth is delimited by a massive layered petrocalcic horizon to 18 cm depth. The soil surface under the *S. tenacissima* tussocks is slightly higher than the surrounding bare places and the soil surfaces can be distinguished into three main zones. The central zone of the living *S. tenacissima* tussock, has high porosity, high biological activity and an active root system. This part of the plant transmitted large amounts of rainfall directly to the soil via stem flow and root flow. After 10 min of rain at 40 mm h^{-1} (6.8 mm of rainfall) the wetting front protruded about 5–8 cm around the central rooting system into the soil matrix. The plant tussock is surrounded by a zone with some plant debris water repellent in nature, cryptogamic crusts and worm casts which are often colonised with lichen. This zone is overshadowed by dead standing litter at the sides of the *S. tenacissima* tussock with very high interception and storage capacities. Around this zone, a bare strongly crusted area with small embedded rock fragments is found. The 0.5–1 cm thick crust is underlain by a powdery layer, about 3 cm thick, with no soil structure at all. During rainfall simulations (intensity 40 mm h^{-1}) it was observed that the bare central areas were completely ponded and no overland flow occurred over the flat surfaces.

Rainfall simulations carried out on *S. tenacissima* tussocks clearly demonstrated the fast transmittance of soil water under living plants and the intercepting effect of the dead canopy. The wetting front under the plants showed clear quickly extending wet pockets around the central root system under the living central part of the plant. Under the dead standing part of the canopy no infiltration was observed, whereas in the surrounding bare areas the wetting front moved more slowly but regularly with increasing rainfall depth. This can be explained by the following mechanisms: water intercepted in the living part of the canopy is partly transmitted as stemflow directly to the rooting zone, where water is transported by rootflow and along other preferential flowpaths of water in the partly water repellent subsoil. Some rain, falling through the canopy on the litter floor is also reallocated to the central part of the *S. tenacissima* tussock due to the water repellency of the litter material at the soil surface. Most water falling on the dead standing canopy is stored in the dead canopy or falls on the water repellent surface and is also redirected to the plant centre. After five successive short showers the importance of the stem-rootflow mechanism became clear, even under low amounts of precipitation.

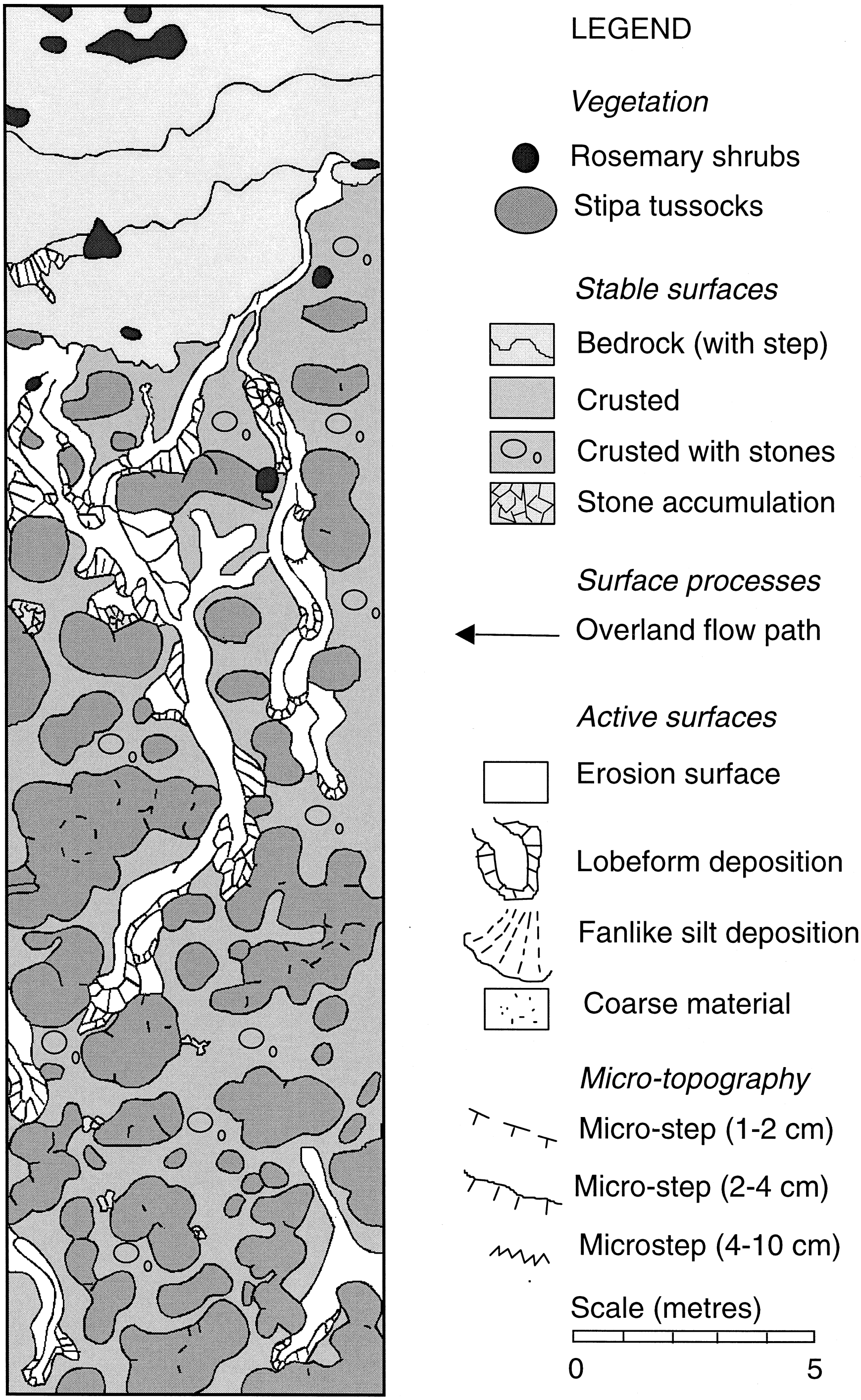
The slopes have an open *S. tenacissima* vegetation cover (Fig. 2). The *S. tenacissima* plants are more widely distributed on the upper part of the slope, compared to the lower part of the slope, and also other species occur on the upper part of the slope such as rosemary bushes (*Rosmarinus officinalis*) and isolated pine trees (*Pinus halepensis*). Often the micro-topography of the slope surface shows miniature terracing, as a result of the accumulation of coarse and fine material in front of the *S. tenacissima* tussocks.

On the steeper parts of the slopes rock fragments are very common. They are derived from either limestone outcrops at the plateau rim, or are transported petrocalcic fragments. Most of them are not embedded in the soil crust and the amount of rock fragments decreases down slope as the gradient decreases.

During rainfall events which generate overland flow the water is transporting considerable amounts of sediment as could be derived from many traces on the soil surface. Fig. 2 illustrates the presence of overland flow pathways, visible as narrow channels of clean crusted surfaces, ending in sedimentation lobes, of gravel sized material near *S. tenacissima* tussocks. Some larger channels continue over much longer distances in between the widely distributed *S. tenacissima* tussocks, with deposition of gravel sized material along the channel sides as small natural levees of 5–10 cm width and 3–4 cm height. In larger complexes of *S. tenacissima* tussocks, complete infiltration may occur and no trace of overland flow was observed below these complex tussocks. In general the density and width of overland flow channels increases down slope, notwithstanding slope angle decrease.

In Fig. 3 the runoff characteristics are displayed obtained from experiments with the large sprinkler rainfall simulator. The sprinkled zone covered several connected open areas around isolated *S. tenacissima* tussocks. The experiment consisted of four 10-min and one 30-min shower carried out on two days. On a wetted surface and with rainfall durations longer than 10 min at an intensity of 40 mm h^{-1} runoff percentages reach over 60% at the plot scale. The soil moisture content at 5 cm depth under bare surface rose from an initial level of 0.06 cm^3 cm^{-3} to 0.17, 0.25 and 0.28 cm^3 cm^{-3} at the onset of the 2nd, 3rd, and 4th. event. The fifth event started with a level of 0.37 cm^3 cm^{-3}.

Fig. 2. Sketch map of the upper hillslope (22° to 12°) indicating relative dense arrangement of *S. tenacissima* tussocks and indicating the traces of overland flow as well as the places where sediment was deposited. Top of figure is the top of the hillslope.


LEGEND
Vegetation
Rosemary shrubs
Stipa tussocks
Stable surfaces
Bedrock (with step)
Crusted
Crusted with stones
Stone accumulation
Surface processes
Overland flow path
Active surfaces
Erosion surface
Lobeform deposition
Fanlike silt deposition
Coarse material
Micro-topography
Micro-step (1-2 cm)
Micro-step (2-4 cm)
Microstep (4-10 cm)
Scale (metres)
0
5

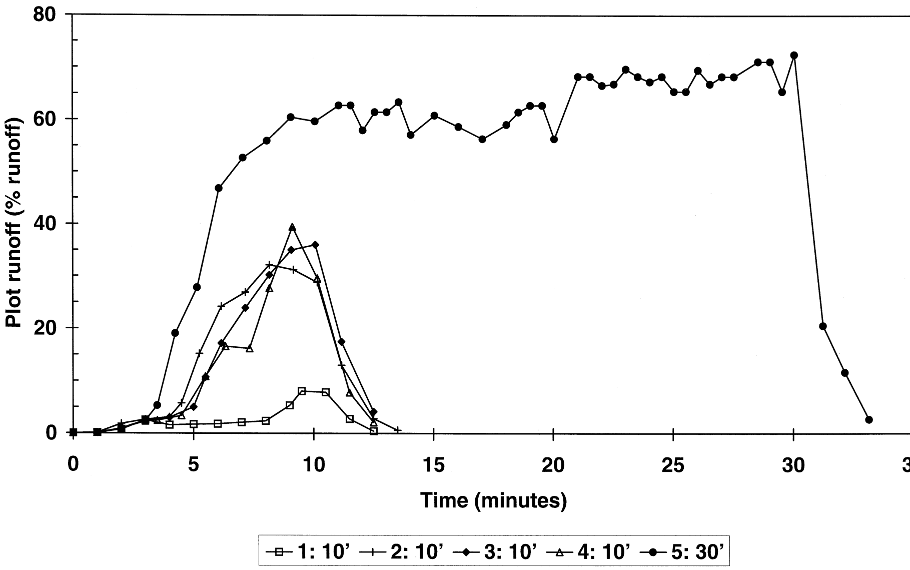


Fig. 3. Results of a rainfall simulation experiment on a sloping *S. tenacissima* covered area (2.5 × 5 m). Five small events of 40 mm h^{-1} are indicated, lasting 10 min except for the last one, which lasted 30 min. The events were divided over two days.

It is clear that the length and the frequency of relatively small rainfall events are very much determining the response of the soil. The first produced hardly any runoff, whereas the second to fourth shower gave similar results with respect to runoff with infiltration rates still decreasing during the storm. The fifth shower, carried out under wet initial conditions inherited from the previous showers, showed a strong increase in runoff levels and reached the final infiltration rate of this soil surface within 10 min after the start of the storm. Infiltration pattern showed similar subsurface distribution patterns as on the *S. tenacissima* covered plateau, with a larger infiltration depth in the upslope area of the plant tussock.

On the more gently sloping areas, two land-use types occurred (open *S. tenacissima* vegetation and sparsely vegetated abandoned fields). In both cases overland flow traces are still very common. This area is a remnant of a much larger area originally covered with *S. tenacissima* before it was brought into cultivation around the early 1960s and then successively abandoned in 1983. Aerial photographs of 1957 (M.A.P.A., 1957) reveal that the whole abandoned zone around the plateau was covered with semi-natural shrubland and that only the talwegs were being cultivated.

A part of the area presently covered with *S. tenacissima* is shown in Fig. 4, indicating its spatial distribution and the patterns of overland flow, deposition and erosion. The *S. tenacissima* tussock density is much less than on the steeper slope. Continuous flow paths of runoff were observed coalescing into larger pathways. Sediment deposition is not in the form of lobes of gravel sized material, but in accumulative sheets of fine (sand, silt and clay) material, selectively deposited in front of a *S. tenacissima* tussock,

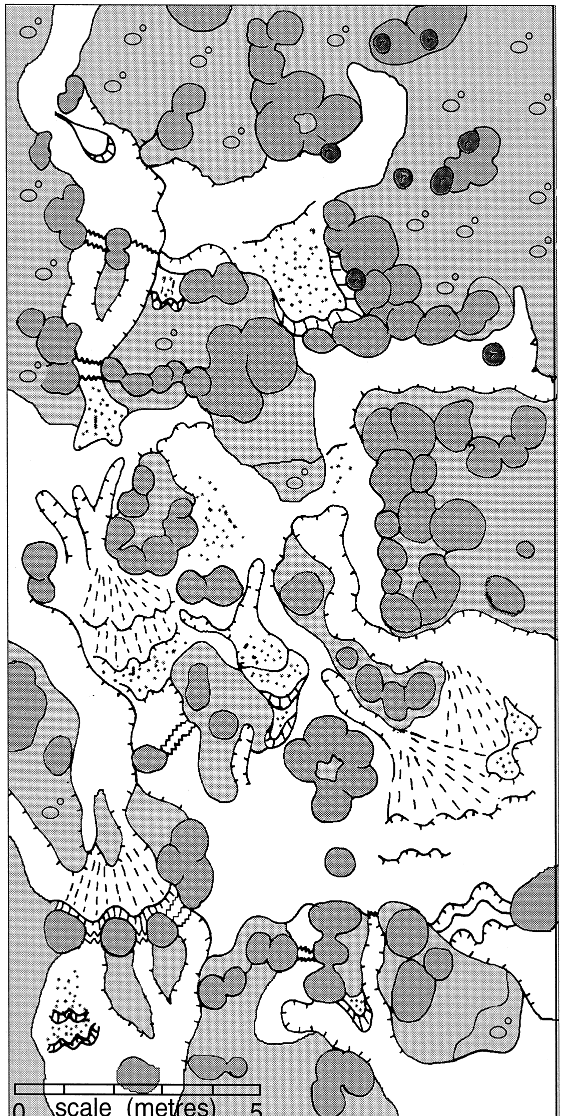


Fig. 4. Sketch map of the lower hillslope (8° to 2°) indicating a relative open arrangement of *S. tenacissima* tussocks with a clear presence of overland flow traces and sediment deposition. Legend as in Fig. 2.

forming small discontinuities in the micro-topography of the slope. In between bordering tussocks surface micro-steps occurred in the surface, which were being eroded upslope. The soil surface has strong depositional crust with a one grain thick coarse sand or fine gravel layer on top. The crust has a massive structure and is breaking into blocky elements, of about 3 cm thickness, at erosional micro-steps. These blocks disintegrate into smaller parts, micro-aggregates and primary particles which are deposited lower on the slope.

The area where the *S. tenacissima* has been cleared for agricultural use, and which has been abandoned in 1983, a massive continuous bright crust is present, most probably formed by slaking and/or depositional processes. The silt loam material at the surface was found to be very sensitive to dispersion in relation to the electrical conductivity of the water. At very low electrolyte contents ($EC_{25} = 25$ μS cm^{-1}) material readily dispersed whereas at $CaCO_3$ dominated water ($EC_{25} = 800$ μS cm^{-1}) flocculation occurred much faster. Small desiccation cracks were found on the surface, rapidly disappearing upon wetting.

On this surface hardly any plants were present. This can be explained by a combination of several factors such as a hindered germination of seeds and very limited infiltration in the dense crust, the very low amounts of precipitation during recent years, the marly character of the soil with lower water retention capacities, and also grazing.

One of the dominant vegetation species is *P. albicans*, which is very small and adapted to trampling, and occurs in semi-linear bands or lines, developed in a direction parallel to the contours, at a more or less regular interval. Directly downslope of these plants micro-steps of a few (1–4) centimetres height have developed in the soil surface, due to the accumulation of mainly fine soil material and some organic debris.

It was also observed that at zones where more runoff is produced, especially in shallow depressions in the plateau slope, small rills and gullies have developed on the slope. They end shortly downslope of the break in the slope or piedmont junction in the footslope (Kirkby and Kirkby, 1974; Abrahams et al., 1994). Here they become transformed into blankets of silty sediments spreading out just below the slope transition, indicating a threshold in hydraulic conditions from sediment carrying overland flow and rill-flow towards a sedimentation dominated regime. This is also reflected by the effects of two short convective storms (approximately 30 mm within 30 min) in May and September, that produced overland flow in considerable amounts, resulting in the burying of the *P. albicans* plants under a silt blanket.

4.2. Patterned phenomena in burnt oak forests NE Spain

This section summarises the results of more than one hundred rainfall simulation experiments made on burnt areas in the vicinity of Vilobí and from studying runoff in natural storms. Measurements were first made at Vilobí one year after the fire. At other sites nearby, infiltration rates were measured directly following a fire and found to be relatively high. Due to wind, very intense thunderstorms and disturbance, the ash and burnt topsoil is redistributed and the surface attains patterned properties relatively quickly. In some cases this is enhanced by dead needles that drop from the trees killed by the fire.

At Vilobí, after one year micro steps, strips and polygonal patterns characterised the upper parts of the slope and the local terrace plateau. The polygons were formed by *Cistus* species. and other seedlings, and fine accumulating organic debris. About 80% of the area appeared as a bare sandy surface and the remainder appeared as vegetation covered areas. The vegetation covered areas consisted of the resprouting stems of plants such as *A. unedo* and *E. arborea* around the bases of which organic rich debris and ash had accumulated. These areas formed bands along the slope. The bare areas were usually found where the organic top soil had been lost and thin layers of fine gravel and sand had accumulated. In places *Cistus* species. seedlings were present on the bare areas. On the steeper slopes clayey Bt horizons had been exposed on the surface.

Rainfall simulation experiments and laboratory investigations of samples from soils on the upper part of the slope where the Bt horizon was not on the surface, revealed that the soil below the bare surface was hydrophobic to a depth of 5 to 10 cm. The effects of the hydrophobicity were such that during rainfall simulation experiments the runoff would sometimes be high at the start of the storm, decrease during the experiment as the soil lost its water repellency and then increased again as the soil became wet. It was also apparent that not all of the area was hydrophobic. About 5% of the surface consisted of the openings of channels that contained organic rich soil or debris. These acted as conduits through the hydrophobic layer so that water by-passed the E horizon. Infiltration and runoff measurements were consequently highly variable as they reflected the interaction of three processes: the gradual decrease of the hydrophobic effect; the effect of soil moisture on sorptivity and the number of organically rich channels that were present to transmit by-pass flow.

Fig. 5 shows a number of successive rainfall simulation experiments made on a bare surface, two years after the fire. In order to emphasise the significance of hydrophobicity for low intensity storms results from a simulated intensity of 20 mm h^{-1} are shown. The measurements were made at 2 h intervals and the moisture content in the series shown

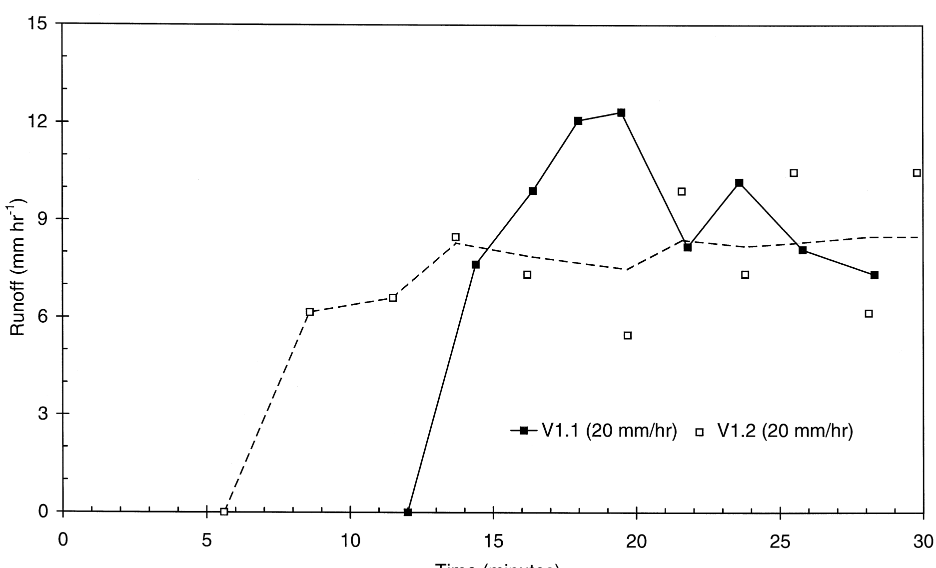


Fig. 5. Runoff curves from rainfall simulation experiments on burnt land at Vilobí (NE Spain), showing the effect of hydrophobicity. The line for V1.2 is interpolated between the observed points.

increased from 7 to 11 and 20%. During the first simulation event the loss of the hydrophobic effect can be seen in curve V1.1 after 20 min. The second curve shows a more regular infiltration behaviour after the loss of the water repellency effect upon wetting. At higher rainfall intensities it was found that the first events produced high rates of runoff and the second events very little or no runoff. In the winter, when soils are sometimes wet, this is not the case.

Fig. 6 illustrates the behaviour of the clayey soils during the summer. In these soils, there is no hydrophobic effect. A 30 min rainfall intensity of 20 mm h^{-1} produces no runoff so that data for higher intensities are shown to illustrate the behaviour. Runoff reaches a constant value that reflects the hydraulic conductivity of the horizon. In the summer this is quite high. The amount of runoff also reflects the rainfall intensity. At the forest site this ranged from 57 (V2.1) through 45 (V.2.2) to 31 (V2.3) mm h^{-1}. In the winter infiltration rates were found to be 20 to 40% lower than those in the summer and the clay soils always produced runoff within 5 min.

The rainfall simulation experiments described above showed that for bare areas runoff coefficients were often as high as 50%. These measurements were made on 1 m long plots. When the plot length was increased to 10 m on the bare soils with the AE horizon at the surface, it was found that very little or no runoff left the plots for 40 min storms with intensities of about 40 mm h^{-1}. What occurred was that the bare hydrophobic sand covered patches rapidly became ponded to a depth of several cm. Flow velocities were very low and it was apparent that the gravel and sand was a lag deposit. Although the material was moved by splash creep, the transport capacity of the runoff, calculated from measured values was too low to transport the sand and gravel. It was apparent in view of the ponding and lack of runoff that most of the infiltration was

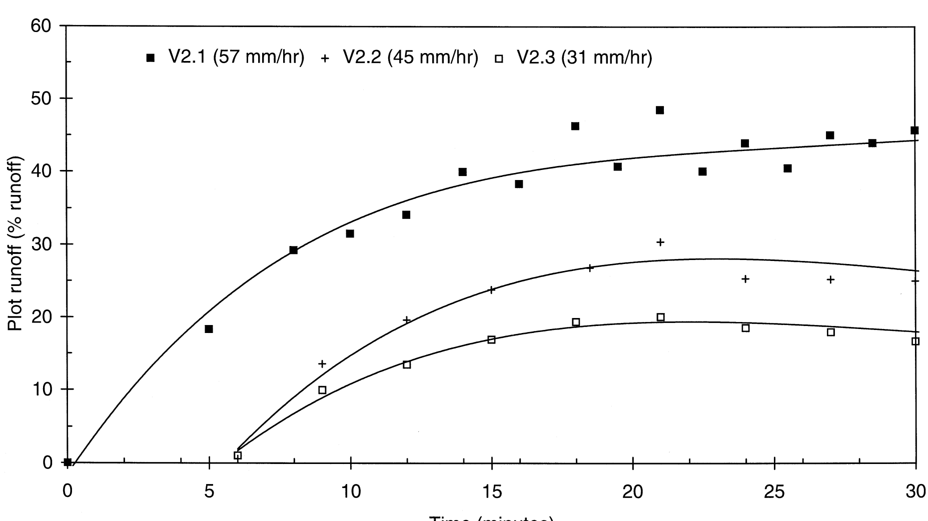


Fig. 6. Runoff curves from rainfall simulation experiments with different rainfall intensities under summer conditions on burnt land at Vilobí, (NE Spain).

taking place beneath the resprouting bands of shrubs. This was verified by excavating the sites after the rainfall simulation experiments.

5. Discussion

5.1. Patterned phenomena on S. tenacissima covered and abandoned land in SE Spain

In Fig. 7 the relation between rainfall intensity and time to ponding is given, indicating the differences in infiltration rates on bare areas at the different land use units discussed. It is very evident that the infiltration rates are lowest in the abandoned zone, due to the presence of the dense silty crust of the soil surface. It gives a result for the abandoned zone which can be used for upscaling, as the spatial heterogeneity is present at a much more detailed scale, falling within the spatial limits of the dripping plate simulator. The infiltration rates of the other land-use types are only reflecting the infiltration properties of the bare areas. Cerdà (1997) describes infiltration rates for small radial plots (50 cm diameter) for the bare, and vegetation covered sites in the area of study. He reports clear differences in infiltration rates for the different types of cover. However, these properties cannot directly be translated to larger areas, as the interaction between the different infiltration characteristics of the bare runoff and vegetated runon (water absorbing) areas are non-linear (Dunne et al., 1991; Bergkamp et al., 1996; Morin and Kosovsky, 1995). For this reason intermediate scale simulations were carried out,

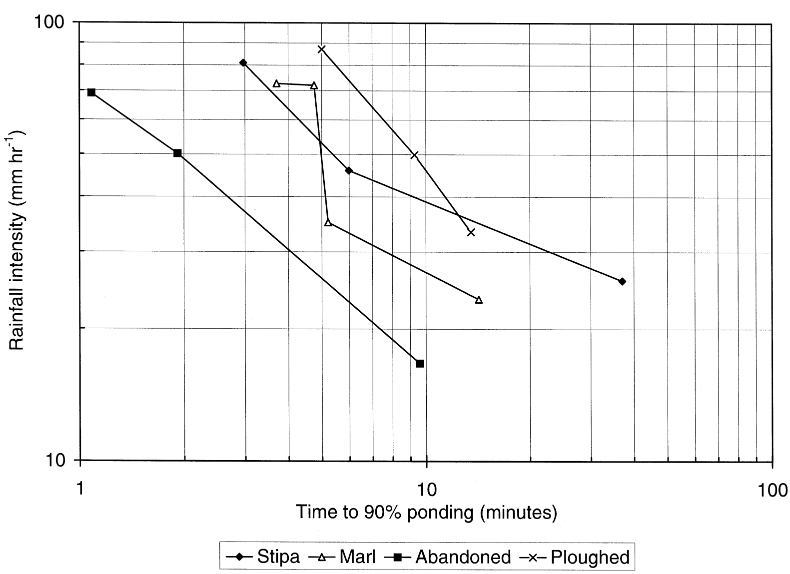


Fig. 7. Relation between rain fall intensity and time to ponding indicating the deterioration in infiltration after abandonment on strongly crusted and silty topsoils for the Cañada Cazorla region (SE Spain).

containing both vegetated, and bare areas to incorporate their mutual effect on infiltration and runoff production which were described before.

Under *S. tenacissima* tussocks infiltration was found to be greatly enhanced by an active stem-root flow system. This resulted in a deeper penetration of the wetting front under the living plant. It was not clear how much water was totally absorbed by the dead standing biomass and how much water was diverted towards the plant root system over the water repellent material on the soil surface. The bare area showed a slow regular increase in infiltration depth, and it might be suggested that two different rooting systems are active, one dealing with diverting water efficiently directly to the roots under small rainfall amounts and a second system, which is active under more wet conditions, when the wetting front under bare soil surfaces reaches deep enough to pass the surface crust and the dusty layer.

On the hillslope the *S. tenacissima* tussocks are situated at the downslope rim of small terracettes, built of accumulated sediment at the upslope side of the tussocks. This process of accumulation is described for mountain slopes in the Pyrenees (Gallart et al., 1993) and on metamorphic rocks (Sanchez and Puigdefabregas, 1994). Processes responsible for movement of slope material are wash and deposition by overland flow and rock fragments displaced by trampling, grazing animals. The downslope splash of soil material may also play a role.

On sloping areas the lateral redistribution of water over the surface becomes important and plant patterns develop over the slope. These become significant in determining whether overland flow is generated over longer distances or not. On more bare areas with less tussocks, more traces of overland flow and sediment deposition were found. The density of the *S. tenacissima* tussocks on the slopes studied showed a decrease with lower slope angles at lower slope position. On these slopes a decrease in rock fragment cover at the soil surface and a decreasing surface roughness are found in a downslope direction. Apparently, on these slopes so much water is produced that, with decreasing slope angles, more and more water is concentrated downslope. This conform with the results of the rainfall simulations, which indicate very high runoff figures for slopes with an open plant cover and for heavily crusted areas. Deposition of material increases with lower slope angles and the material is preferably deposited directly upslope of the *S. tenacissima* tussocks (see also Fig. 4). Puigdefabregas and Sanchez (1996) found that the sedimentation rate is a very important factor in the openness of the vegetation. It must be said, however, that the amount of rock fragments, which decreases downslope, certainly will influence infiltration properties and therefor also the transport capacity of overland flow (Poesen and Lavee, 1994). In other nearby areas where the banded nature of vegetation layout becomes prominent, virtually all water is absorbed in the plant tussocks and infiltrates into the soil. This was also found on thyme and rosemary type of matorral growing on an arch-form terracette micro-topography on limestone slopes in other areas in SE and Central Spain (Bergkamp et al., 1996). It is suggested that vegetation structure ranging from banded via arch formed and open polygon-like *S. tenacissima* structure towards a more spotted vegetation structure is leading towards an increasing amount of runoff concentration and sediment transport. This phenomenon is also described for semi-arid regions in Australia (Tongway and Hindley, 1995). Local factors related to this are also gradient and aspect, soil roughness (rock fragment cover), soil surface conditions (crusting and infiltration capacity), sediment delivery, and cover percentages of vegetation. More regional factors affecting these processes are climatological conditions as well as geological properties.

The tussocks of the *S. tenacissima* plants act as important sinks for water, sediments and nutrients. The more continuous the vegetation structure is, the more effective it will be in capturing these important resources. The tussocks themselves also act as fertile islands on the slope, where organic matter and other nutrients are retained. They give shade and shelter to many soil animals which play an active role in bioturbation. This in turn positively affects infiltration and incorporation of organic matter in the soil which positively influences soil structure (Cammeraat and Imeson, 1998). This will favour the health of the plant and this whole cycle could be seen as a positive feed-back mechanism. In fact the presence of a (banded) vegetation structure could be used as an indicator of health of the ecosystem as also is proposed by Tongway and Hindley (1995) in Australian areas. The processes of sedimentation, erosion and water reallocation show a very dynamic interaction with vegetation. Sanchez and Puigdefabregas (1994) showed that the *S. tenacissima* tussocks have a radial growth pattern. Once the tussock becomes too large, it falls apart into a polygon of clumps of plants, each evolving into a separate new plant. This growth pattern is strongly influenced by gradient, sediment flux and water reallocation. The development of these vegetation structures is highly dynamic and different from the patterns as observed by Dunkerley and Brown (1995), who describe a type of vegetation banding as old stable features.

At much lower slope positions, at the slope break, deposition clearly becomes more and more important, and blankets of silt sized material are deposited, both in open *S. tenacissima* matorral and on abandoned fields. On this latter zone a thick silty crust is present, which micro-topographical steps are coinciding with bands of *P. albicans*. The vegetation bands have a wavelength with an average of 1.2 m. The general percentage cover of vegetation is very low, and this is apparently related to persistence of drought, presence of a heavy crust and grazing, although no actual traces of grazing were found. The small bands of plants act as a sediment trap during the scarce periods of overland flow, when silty sediments are transported downslope. Directly under the small steps erosion takes places during overland flow, creating small steep cuts in the surface with a height of about 2 cm, exposing coherent layered silts. Vegetation banding and the resultant stepped topography, are probably related to the dynamics of the erosion and sedimentation. A process is supposed where sediment is deposited in small lobes from concentrated flow lines. The sediments form a dense crust where germination is difficult and infiltration is reduced. Just downslope the micro-steps the new silt deposit and crust is less dense and infiltration and germination are expected to be favoured in this position. Hence the upslope part of the sedimentation lobe acts as a runoff producing area, whereas the lower rim of the sedimentation lobe acts as a water absorbing area (runon area). When several lobes of sediment grow laterally together over a longer period, and plants have established along its rim, this could result in a alternating banding of relative broad strongly crusted areas, and a narrow zone with plants. However, several other processes could also play a role, of which the formation of tracks by passing grazing flocks is one, as well as inheritance of micro-topography resulting from parallel contour ploughing.

5.2. The significance of patterned phenomena following fire (Vilobí area, NE Spain)

The results from Vilobí d'Onyar in NE Spain show that soil hydrophobicity plays an important role in concentrating infiltration beneath vegetation. The hydrophobic layer has a very positive effect as a rainwater harvesting mechanism. It does not seem to be produced as a result of the fire. Rainfall simulation experiments in undisturbed forests showed that as on the burnt land, the AE horizons were hydrophobic, except for both areas around the roots and in old root channels filled with organic matter. Low to moderate intensity summer rainfall is trapped by this mechanism and conserved in the BC horizons for use by shrubs and trees. It is a coincidence that just as is the case with the *S. tenacissima*, roots are concentrated probably in relation to different types of hydrological event and runoff generating mechanism. They are located both beneath the shrubs where runon water accumulates during periods that are antecedently dry but also in the BC horizon beneath the hydrophobic AE horizon. This area receives water through the by-pass channels during minor events that do not produce runon. In the winter during wet weather, completely different mechanisms sometimes exist when subsurface saturation overland flow can occur above the Bt horizon.

An important research question concerns the degree to which the resilience of the burnt area is affected by the runoff and infiltration patterns that are present prior to the fire. Patterns in soil structure and infiltration rates that have evolved under the forest over perhaps hundreds of years ensure that after a fire water is trapped and protected from evaporation by the hydrophobic effects. Observations and data suggest that soil erosion seldom occurs following a fire if the soil surface is left undisturbed. Management practices such as ploughing and terracing and post fire tree extraction destroy the natural runoff trapping mechanisms that are present. Perhaps a reason why post fire soil erosion is so high on plantations of exotic and other vegetation is that these do not have the facility to generate soil water harvesting strategies or that they cannot do so because of a lack of synergetic relationships with other ecosystem components.

6. Conclusions

From the study in SE Spain it is concluded that patterned phenomena are of great significance in explaining hillslope hydrology and patterns in soil erosion. These patterns form a potential key to understanding an important component of the resilience of the systems studied. The results also demonstrate that the non-random distributions of patterned phenomena on hillslopes need to be considered in up-scaling. The individual responses of bare and vegetated area to infiltration and overland flow cannot be understood without studying their spatial configuration. At the hillslope or basin scale, the spatial patterning of vegetation determines the flow concentration of overland flow as different bare areas may become connected if the infiltration rates of bares areas are exceeded by rainfall intensities and the absorption of water in the vegetated structures. The larger the upslope perimeter and perimeter/surface area ratio, and the larger the vegetation cover, the larger the capacity of infiltration will be. The semi-natural vegetation therefore is an important factor in reducing overland flow and land degradation. The disturbance of these areas by drought or overgrazing, or by removal of the vegetation will therefor decrease the ability to absorb the water at a local scale and increase the generation of runoff over larger areas. The natural revegetation was found to be very low indicating that these areas are vulnerable to land degradation after the destruction of the semi-natural *S. tenacissima* vegetation. Under these degraded circumstances the development of fine scale banded vegetation structures, dominated by *P. albicans* was observed, indicating a strong interrelationship with plant development, sedimentation and soil surface crusting.

Two conclusions from the study in NE Spain are emphasised. The first concerns the conclusion that hydrophobic effects are positive and not negative. There are two possible explanations. The first is that conditions in NE Spain are different from elsewhere. The second is that previous studies have considered infiltration and runoff rates measured from small scale experiments and scaled up to a hillslope or catchments scale using statistics. When larger scale measurements are used to establish how large scale slope sections generate runoff, it is clear that the system is behaving differently at this higher hierarchical level of scale. In other words when a hierarchical systems concept is applied to the interpretation of the data, it is evident that the small scale structures that have evolved create positive feedbacks at a higher scale that enable the vegetation to trap and conserve water and also to recover efficiently following a disturbance.

The second conclusion, which also applies to SE Spain is that patterns that take decades or hundreds of years to evolve are stabilising properties of ecosystems that help them to recover from disturbance or to resist stressors. Management should take this into account and follow strategies that enable these to be promoted or conserved. It seems that many attempts to restore land that has been burnt or abandoned are doomed to fail because they not only neglect the importance of water redistribution phenomenon, but actually promote their destruction.

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