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HYDROLOGICAL RESPONSE AND SEDIMENT PRODUCTION UNDER DIFFERENT LAND COVER IN ABANDONED FARMLAND FIELDS IN A MEDITERRANEAN MOUNTAIN ENVIRONMENT

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ABSTRACT

Rainfall simulation experiments were carried out in plots on three types of land cover (scrubland, grassland and rock fragment). Infiltration rates were similar for all three land cover types. Sediment concentrations and sediment detachments were moderate-to-low. The results confirm moderate hydrological and sediment responses associated with abandoned agricultural slopes. They also illustrate the complexity and variability of slope behavior associated with management of the fields, and are related to topographic features, in particular slope aspect.

Key words: Infiltration rate, sediment response, rainfall simulation, abandoned fields, Central Spanish Pyrenees.

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RESUMEN

En microambientes de campos abandonados (matorral, prado y enlosado de piedras) se realizaron ensayos de simulación de lluvia. Las tasas de infiltración fueron similares en los tres microambientes. La concentración y producción de sedimento fueron entre bajas y moderadas. Los resultados confirman que la respuesta hidrológica y erosiva en laderas agrícolas abandonadas es moderada. Se comprueba también la complejidad y variabilidad del comportamiento hidromorfológico en laderas, asociadas a la gestión de los campos, a las características topográficas y a la exposición de la ladera.

Palabras clave: Tasa de infiltración, respuesta erosiva, simulaciones de lluvia, campos abandonados, Pirineo Central español.

I. INTRODUCTION

The abandonment of agricultural practices in most Mediterranean mountains has resulted in significant changes to the landscape (MacDonald et al., 2000;Vila-Subirós et al., 2009), notably a marked recovery of natural vegetation (Poyatos et al., 2003; Chauchart et al., 2007; Sluiter and Jong, 2007; Lasanta et al., 2008). The large-scale land cover changes have modified the hydrological and erosional behavior of affected areas and have had a significant impact on the availability and quality of water resources, as well as affecting soil erosion and conservation (Llorens et al., 1997; Liébault and Piégay, 2002; Gallart and Llorens, 2003). Regional studies in the Central Spanish Pyrenees have shown a decrease in streamflow and the intensity and frequency of floods, most probably associated with vegetation regrowth (Beguería et al., 2003; López-Moreno et al., 2006). Sediment sources have diminished spatially, and there has been a decrease in the activity of braided rivers and an increase in channel incision processes (García-Ruiz and Valero-Garcés, 1998; Beguería et al., 2006). Research carried out in small research catchments with differing land use histories has demonstrated the influence of land cover on runoff generation and sediment transport (García-Ruiz et al., 2008). At the plot scale, a decrease in both erosion rates and runoff coefficients was observed from (traditionally) cultivated slopes to abandoned and revegetated slopes (García-Ruiz et al., 1996; Lasanta et al., 2006a).

The recovery of natural vegetation following farmland abandonment is highly variable (Molinillo et al., 1997; Vicente-Serrano et al., 2005; Lasanta et al., 2006) and dependent on several factors, particularly management of the fields prior to and since abandonment, time since abandonment, and topographic features of the field slopes (Ruiz-Flaño et al., 1992; Molinillo et al., 1997; Seeger and Ries, 2008). Research in an abandoned agricultural catchment (the Arnás experimental catchment) has shown that the resulting landscape comprises a mosaic of land patches that react differently to varying rainfall and catchment moisture conditions (Lana-Renault and Regüés, 2009). During short storms and in the dry season runoff generation is limited and soil erosion is concentrated in a few places close to the main channel, whereas the slopes show limited geomorphic activity because of the presence of dense shrubs and grasslands (González et al., 1997; Lana-Renault and Regüés, 2009).

However, under wet conditions and with prolonged rainfall periods there is an enlargement of sediment and water contributing areas, although it is unknown how the different land covers influences in the hydrological and erosion response. Ruiz Flaño (1993) distinguished the different land covers in abandoned fields based on the vegetation cover and the rock fragment density, resulting in three different land covers: scrubland, grassland and rock fragment.

To evaluate the hydrological and erosional behavior of previously cultivated slopes in a catchment, we carried out rainfall simulation experiments in three micro-environments representative of recently abandoned fields. Such experiments have been widely used to compare and evaluate infiltration and erosion produced by rain splash because they enable initial conditions to be established and provide for control over rainfall characteristics (Foster et al., 2000). We investigated hydrological responses and sediment production on three different types of land cover in abandoned fields (scrubland, grassland and rock fragment) and explored site factors controlling the various responses. The results are discussed within a larger spatial and temporal framework, dictated by the increase in vegetation cover in Mediterranean mountains.

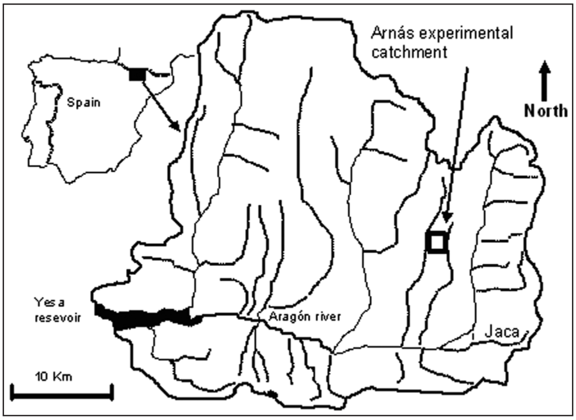
In short, the main objective of this study is to understand how the different micro-environments in abandoned field contribute to the hydrological response and sediment production during short intense rainfalls. In this way, it is not only understand the hydrological behavior of a catchment of abandoned fields, but also it's really important to contribute to obtain information to establish strategies of management oriented to the soil conservation, an essential element in the vegetation spatial distribution, the biodiversity, the availability and quality of water resources and the use of the mountain with extensive cattle (García-Ruiz et al., 1996).

II. STUDY AREA

The Arnás catchment (2.84 km^2) is located in the headwaters of the Aragón River, Central Spanish Pyrenees, between 900 and 1400 m a.s.l. (Figure 1). The mean annual precipitation over the water years (October to September) 1999-2006 was 935 ± 210 mm, most of which occurred in autumn and spring; intense short-duration convective storms are relatively frequent in summer. During this period the most intense event involved rainfall of more than 31 mm over a half-hour period (62 mm h^{-1}). According to Creus and Puigdefábregas (1978) rainfall of this intensity has a return period of 5 years in this area of the Pyrenees.

The bedrock of the Arnás catchment is Eocene flysch with alternating sandstone and marl layers sloping northward. The west-east orientation of the ravine has resulted in a marked contrast between the south and north facing slopes, the former being much steeper than the latter. The soils on the south-facing slope are mostly poorly developed, shallow carbonate-rich Regosols (FAO, 1998). They are shallow and compact, and show signs of major degradation (Navas et al., 2005). The soils on the north-facing slope are more developed because they are less steep, have a more dense vegetation cover, and accumulate more organic material. The predominant soil types are Kastanozems which may also be strongly influenced by stagnant water and accumulation and erosion processes on the concave slopes. All soils have a low infiltration capacity, decreasing below 5 mm h^{-1} when moist, as a result of the high clay content. Satured hydraulic conductivity tends to decrease with soil depth (Seeger, 2001). The soil matrix is highly erodible, but often protected by a stone layer (Seeger et al., 2004).

Figure 1
LOCATION OF THE STUDY AREA



The entire catchment was cultivated with cereal crops in nonterraced fields until the middle of the 20th century, then progressively abandoned and subsequently colonized naturally with scrubs including *Genista scorpius*, *Echinospartum horridum*, *Juniperus communis*, *Rosa* gr. *canina* and *Buxus sempervirens* (Lasanta et al., 2005). The vegetation cover in the catchment is now very heterogeneous, with patches corresponding to fields abandoned at different times. The more recently abandoned fields still have an herbaceous cover, but in some areas (mostly on north facing slopes) the plant succession is in its final stages and the land is dominated by dense forest. The areas exposed to the most intense human pressure in the past are now characterized by a high degree of stoniness, and many are subject to severe sheetwash erosion and occasional grazing activity. These more degraded patches occur mostly on south facing slopes. Approximately 20% of the catchment is covered by forest, 72% by scrubs, 5.5% by grassland, and 1.5% by bare land (Lana-Renault, in press).

III. MATERIALS AND METHODS

Forty six rainfall simulation experiments were carried out under relatively dry conditions (soil water content=0.2). Experimental plots were defined by a circular ring with an area of 0.25 m^2. Each plot had a drain pipe outlet for collection of runoff samples, located down slope at surface level. Because of the inaccessibility of the plots the rainfall simulation experiments were undertaken using a portable rainfall simulator designed for rugged terrain (Calvo et al., 1998). The simulator consists of a metallic structure with telescopic metal legs, and was covered with plastic to protect the experiments from wind. The simulated rainfall reached a Christiansen coefficient of 93% under laboratory conditions. The mean drop size was 2.53 mm, the mean drop velocity was 3.4 m s^{-1}, and mean drop kinetic energy was 7.1 J m^{-2} mm^{-1}. Rainfall was applied at an average intensity of 56 mm h^{-1} for 30 min (the rainfall intensity ranged from 41.8 to 74.6 mm h^{-1}), which is similar to the maximum natural rainfall intensity reached in the area during the study period.

This type of rainfall simulator is used by many research groups for similar investigations (Ternan et al., 1996; Cerdà, 1997; Lasanta et al., 2000; Boix-Fayos et al., 2005; Marqués et al., 2005; Arnáez et al., 2007; Seeger, 2007; Ries, 2010). A good review of older literature on the topic is provided by Cerdà (1999).

Table I provides descriptive information on the 46 rainfall simulation experiments, including site characteristics, rainfall intensity, and the hydrological and sediment results.

Three representative land cover types were selected for the experiment: scrubland (20 plots), grassland (17 plots) and rock fragment (9 plots) (Figure 2a, b and c, respectively). Plots dominated by *Genista scorpius* were selected to represent scrubland because this species dominated during the first 30 years following abandonment (Molinillo et al., 1997). Under the *Genista scorpius* appears an herbaceous cover where *Carex flacca* and *Brachipodium pinnatum* predominate. In the grassland plot dominate *Carex flacca*, *Brachipodium pinnatum*, *Hieracium gr. Pilosella*, *Sanguisorba minor*, *Medicago sativa*. The areas with high stone pavement have very sparce vegetation (10-15%). The mean size of the stones corresponds to thick gravels (more than 5 cm) and its origin is autochthonous, because they appear in the surface when the thin material has been evacuated by the runoff and diffuse erosion.

The 46 experimental plots were located on different slope aspects (south and north), and on concave and convex slopes. Table II shows that the mean density of vegetation cover was about 88% in the scrubland plots, 84% in the grassland plots, and 40% in the rock fragment plots. Rock fragment cover in the scrubland and grassland plots was always less than 20% and 30%, respectively, but varied between 20% and 95% in the rock fragment plots. Statistical differences in vegetation and rock fragment cover were only found between the vegetated and rock fragment plots.

FIGURE 2

THE THREE EXPERIMENTAL PLOT TYPES: A) SCRUBLAND, B) GRASSLAND AND C) ROCK FRAGMENT

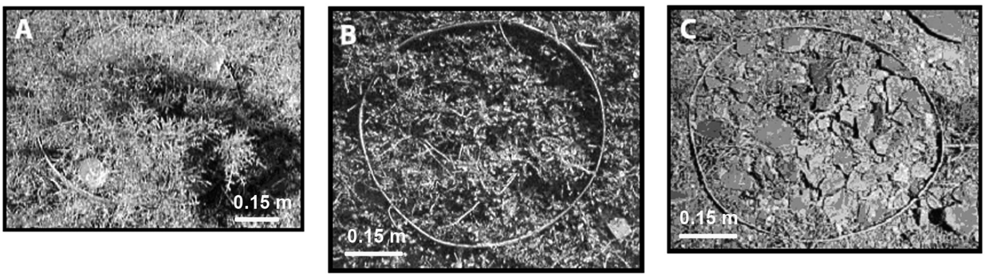


Table 1

CHARACTERISTICS OF THE 46 RAINFALL SIMULATION EXPERIMENTS, INCLUDING THE LAND COVER TYPE (1: SCRUBLAND, 2: GRASSLAND, 3: ROCK FRAGMENT COVER), THE VEGETATION AND ROCK FRAGMENT COVER, THE RAINFALL INTENSITY, AND THE HYDROLOGICAL AND SEDIMENT RESULTS. SSC: SUSPENDED SEDIMENT CONCENTRATION

Plot	Aspect	Land cover type	Veg. cover (%)	Rock frag. cover (%)	Rainfall intensity (mm h^{-1})	Time to runoff (s)	Wetting front (cm)	Infiltration rate (mm h^{-1})	Averaged SSC (gl^{-1})	Maximum SSC (gl^{-1})	Sediment detachment (g m^{-1} h^{-1})
1	N	3	20	95	64.4	187	18.00	56.13	1.01	3.76	7.68
2	N	1	90	5	61.1	770	29.00	60.76	2.85	3.48	0.94
3	N	1	90	15	67.3	995	21.00	63.68	0.69	1.00	2.20
4	N	2	50	30	61.9	228	12.00	53.29	2.76	5.47	18.54
5	N	3	70	50	43.9	421	22.00	39.08	5.92	8.98	24.03
6	N	1	100	5	50.1	1800	19.00	50.10	0	0	0
7	N	3	30	50	54.9	330	21.00	45.43	0.90	3.04	6.02
8	N	1	90	5	45.8	1587	20.50	44.96	1.59	3.00	0.88
9	N	1	85	10	55.9	1233	17.00	54.39	3.36	5.69	3.91
10	N	1	90	5	50.6	687	19.00	45.18	0.53	0.67	3.00
11	N	1	100	5	61.1	1800	23.00	61.10	0	0	0
12	N	1	85	5	60.1	2256	16.00	55.18	1.04	2.11	5.99
13	N	1	70	5	50.6	210	19.00	48.84	0.55	0.84	1.02
14	N	2	100	5	53.0	403	16.00	46.87	0.95	3.32	6.37
15	N	1	90	5	69.4	390	16.00	60.21	0.82	1.55	6.27
16	N	2	100	5	47.7	388	16.00	42.02	1.11	2.31	6.44
17	N	2	70	5	74.6	295	14.00	64.92	0.61	1.88	5.26
18	N	1	90	5	47.7	920	14.00	47.27	1.15	1.15	0.49
19	N	2	100	5	59.7	1800	17.00	59.70	0	0	0
20	N	2	90	5	60.7	1067	12.00	53.33	0.67	1.36	4.57
21	S	2	50	20	63.4	1125	12.00	57.83	1.10	1.12	6.08
22	S	3	20	60	67.9	1020	16.00	62.54	1.39	3.01	7.14
23	S	3	20	50	63.4	438	18.00	59.81	2.98	5.32	6.50
24	S	2	80	5	69.4	832	21.00	66.63	3.59	5.07	7.19
25	S	2	80	5	60.4	388	18.00	60.09	1.57	1.57	0.48
26	S	3	40	20	52.2	870	20.00	52.17	-	-	1.33
27	S	2	100	5	52.2	1676	18.00	52.08	-	-	4.12
28	S	3	60	20	52.2	360	11.00	46.91	3.14	10.37	12.85
29	S	2	85	15	55.0	1800	15.00	55.00	0	0	0
30	S	1	95	5	59.7	870	14.00	59.62	0.90	0.90	0.07
31	S	1	85	5	56.9	280	12.00	46.72	2.58	6.53	9.87
32	S	1	95	5	43.3	1335	12.00	43.02	0.07	0.07	0.02
33	S	3	40	20	59.7	630	15.00	59.20	2.79	2.79	1.41
34	N	1	95	5	56.7	1080	18.00	26.66	1.25	1.25	0.05
35	N	2	80	5	43.3	790	17.00	42.89	1.41	1.41	0.58
36	N	1	70	5	58.2	1610	26.00	56.98	3.38	3.38	4.09
37	N	1	80	5	56.7	1800	16.00	56.70	0	0	0
38	N	1	90	10	69.4	1800	19.50	69.40	0	0	0
39	N	2	95	5	58.1	1800	17.50	58.10	0	0	0
40	N	2	100	20	47.7	1800	20.00	47.70	0	0	0
41	N	2	80	5	45.5	1214	18.00	44.90	9.65	9.65	5.79
42	N	2	80	5	41.8	565	14.30	40.68	1.73	2.34	2.14
43	N	3	60	35	55.6	530	15.00	54.68	1.69	2.81	1.89
44	N	1	100	5	51.3	1800	12.00	51.30	0	0	0
45	N	1	80	5	48.9	1800	36.00	48.90	0	0	0
46	N	2	85	5	61.0	767	16.00	60.89	1.94	3.40	0.15

Table 2
MAIN CHARACTERISTICS OF THE THREE LAND COVER TYPES. MEANS WITH DIFFERENT LETTERS ARE SIGNIFICANT AT THE 0.05 LEVEL (ANOVA, BONFERRONI TEST)

	Scrubland (n=20)			Grassland (n=17)			Rock fragment (n=9)		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
Slope (º)	13a	22	5	13a	18	10	13a	20	10
Veg. cover (%)	88a	100	70	84a	100	50	40b	70	20
Rock fragment cover (%)	7a	20	5	9a	30	5	43b	95	20

A steady state runoff rate was reached in all plots. The runoff and its sediment content were assessed at 2-4 min intervals. Following the simulated downpour the depth of the wetting front was determined by digging a hole and measuring the average depth of the wetted area. The parameters measured for each simulation were the time from the beginning of the rainfall simulation until runoff occurred (time to runoff; s), the wetting front (cm), infiltration rate (mm h^{-1}), suspended sediment concentration (g l^{-1}) and sediment yield by detachment (g m^{-2} h^{-1}).

IV. RESULTS AND DISCUSSION

4.1. Hydrological response

Table III summarizes results for the scrubland, grassland, and rock fragment land cover types. Only time to runoff was significantly higher in the scrubland plots (mean 1261 sec; coefficient of variation, CV=0.49) than in the rock fragment plots (mean 531 sec; CV=0.55). No significant differences among the three land cover types were found in the wetting front or the infiltration rate. The average wetting fronts were 18.8 cm (CV=0.32) in scrubland, 16.1 cm (CV=0.16) in grassland, and 17.3 cm (CV=0.20) in rock fragment, respectively, and the average infiltration rates were 53.7 mm h^{-1} (CV=0.13), 53.3 mm h^{-1} (CV=0.15), and 52.9 mm h^{-1} (CV=0.15), respectively. Figure 3 shows typical examples of the temporal evolution of infiltration rates for the three land cover types. The steady-state infiltration rates were relatively high (always greater than 40 mm h^{-1}) and of relatively low variability. Runoff was usually attained later in scrubland plots.

Infiltration rates were much higher than those reported for more degraded and extreme environments. Under similar rainfall and soil moisture conditions, and using the same rainfall simulator as in the present study, Nadal-Romero and Regüés (2009) reported an average infiltration rate of 29.5 mm h^{-1} (CV=0.3) for a nearby badland area on Eocene marls. Using lower rainfall intensities (48 mm h^{-1}), in a badland area in the Eastern Pyrenees, Regüés and Gallart (2004) found infiltration rates of approximately 31 mm h^{-1} (CV=0.1). Lower infiltration rates have also been observed in a Spanish *dehesa* landscape (a land use system adapted to poor soils and low rainfall conditions), especially in grassland and trial plots, where infiltration rates were 23-28 mm h^{-1} (Cerdà

Figure 3

INFILTRATION RATES DURING SIMULATION EXPERIMENTS IN A) SCRUBLAND, B) GRASSLAND AND C) ROCK FRAGMENT PLOTS

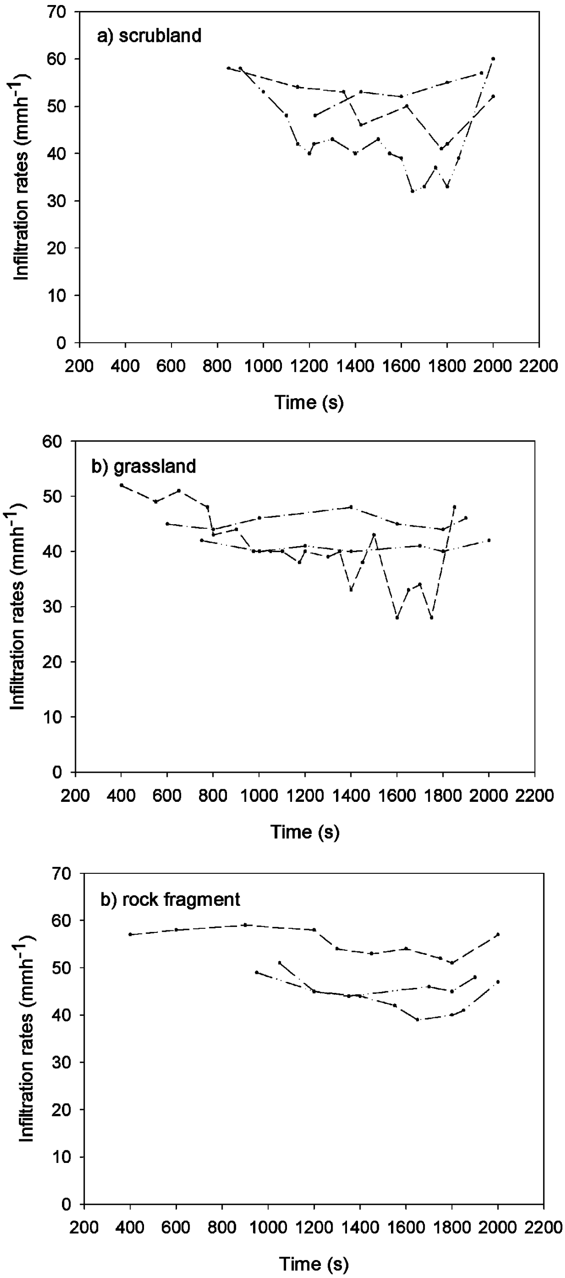


Table 3

SUMMARY HYDROLOGICAL AND SEDIMENT RESULTS FROM THE RAINFALL SIMULATIONS TESTS ON DIFFERENT LAND COVER TYPES (SCRUBLAND, GRASSLAND AND ROCK FRAGMENT). MEANS WITH DIFFERENT LETTERS ARE SIGNIFICANT AT THE 0.05 LEVEL (ANOVA, BONFERRONI TEST). CV: COEFFICIENT OF VARIATION; SSC: SUSPENDED SEDIMENT CONCENTRATION

	Scrubland (n=20)				**Grassland (n=17)**				**Rock fragment (n=9)**			
	Mean	Maximum	Minimum	CV	Mean	Maximum	Minimum	CV	Mean	Maximum	Minimum	CV
Time to runoff (s)	1261a	2256	210	0.49	996a	1800	228	0.59	531b	1020	187	0.55
Wetting front (cm)	18.8a	36.00	12	0.32	16.1a	21	12	0.16	17.3a	22	11	0.20
Infiltration rate (mm h^{-1})	53.7a	69.4	43	0.13	53.3a	66.6	40.7	0.15	52.9a	62.5	39	0.15
Averaged SSC (g l^{-1})	1.1a	3.4	0	1.08	1.7a	9.6	0	1.38	2.4a	5.9	0.90	0.69
Maximum SSC (g l^{-1})	1.6a	6.5	0	1.18	2.4a	9.6	0	1.07	5b	10.4	2.80	0.60
Sediment detachment (g m^{-2} h^{-1})	2.2a	9.9	0	1.29	4.0a	18.5	0	1.17	7.6b	24.1	1.33	0.94

et al., 1998). However, high infiltration rates are not rare under Mediterranean climate conditions where scrubland cover develops (Cerdà, 1996). In the present study the high infiltration rates observed in scrubland and grassland plots confirm the role of vegetation cover in enhancing infiltration and percolation after farmland abandonment. This is mainly because of improved soil properties and the presence of roots, which contribute to the development of macropores (Bond and Harris, 1964; Molina et al., 2007). The high infiltration rates found in rock fragment plots were associated with a high proportion of rock fragments on the soil surface, which has been demonstrated to favor infiltration under laboratory (Poesen and Ingelmo, 1992) and field conditions (Agassi and Levy, 1991; Ruiz-Flaño, 1993).

4.2. Erosive response

The sediment yield was highly variable among plots, especially for those in scrubland and grassland (Table III). The maximum sediment concentrations were significantly higher in the rock fragment plots (mean 5 g l^{-1}; CV=0.6) than in vegetated plots (grassland: 1.6 g l^{-1}, CV=1.18; scrubland: 2.4 g l^{-1}, CV=1.07). Sediment detachment was also significantly higher in rock fragment plots (mean 7.6 g m^{-2} h^{-1}) than in grassland (4 g m^{-2} h^{-1}) and scrubland (2.2 g m^{-2} h^{-1}) plots. These results reflect the protective role of vegetation against erosion, mainly because plant cover can mitigate raindrop impact and reduce overland flow velocity (Cerdà, 1999; Martínez-Zavala et al., 2008; Arnáez et al., 2009). Figure 4 shows typical examples of temporal evolution of sediment concentration response to rainfall simulation in the three plot types. Sediment response in rock fragment plots was usually higher throughout the simulations. Sediment concentrations similar to the highest recorded at the beginning of the experiment have been observed elsewhere (Regüés and Torri, 2002; Nadal-Romero and Regüés, 2009), and were related to low initial soil moisture conditions at the commencement of experiments, which favor splash effects. A thin laminar flow may subsequently provide protection against rain splash (Cerdà, 2001; Regüés and Torri, 2002) and reduce the erosive response.

Soil erosion was very low relative to that observed in more degraded environments. In the nearby mountain badland area, Nadal-Romero and Regüés (2009) reported an average sediment concentration of 23.8 g l^{-1} and an average sediment detachment of 332 g m^{-2} h^{-1} (with a maximum value of 1196 g m^{-2} h^{-1}). Regüés and Gallart (2004) found average sediment concentration of 14 g l^{-1} and a similar average sediment detachment (330 g m^{-2} h^{-1}, with a maximum value of 1080 g m^{-2} h^{-1}). In two arid badland areas in southeast Spain, Cerdà and Navarro (1997) reported average sediment concentrations of up to 60 g l^{-1} and average sediment detachments of 1020 and 1933 g m^{-2} h^{-1}. In simulation experiments using similar rainfall intensities, Solé-Benet et al. (1997) found contrasting sediment responses in a bare badland area (sediment detachment up to 260 g m^{-2} h^{-1}) and a vegetated badland area (average sediment detachment 10 g m^{-2} h^{-1}).

Figure 5 contrasts the relationships between average infiltration rates and sediment concentrations seen in the present study and in others involving more degraded and extreme environments (Cerdà and Navarro, 1997; Regüés and Gallart, 2004; Nadal-Romero and Regüés, 2009). Figure 5 shows that the behavior of the three different land

Figure 4

SUSPENDED SEDIMENT CONCENTRATION (SSC) DURING SIMULATION EXPERIMENTS IN A) SCRUBLAND, B) GRASSLAND AND C) ROCK FRAGMENT PLOTS

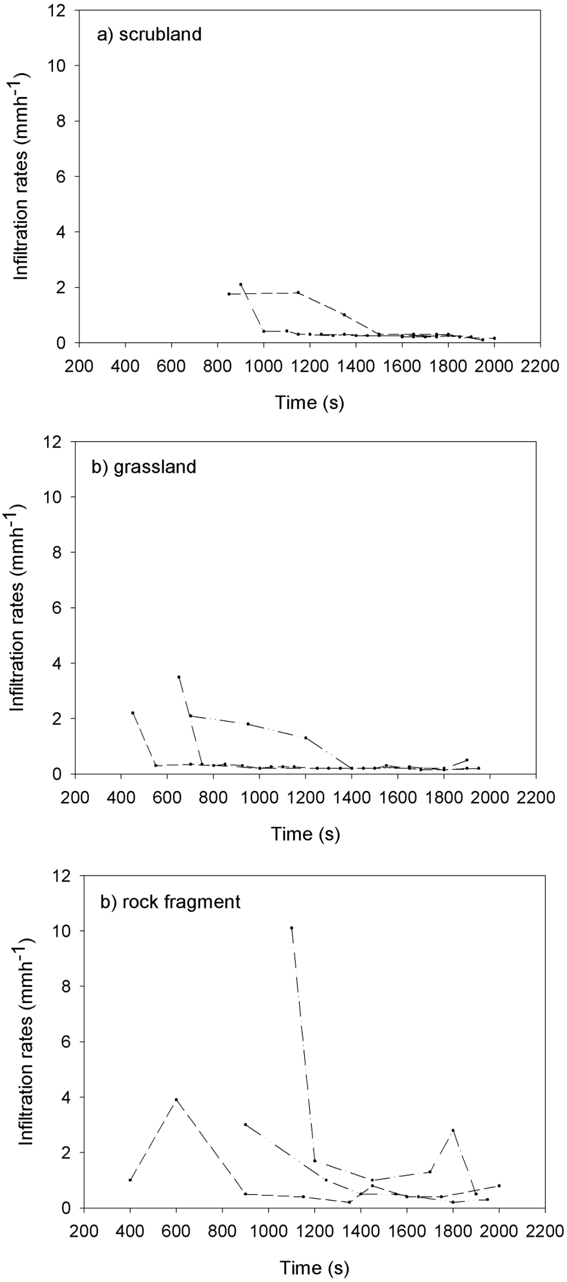
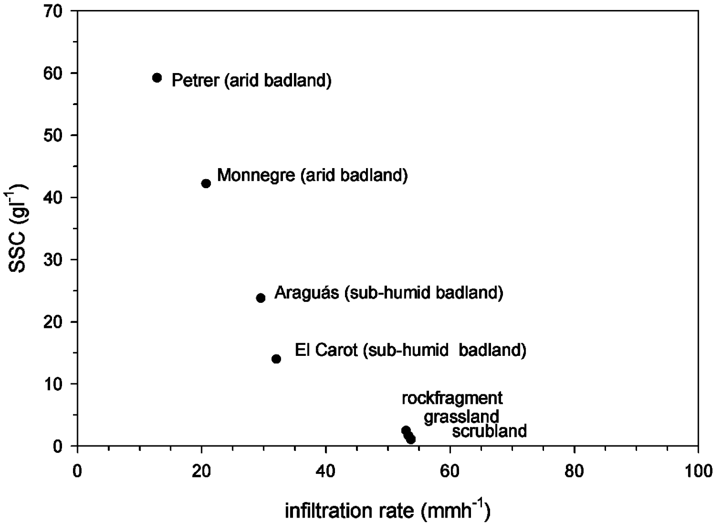


Figure 5

COMPARATIVE AVERAGE INFILTRATION RATES AND CONCENTRATIONS (SSC) FROM OTHER RAINFALL SIMULATION STUDIES BASED ON SIMILAR RAINFALL INTENSITIES (50–55 MM H−1): MONNEGRE ARID BADLANDS (CERDÀ AND NAVARRO, 1997); PETRER ARID BADLANDS (CERDÀ AND NAVARRO, 1997); ARAGUÁS SUBHUMID MOUNTAIN BADLANDS (NADAL-ROMERO AND REGÜÉS, 2009); EL CAROT SUBHUMID MOUNTAIN BADLANDS (REGÜÉS AND GALLART, 2004); SCRUBLAND COVER (THIS STUDY); GRASSLAND COVER (THIS STUDY); ROCK FRAGMENT COVER (THIS STUDY)



covers in abandoned fields was relatively similar, especially when compared with degraded environments, and clearly demonstrates that sediment responses were an order of magnitude lower than those in more degraded areas. Conversely, infiltration rates were much higher in abandoned fields than in degraded areas, being more than double those in arid badlands and around 1.8-fold higher than in mountain badlands. There was a notably opposing trend between hydrological and sediment responses in arid badland areas (the most degraded environments) relative to subhumid badland areas and abandoned fields (less degraded environments); the former had high suspended sediment concentrations and low infiltration rates whereas the latter two categories of area had low suspended sediment concentrations and high infiltration rates.

4.3. Influence of site characteristics

Linear correlation analysis was used to explore the influence of site and rainfall characteristics on hydrological and sediment responses in the rainfall simulations (Table IV). The results show that slope had no influence on any response variable. The effects of each of the two types of vegetation cover and the rock fragment cover on hydrological response

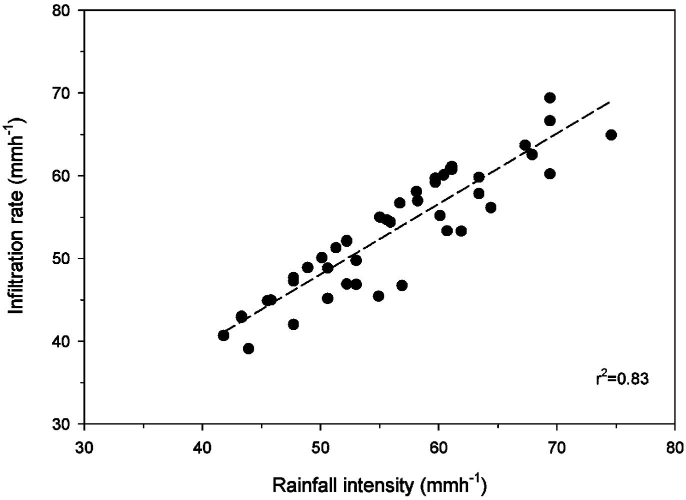
Table 4

CORRELATION COEFFICIENTS BETWEEN PLOT CHARACTERISTICS AND MEAN RAINFALL INTENSITY (IP), AND THE RESPONSE OF VARIABLES TO SIMULATED RAINFALL. CORRELATIONS WERE CONSIDERED SIGNIFICANT AT THE 0.01 (**) AND 0.05 (*) LEVELS

	slope (°)	**Veg. cover (%)**	**Rock frag. cover (%)**	**IP (mm h^{-1})**
Time to runoff (s)	0.116	-0.003	-0.118	-0.079
Wetting front (cm)	-0.031	0.040	-0.025	-0.042
Infiltration rate (mm h_{-1})	-0.146	-0.127	-0.016	0.911**
Averaged SSC (g l^{-1})	-0.006	-0.142	0.019	-0.139
Maximum SSC (g l^{-1})	0.001	-0.203	0.086	-0.127
Sediment detachment (g m^{-2} h^{-1})	0.236	-0.369*	0.474**	0.055

were not clear. Only sediment detachment was statistically correlated with these two site characteristics. The negative correlation between sediment detachment and vegetation cover was consistent with the protective effect of plant cover against rain splash. A number of studies have shown that the effect of rock fragment cover on soil erosion (Lowdermilk and Sundling, 1950; Poesen et al., 1994; Ferre et al., 2009) is dependent on the time and spatial scales involved. Although it is clear that rock fragment cover can protect the underlying soil from raindrop impact, the role played by fragment cover is very complex, and can have a negative effect on soil erosion depending on topsoil structure and the size and position of the soil surface slope, among other factors (Poesen et al., 1994). In the present study, rock fragment cover, which never completely covered the soil surface, was positively correlated with sediment detachment. Weak statistical relationships between response variables and site characteristics have been reported in most studies based on rainfall simulation (Regüés and Gallart, 2004; Molina et al., 2007; Seeger, 2007; Jordan et al., 2008; Nadal-Romero and Regüés, 2009). This methodological approach is not free from unknown factors including those related to experimental design, such as the use of small areas and simulated rainfal. Only rainfall intensity was significantly correlated with infiltration rate. The variability in characteristics among plots, in terms of vegetation and rock fragment cover, may explain the slight differences in correlation between rainfall intensity and infiltration rate relationships (Figure 6). The positive and strong relationship between rainfall intensity and infiltration rate can be explained by the fact that the infiltration capacity of most soils in the catchment is greater than the highest rainfall intensity used in the present study. It is noteworthy that the time to runoff was not statistically correlated with rainfall intensity, suggesting that, in the environments represented in this study, surface runoff is probably less related to infiltration excess processes than to other runoff generation parameters (*i.e.,* saturation excess processes) (Lana-Renault et al., 2007). Rainfall intensity was not significantly correlated with sediment variables, again suggesting the protective effect of vegetation against raindrop impact.

Figure 6
RELATIONSHIP BETWEEN RAINFALL INTENSITY AND INFILTRATION RATE FOR THE 46 RAINFALL SIMULATION TESTS



Hydrological and sediment responses were also analyzed with respect to north- and south-facing slope aspects (Table V). The wetting front was statistically deeper (18.4 cm) in the former than in the latter (15.5 cm), and significant differences were also found in the sediment response, with a higher suspended sediment concentration (SSC) for south-facing slopes than for those with a northerly aspect (maximum SSC=8.4 and 2.3 g l^{-1}, respectively). There were

Table 5
MEAN HYDROLOGICAL AND SEDIMENT RESULTS FROM THE RAINFALL SIMULATIONS TESTS IN RELATION TO SLOPE ASPECT (NORTH AND SOUTH FACING)

	North (n=32)	South (n=14)	ANOVA, *p*
Time to runoff (s)	1084	888	*0.176*
Wetting front (cm)	18.4	15.5	*0.051*
Infiltration rate (mmh_{-1})	53.1	53.8	*0.316*
Averaged SSC (gl^{-1})	1.4	7.1	*0.024*
Maximum SSC (gl^{-1})	2.3	8.4	*0.016*
Sediment detachment ($gm^{-2}h^{-1}$)	3.6	4.5	*0.618*
Veg. cover (%)	81.6	66.4	*0.039*

no significant differences in time to runoff, infiltration rate, or sediment detachment between north- and south-facing slopes. However, the results suggest that south-facing slopes tend to respond more rapidly to rainfall (888 *vs*. 1084 sec) and produce slightly more sediment (4.5 *vs*. 3.6 g m^{-2} h^{-1}). These differences may be related to vegetation cover density, which was significantly higher on north-facing slopes, and contrasting soil types. As a consequence of severe erosion after land abandonment the soils of south-facing slopes are impoverished and degraded, a condition exacerbated by the steeper slope and sunny orientation (Navas et al., 2008). Rendsic leptosols and calcaric regosols have low organic matter content, and consequently have poor aggregate (Tisdall and Oades, 1982) and structural (Farres, 1987) stability. In contrast, deep and well-developed haplic kastanozems and haplic phaeozems predominate on north-facing slopes, which have a lower gradient, and a dense vegetation cover composed of a scrub layer where *Genista scorpius* predominate and a herbaceous cover underneath. These soils have high organic matter content, and consequently show greater aggregate and structural stability (Seeger & Ries, 2008).

4.4. Implications at the catchment scale

The relatively high infiltration rates found in plots in the three abandoned fields, the good correlation with rainfall intensity, and the relatively long times to runoff suggest the potential importance of water storage in the soil, particularly in relation to more degraded environments (*e.g.,* badlands). These results are consistent with research at the catchment scale, which has demonstrated that the streamflow response at the outlet of the catchment is strongly determined by water reserves therein (García-Ruiz et al., 2005), especially the development of saturated areas (Lana-Renault et al., 2007). Similarly, the small sediment response observed in the three different land covers in abandoned fields is consistent with the finding that slopes within the catchment have limited geomorphic activity, and soil erosion is concentrated in a few places (Lana-Renault and Regüés, 2009). The low erosive response found in the present study (with sediment concentrations less than 10 g l^{-1}) may also explain why sediment yield at the catchment scale is dominated by solutes, which represent more than 60% of the annual sediment yield (García-Ruiz et al., 2008).

A result obtained in this work is that the hydrological and erosion response is similar in scrubland and grassland, confirming previously reported results in experimental plots (García-Ruiz et al., 1995). This result is really interesting in terms of land management because the implementation of scrub clearance (i.e., substitution of scrubs by grassland) conducted in some abandoned fields (Lasanta et al., 2009) would increase the fodder production for the extensive cattle, would diminish the fire risk and would improve the structure and aesthetic quality of the landscape.

V. CONCLUSIONS

Hydrological and sediment responses to simulated rainfall were studied in plots representative of three land cover types (scrubland, grassland, and rock fragment) in abandoned fields in the Central Spanish Pyrenees. Although the results of rainfall simulations must be interpreted carefully because of limitations in the methodology (Rickson, 2001), the results allow understanding the hydrological and geomorphological behavior of abandoned cultivated slopes subject to revegetation.

No significant differences were found among the hydrological responses of the three land cover types. Infiltration rates for the scrubland, grassland, and rock fragment covers were similar, and relatively high (53.7, 53.3 and 52.9 mm h^{-1}, respectively). Significant differences between rock fragment plot and vegetated plots were seen only for maximum sediment concentration and sediment detachment, with relatively moderate-to-low values for the former (mean values 5 g l^{-1} and 7.6 g m^{-2} h^{-1}, respectively), and low values for the latter (less than 2.5 g l^{-1} and less than 4 g m^{-2} h^{-1}, respectively).

The influence of vegetation cover and rock fragment cover on the hydrological and erosive responses of the plots was weak. Only sediment detachment showed a clear relationship, being negatively correlated with vegetation cover and positively correlated with rock fragment cover; this illustrates the protective role of vegetation against splash. Significant hydrological and sediment differences were found between north- and south-facing slopes. The former had longer times to runoff, deeper wetting fronts, and a smaller erosive response. On south-facing slopes the hydrological response was more rapid and the sediment response greater. Differences in vegetation cover density (higher densities on north-facing slopes) partly explain these differences in behavior, which may also be related to the contrasting quality of the soils, which were much more developed on north-facing slopes (Dunjò et al., 2003).

It has been well-demonstrated that the expansion of natural vegetation following farmland abandonment moderates the hydrological and sediment behavior of slopes. The plot scale results of the present study, which show the small hydrological response of abandoned fields, and high infiltration rates, suggest the potential importance of water storage in the soil. The results also confirm the low geomorphic activity of the slopes reported in catchment studies, with low values for sediment detachment found even at high rainfall intensities. However, the process of natural revegetation is irregular and determined by many factors including management of the land prior to and since abandonment, and topographic features. In the Central Pyrenees, south- facing slopes were cultivated for a longer time and more intensively than were north- facing slopes, and show signs of major degradation (Seeger et al., 2004). The plot scale results suggest that differences in the hydrological and sediment responses are mostly related to the slope aspect. Past farmland practices introduced heterogeneity into the landscape, and this remained after abandonment. Ongoing studies that integrate slopes and catchments and consider a variety of scales will need to take this heterogeneity into account if the complexity of the hydrological and sediment responses of Mediterranean mountains is to be better understood.

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