



Water-related ecological impacts of rill erosion processes in Mediterranean-dry reclaimed slopes

M. Moreno-de las Heras^{a,*}, T. Espigares^b, L. Merino-Martín^b, J.M. Nicolau^c

^a Faculty of Engineering and Built Environment, School of Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia

^b Departamento de Ecología, Universidad de Alcalá, Alcalá de Henares (Madrid), E-28871, Spain

^c Departamento de Agricultura y Economía Agraria, Escuela Politécnica Superior de Huesca, Universidad de Zaragoza, Huesca, E-22071, Spain

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ABSTRACT

Soil moisture is considered the main limiting factor governing the structure and dynamics of vegetation in drylands. Soil erosion is perceived as a critical process affecting these systems, especially when rill formation occurs, as rill networks can condition the availability and spatial distribution of soil moisture. To assess the impact of soil erosion processes on the dynamics of Mediterranean-dry reclaimed systems, during the 2005–06 hydrological year we monitored the soil moisture regime (temporal availability and spatial distribution) and the associated responses describing vegetation performance (plant water status and potential seed germination) and vegetation structure in five coal-mining reclaimed slopes subjected to different rill erosion rates (from 0 to about 70 t ha⁻¹ year⁻¹). Rill network development leads to increased runoff connectivity and to concentration of water flow along the channeling network. As a result, water loss from the slope system is maximized. Simultaneously, the spatial distribution of soil moisture is ruled by the pattern of geomorphic forms (rill and interrill units). The ecological consequences are led by the intensification of water stress and the occurrence of unfavorable conditions for plant recruitment and natural colonization, causing a non-linear decline of species richness and aboveground biomass at the slope scale level. When dense rill networks are developed, long-term effects of erosion result in a sharp ecosystem transition to a very simple and low productive plant community spatially organized in downward spots adjacent to the rills, where plants minimize simultaneously water stress and the mechanical disturbance associated to concentrated flows.

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1. Introduction

The analysis of the factors determining the temporal and spatial patterns of soil moisture is a fundamental task for the understanding of water-limited ecosystems, wherein the interactions between hydrological processes governing soil moisture and vegetation are particularly coupled (Wilcox and Newman, 2005). Indeed, water availability is widely recognized as the main controlling resource for vegetation structure and dynamics in both natural and human-made environments under Mediterranean-dry climate (Cantón et al., 2004; Tormo et al., 2006).

The availability and spatial distribution of this limiting resource can be noticeably altered when accelerated soil erosion occurs, affecting ecosystem dynamics and function (Thornes, 1985; Pimentel et al., 1995). The loss of water by runoff in highly eroded slope systems is maximized by different mechanisms: the reduction of water infiltration by surface crust formation and cross-slope surface roughness reduction, and the efficient evacuation of water flows from

the slope by rill networks, which increase runoff connectivity on the slopes and provide efficient pathways to drive water out of the system (Lal, 1998; Nicolau, 2002; Bracken and Croke, 2007).

A consistent reduction of water availability induced by soil erosion processes could promote the activation of a long-term self-reinforcing degradation process, reducing plant growth and, consequently, increasing the intensity of erosion and the associated loss of water by surface runoff (Illius and O'Connor, 1999; Wilcox et al., 2003). In fact, the soil–vegetation system has feedback mechanisms which regulate soil formation, vegetation development and erosion–sedimentation processes (Puigdefábregas, 2005). However, although the positive influence of vegetation increasing infiltration rates and decreasing soil erosion has been widely documented, less attention has been paid to the ecological effects of soil erosion (Jiao et al., 2009; Wainwright and Parsons, 2010). In this way, several works indicate a critical role of the knowledge of erosion–vegetation interactions for the comprehension of degradation processes in water-limited environments, especially in the present context of land use and climate changes (Thornes, 2004; Zehe and Sivapalan, 2009).

Reclaimed slopes derived from opencast mining and road building activities are particularly vulnerable to the effects of accelerated soil erosion processes (Loch, 2000; Bochet and García-Fayos, 2004). The

* Corresponding author. Tel.: +61 02 4921 5432; fax: +61 02 4921 6991.

E-mail address: Mariano.Morenodelasheras@newcastle.edu.au
(M. Moreno-de las Heras).

particular characteristics of freshly reclaimed soils (e.g. poorly developed, massive structure) in addition to the frequent occurrence of mistakes in the geomorphological design can lead to the genesis and concentration of important amounts of overland flow, promoting soil erosion processes (Nicolau, 2003; Hancock and Willgoose, 2004). The development of rill and gully networks in these reclaimed systems can markedly limit water availability and modify the spatial distribution of soil moisture at the slope scale, by reducing the opportunities for down-slope runoff re-infiltration and by concentrating the water flow along the channeling network (Biemelt et al., 2005; Moreno-de las Heras et al., 2010).

A previous regional work carried out in reclaimed coal-mining slopes of Mediterranean-dry Spain identified rill erosion as a driving force constraining the long-term vegetation succession (Moreno-de las Heras et al., 2008). Also, Espigares et al. (in press) documented the impact of soil erosion processes on vegetation performance in these reclaimed environments, suggesting a desiccant filtering effect of rill erosion for plant colonization. In these highly eroded slopes vegetation is represented by a very scarce and simple community, essentially made up of a few aged *Medicago sativa* L. (alfalfa) plants growing on interrill areas (avoiding the unstable nature of rill beds) without apparent plant recruitment. This is a perennial legume introduced by revegetation which is able to survive intense periods of water deficit thanks to its extensive tap root system and its ability to remain dormant, shedding leaves and stems, when soil moisture is scarce (Bell et al., 2007).

The purpose of this investigation is the analysis of the soil moisture regime (i.e. temporal availability and spatial distribution of soil moisture) and its ecological implications for vegetation in five reclaimed coal-mining slopes of Mediterranean-dry Spain subjected to different soil erosion intensities since their construction. Therefore, this work intends to improve the understanding of the ecological effects of soil erosion in water-limited reclaimed environments, applying an ecohydrological perspective. Both species specific and plant community levels are considered for analysis. In this way, performance and pattern analysis on vegetation (i.e. plant water status, plant spatial distribution and potential seed germination in field conditions) especially focuses on alfalfa species, as this is the essential component of vegetation in the analyzed eroded landscape, while structural attributes (i.e. diversity and aboveground biomass) are considered at the slope scale plant community level.

Our main hypothesis is that soil erosion processes alter water availability for vegetation and the spatial distribution of soil moisture, especially when rill network development occurs. We expect that higher soil erosion rates will affect vegetation by increasing plant water stress and, simultaneously, by reducing potential seed germination in field conditions. Likewise, we expect that plant spatial distribution will reflect the pattern of soil water availability on the slopes.

2. Site description

This work was carried out in the *Utrillas* field site, which is located in the reclaimed mine *El Moral* (*Utrillas* coalfield), Central-Eastern Spain (40°47'24" N, 0°47'24" W, 1100 masl; Fig. 1a). Mean annual air temperature is 11 °C (6.8 °C in December and 23.5 °C in July). The local moisture regime is Mediterranean-dry (*sensu* Papadakis, 1966): mean annual precipitation is 466 mm (concentrated in spring and autumn) and potential evapotranspiration is 758 mm. Vegetation development in this area is constrained by a long frost period (from October to April) and an intense summer drought (from June to October).

The study site consists of five 30 m wide adjacent reclaimed slopes located in the northern side of a spoil bank. These slopes were restored during 1988–89 by the *Minas y Ferrocarril de Utrillas S.A.* company using the same treatments. Slope angle is 20°; the substrate

used to cover the spoil bank is overburden material from the *Escucha* Cretaceous formation, of *Albian* age. This is a clay-loam textured spoil (kaolinitic–illitic mineralogy) with basic pH (Table 1). Revegetation was undertaken by sowing a commercial seed mixture of perennial grasses and leguminous herbs.

In spite of having very similar initial features, rill erosion has accelerated to varying degrees of intensity, mainly because a flawed geomorphological design has enabled excessive amounts of overland flow to be generated from up-slope water-contributing areas of different length (Fig. 1b). In fact, a bare and nearly flat area (gradient 4–6°, 6–9 m long) is connected to the top of the two most eroded slopes (slopes 1 and 2), a bare steep bank (gradient 40°, 3–7 m long) is connected to the top of the two moderately eroded slopes (slopes 3 and 4), while there are no connected water-contributing structures at the top of the least eroded slope (slope 5). Eighteen years of soil erosion processes of different intensity (rill erosion rate from about 70 t ha⁻¹ year⁻¹ in slope 1 to 0 t ha⁻¹ year⁻¹ in slope 5) have induced large differences in vegetation development (total vegetation cover ranging from about 1% in slope 1 up to 60% in slope 5), vegetation composition (relative abundance of alfalfa ranging from about 80% in slope 1 to 10% in slope 5) and associated soil traits (soil organic matter ranging from about 0.5% in slope 1 to 2% in slope 5) following a degradation gradient (Table 1). The characteristics of the rill networks vary largely between the conditions represented by these slopes: the two most eroded slopes (slopes 1 and 2) exhibit very dense and integrated rill networks (rill density *circa* 1 m m⁻²); the two moderately rilled slopes (slopes 3 and 4) show discontinuous networks interspaced by spotted splays where rills break off (rill density 0.3–0.6 m m⁻²); rills are absent in slope 5 (Fig. 1b, Table 1). A more detailed description of this field site can be found in Moreno-de las Heras (2009) and Moreno-de las Heras et al. (2009, 2010).

3. Methods

3.1. Geophysical data sampling

3.1.1. Soil moisture dynamics

During the 2005–06 hydrological year (from October 2005 to October 2006), soil moisture (% v/v) was monitored in the five experimental slopes using Time Domain Reflectometry technology (hereafter TDR). A network of sensors, placed on different positions (interrill and rill geomorphic units) and soil depths within the slopes, was used. In each slope, TDR sensors were installed in eight soil profiles located in different positions spanning the whole slope extension from top to foot: four on interrill units and other four on rill microsites (except in slope 5 where rill networks are absent). On interrill soil profiles, TDR sensors were horizontally inserted at 5, 25, 50 and 80 cm depth; on rill profiles, sensors were inserted at 5, 25 and 50 cm depth. Soil moisture determinations were performed periodically (each 15 days without rain and 24 h after each rainfall event) using a TDR cable tester (Tektronix® 1502 C), following the guidelines of Cassel et al. (1994).

Supplementary weather information (daily precipitation and air temperature) was recorded during the study period in an automatic station (GroWeather, Davis®) located about 400 m from the experimental slopes.

3.1.2. Hydrological characterization of the experimental slopes

In order to determine the characteristic soil water retention curves of the experimental slopes, five composite soil samples were collected from the top 10 cm in each slope (each formed by six subsamples distributed at random). A standard pressure chamber (Klute, 1986) was used to determine soil water content (% v/v) at five different pressures ranging from saturation to the permanent wilting point ($\Psi=0, -0.01, -0.03, -1.00, -1.50$ MPa). Parameterization of soil water retention characteristic curves was made according to van Genuchten (1980).

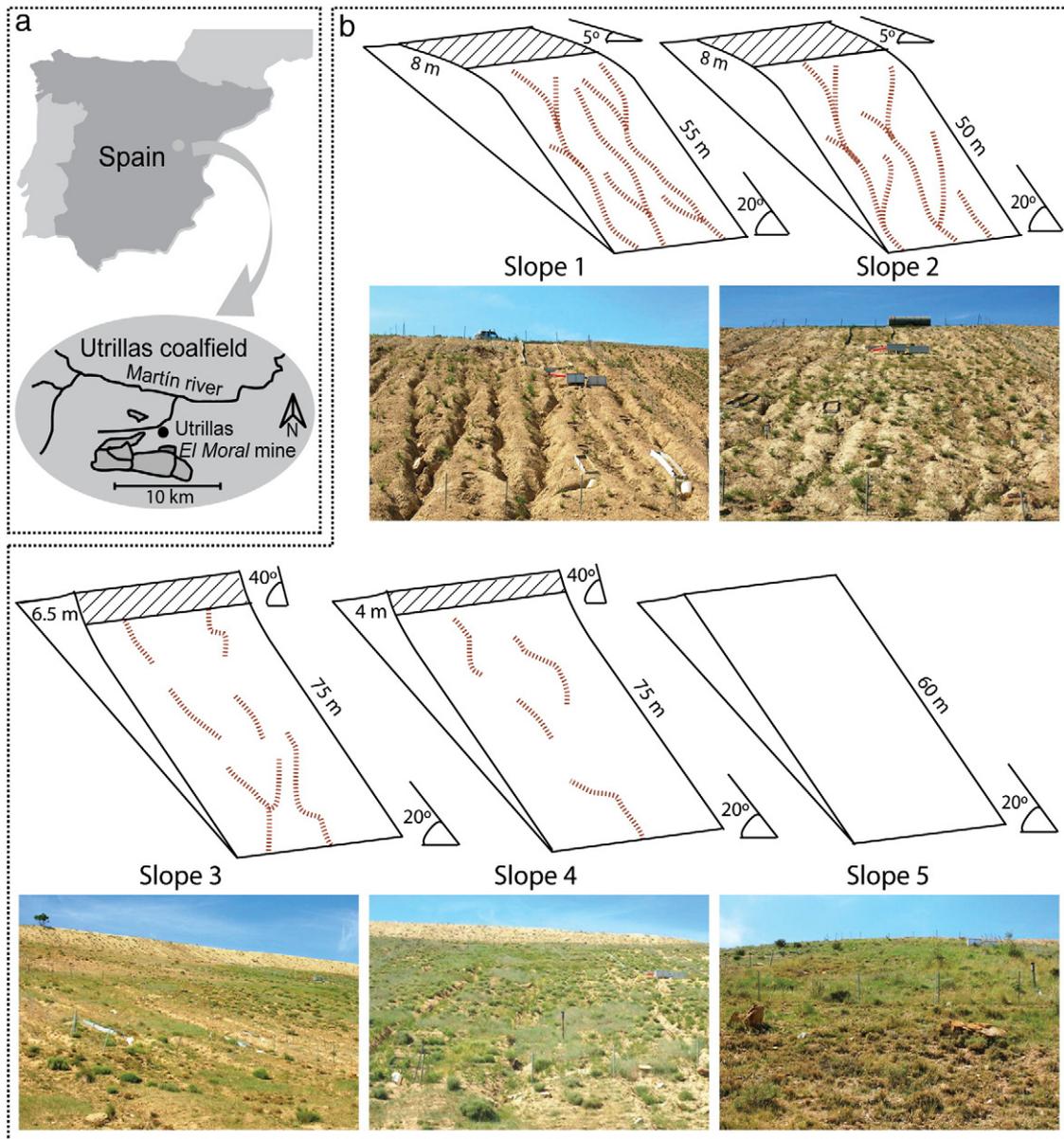


Fig. 1. The Utrillas field site: (a) location map; (b) sketch map and frontal view of the five experimental slopes. Striped surfaces located at the top of the slope represent the up-slope water-contributing areas; dotted lines within the schematic drawing of the slopes represent the rill networks.

Rill network metrics were previously described in Moreno-de las Heras (2009). The total length of rills on the entire extension of each slope was measured, by stretching a tape along the rill networks. Rill density was subsequently calculated as the ratio of the total linear length of the rill networks to the surface area of each slope. Rill sections (width and depth) were determined in all rills intercepted by three equidistant cross-slope transects of 30 m length. The historical rill erosion rates of the slopes were quantified using the former rill network dimensions (density and rill sections) as well as the bulk soil density and slope age from reclamation, following the methodology proposed by Morgan (1995).

Two hydrological studies carried out in the same experimental slopes were used as sources of additional information for discussion purposes: the interrill soil infiltration capacity, the annual cumulated runoff measured in large bounded plots within the slopes as well as the down-slope runoff re-infiltration rates of the slopes (Moreno-de las Heras et al., 2009; Moreno-de las Heras et al., 2010). The interrill soil infiltration capacity was depicted as the final infiltration rates (Interrill f_c , mm h^{-1}) from a series of rainfall simulation experiments (15

experiments in each slope on 0.24 m^2 plots at 63 mm h^{-1} rainfall intensity) reported in Moreno-de las Heras et al. (2009). Broad scale annual cumulative runoff rates, measured as percentage of total precipitation (2005–06 Q_c , %), were recorded during the 2005–06 hydrological year in bounded $3 \text{ m wide} \times 15 \text{ m long}$ runoff plots (Moreno-de las Heras et al., 2010). Finally, down-slope runoff re-infiltration rate (2005–06 R_{ri} , %) was assessed by the scale variation of unit-area runoff comprised between 1 m and 15 m long runoff plots during the same period (Moreno-de las Heras et al., 2010). This information is summarized in Table 1.

3.2. Ecophysical data sampling

3.2.1. *M. sativa* plant water status

Two campaigns of water potential measurements were carried out in mid June and late August 2006, when soil moisture reached the lowest values. Leaf water potential (Ψ_l , MPa) of *M. sativa* plants distributed throughout the whole extension of the slopes was determined using a pressure chamber (SKPM 1400, Skye Instruments®), following the

Table 1
Basic characteristics of the five experimental slopes.

	Slope 1	Slope 2	Slope 3	Slope 4	Slope 5
<i>Topography</i>					
Slope length ^a (m)	55	50	75	75	60
Slope gradient ^a (°)	20	20	20	20	20
Length of water-contributing area ^a (m)	8.0	8.0	6.5	4.0	n.a.
Aspect ^a	North	North	North	North	North
<i>Soil traits</i>					
Stoniness ^b (%)	22.2	24.7	26.2	25.2	24.5
Texture ^b	Clay loam				
pH ^b	8.0	8.0	8.0	8.0	7.9
Organic matter ^b (%)	0.6	0.6	1.3	1.5	2.0
<i>Vegetation traits</i>					
Vegetation cover ^b (%)	1.1	8.2	27.8	44.3	59.4
<i>Medicago sativa</i> rel. abund. (%)	83.1	75.3	39.7	21.3	11.1
<i>Hydrological features</i>					
Rill density ^b (m m ⁻²)	0.95	0.78	0.58	0.30	0.00
Rill erosion rate ^b (t ha ⁻¹ year ⁻¹)	71.41	45.03	16.95	7.86	0.00
Interrill <i>fc</i> ^a (mm h ⁻¹)	11.5	10.1	20.5	22.7	36.7
2005–06 <i>Qc</i> _{15 m plot} ^c (%)	21.46	21.01	15.92	9.32	4.42
2005–06 <i>Rri</i> _{1–15 m plots} ^c (%)	27.17	19.72	31.78	55.23	79.47

Abbreviations: rel. abund.: relative abundance; *fc*: hortonian final infiltration rate; *Qc*: runoff rate; *Rri*: runoff re-infiltration rate; n.a.: not applicable.

^a Data from Moreno-de las Heras et al. (2009).

^b Data from Moreno-de las Heras (2009).

^c Data from Moreno-de las Heras et al. (2010).

methodology proposed by Brown and Tanner (1981). Water potential measurements were restricted to three of the five studied slopes (slopes 2, 3 and 5), as the long operation time required made it impossible to obtain a representative minimum of samples in all slopes. A three-factorial approach was adopted, taking into account slope, position and time. Then, to assess the influence of rill networks in the water status of vegetation (by spatially distributing soil moisture), position within the interrills was considered: Central and Lateral position (i.e. distant and close to rills respectively), as no alfalfa plant was found inside the rills. Additionally, two different moments were considered: pre-dawn (from 05:00 to 07:00 h) and mid-day (from 14:00 to 16:00 h). On the whole, 24 measurements homogeneously distributed by position and time were performed per campaign in slopes 2 and 3, while only 12 measurements per campaign in slope 5, as position was not considered (rills are absent in this slope).

3.2.2. *M. sativa* plant spatial distribution

To assess the impact of rill networks on the spatial organization of vegetation, the distribution of *M. sativa* plants was analyzed in the rilled slopes (slopes 1, 2, 3 and 4). In each slope, 200 quadrats (25 × 25 cm²) were randomly distributed within the interrills (no alfalfa plant was found inside the rills). The number of alfalfa plants which appeared inside each quadrat (plant abundance) was counted. Additionally, the distance to the nearest rill was measured, as well as the width of the interrill where each quadrat was placed. A new variable that describes quadrat position within interrill areas (plant centrality on interrill) was calculated by dividing the distance to the nearest rill by the half of interrill width (which represents the maximum possible distance to the nearest rill). Thus, plant centrality adopts values ranging from 1 (quadrats placed just in the center of the interrill) to about 0 (quadrats in lateral position, adjacent to a rill).

3.2.3. *M. sativa* seed germination along a controlled gradient of water potential

M. sativa seeds of the variety used during the restoration of the Utrillas fieldsite, (Tierra de Campos, Fombellida, 2001), were obtained from a local

seed supplier (Semillas Batlle S.A.), due to the impossibility to collect them in the field, as seed production is very low. Germination of alfalfa seeds was studied under eight different water potentials ($\Psi = 0, -0.03, -0.10, -0.20, -0.33, -0.62, -1.10$ and -1.50 MPa) representing soil moisture values between saturation and the permanent wilting point. Water potentials were simulated using polyethylene glycol concentrations (PEG-6000) following the standard equations of Michel (1983). Ten replicates per water potential level were prepared. Each replicate consisted of 25 seeds placed in a 9 cm diameter Petri dish, on a bed composed of a layer of hydrophilic cotton and filter paper. Replicates were moistened with 37 ml of PEG solutions. The experiment took place inside a phytotron under controlled conditions (day length = 12 h, air temperature = 20 °C, relative air humidity = 75%). The experiment lasted 34 days. Seed germination was monitored every three days; a seed was considered germinated when at least 2 mm of radicle had emerged. Germination rate (%) was calculated as the percentage of germinated seeds during the experiment.

3.2.4. Plant community structural attributes

Plant community determinations took place in spring 2006. In each slope, vegetation cover and composition were determined in thirty 0.50 × 0.50 m² plots, distributed at random. *M. sativa* relative abundance (%) was calculated as the ratio between alfalfa cover and total vegetation cover. Species richness was assessed by the total of species. Aboveground biomass was collected in six additional 0.50 × 0.50 m² plots and subsequently oven-dried (60 °C, 72 h) and weighed (g m⁻²).

3.3. Data analysis

Differences between and within slopes (rill and interrill geomorphic units) on 2005–06 soil moisture dynamics were analyzed using repeated measures ANOVA, with time as within subjects factor and slope and geomorphic units as between subjects factors. Special attention was paid to interrill soil moisture dynamics, as these were the areas where vegetation was present (it must be stressed that rill microsites had hardly any vegetation cover due to the physical disturbance provoked by concentrated flows). Thus, to obtain a synthetic indicator of the impact of soil erosion processes on the soil water content available for vegetation at the slope scale, the best fitting regression function was determined between the historical rates of rill erosion acting in the slopes and the averaged soil moisture measured on interrill soil profiles after rainfall occurrence (24 h after each rainfall event) along the monitored year.

Factorial ANOVA and post-hoc Tukey tests were used to determine differences on alfalfa leaf water potential for the two campaigns (mid June and late August). Slope, time (pre-down and mid-day) and plant position within interrill areas (central and lateral position) were considered subject factors for the analysis.

The influence of rill networks on the spatial distribution of alfalfa plants was analyzed using Spearman's *R* correlation coefficient between plant abundance and plant centrality, which describes relative plant position within interrills.

To analyze the effect of soil water potential on the germination rate of alfalfa seeds, a classical sigmoid shape response function was fitted. From this relation we determined the water potential threshold values for seed germination. These threshold values were transformed into soil water content using the parameterized characteristic curves of soil water retention. We used the obtained soil moisture threshold values to analyze the potential germination performance on field conditions in the five experimental slopes. Additionally, we considered a temperature threshold value for seed germination of 10 °C air temperature, since *M. sativa* seeds (particularly those of the studied variety) show a sharp decrease of germinability below this temperature (Brar et al., 1991; Fombellida, 2001). Thus, to analyze the potential germination on field conditions we used both soil moisture values on interrill areas (where

vegetation is actually growing) at 5 cm depth and daily mean air temperature measured during the 2005–06 hydrological year (2005–06, precipitation = 615 mm). Supplementary data from a dryer hydrological year (1989–90, precipitation = 270 mm) only available for slope 2 (Nicolau, 2002) was used to evaluate the potential performance in a contrasted situation.

Finally, the impact of soil erosion processes on vegetation at the slope scale plant community level was assessed by determining the

best fitting regression equation between the historical rill erosion rates of the slopes and two structural plant community attributes (i.e. species richness and aboveground biomass).

All statistics have been carried out using the STATISTICA 6.0 package (Statsoft, 2001). Data analyzed using ANOVA and Tukey tests fulfilled parametric assumptions, so no data transformation was carried out. The scientific names of the species are in accordance with Flora Europaea (Tutin et al., 1964–1980).

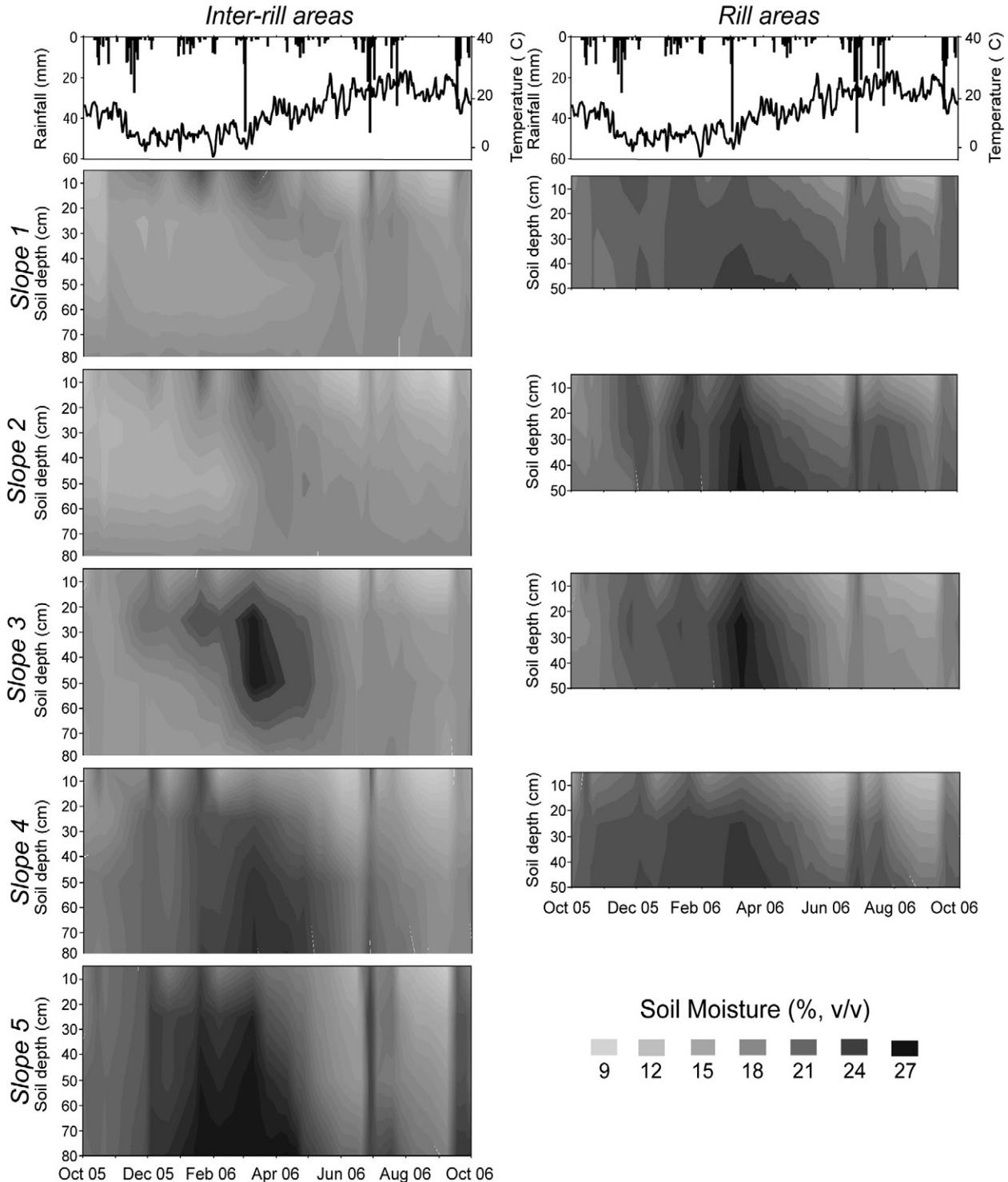


Fig. 2. 2005–06 volumetric soil moisture dynamics in the five experimental slopes. Grey-scaled graphs represent mean soil moisture dynamics of the interrill (left-side) and rill (right-side) soil profiles along the hydrological year. Weather information (daily precipitation and daily mean air temperature) along the monitored period is represented by the top-side graphs.

4. Results

4.1. Soil moisture dynamics

Soil moisture dynamics during the 2005–06 hydrological year followed the annual pattern of precipitations and temperature (Fig. 2). Soil moisture recharge was concentrated mainly during autumn and winter months; nevertheless, some particular increases of soil moisture were generated by summer storms. Major evapotranspiration losses took place in spring and summer.

The spatial distribution of soil moisture was associated to the pattern of rills and interrills (Fig. 2). In general, higher soil water contents were observed on rill than on interrill units ($F_{1,72} = 46.43$, $P < 0.01$). However, soil moisture was differently affected by the type of geomorphic unit (i.e. interrill versus rill areas) in each of the four rilled slopes (slope \times geomorphic unit: $F_{3,72} = 3.37$, $P < 0.05$). In fact, soil moisture was significantly higher on rill soil profiles in the most densely rilled slopes (slope 1: $F_{1,18} = 27.06$, $P < 0.01$, slope 2: $F_{1,18} = 36.91$, $P < 0.01$), while these differences were less important or even disappeared in the two slopes with discontinuous rill networks (slope 3: $F_{1,18} = 10.51$, $P < 0.05$, slope 4: $F_{1,18} = 1.36$, $P = 0.26$).

No differences in soil moisture were found between the slopes on rill areas ($F_{3,44} = 0.55$, $P = 0.65$, Fig. 2). On the other hand, important differences in soil moisture were found on interrill areas ($F_{4,60} = 6.15$, $P < 0.01$). In this way, soil moisture inputs on interrill soil profiles were much lower in the most eroded slopes (slopes 1, 2 and 3), while in slopes 4 and 5 these inputs were higher and resulted in a deeper wetting front (Fig. 2). This effect is well represented by a non-linear shape function with the soil erosion rates (Fig. 3), indicating a reduction of soil water inputs on interrill areas of about 30% in the most degraded conditions (slopes 1 and 2: $40\text{--}70 \text{ t ha}^{-1} \text{ year}^{-1}$ rill erosion) compared to the uneroded slope (slope 5: $0 \text{ t ha}^{-1} \text{ year}^{-1}$).

4.2. Vegetation performance and structure

4.2.1. *M. sativa* plant water status during the seasonal drought period

All *M. sativa* leaf water potential determinations were below -1.5 MPa (Fig. 4), indicating water-stressed plant conditions during the two campaigns (late spring in June and summer in August). Differences in leaf water potential between the slopes showed the

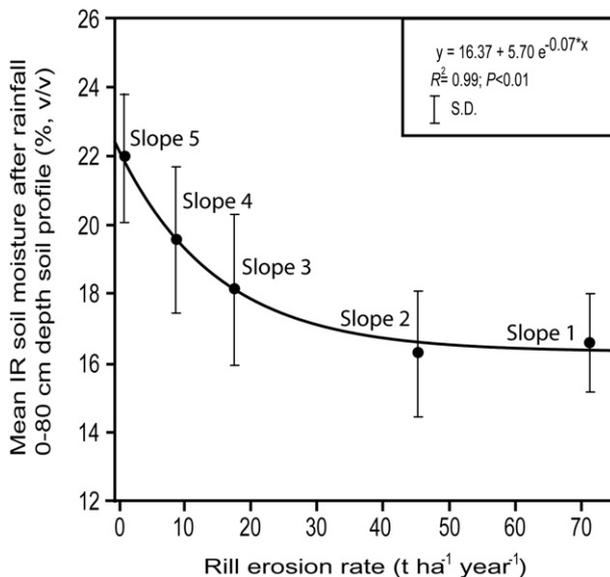


Fig. 3. Diagram representing the relation between soil moisture inputs on interrill soil profiles (annual mean volumetric soil moisture measured 24 h after rainfall occurrence) and the soil erosion rates of the slopes.

same pattern in both campaigns and measurement pulses (pre-dawn and mid-day): plants in the uneroded slope (slope 5) reached higher leaf water potential values than in the eroded slopes (slopes 2 and 3), where plants were significantly more water stressed (June: $F_{2,54} = 11.15$, $P < 0.01$, August: $F_{2,54} = 23.45$, $P < 0.01$, Fig. 4a and c). Worthy of notice are summer leaf water potentials reached in the eroded slopes (between -4.0 and -5.5 MPa), illustrating the intense water stress borne by vegetation in these degraded conditions.

Plant position within interrill areas also showed a significant effect in the rilled slopes (slopes 2 and 3): plants growing in central position were more water stressed than those growing in lateral positions (close to a rill), which generally showed higher pressure values (June: $F_{1,40} = 34.79$, $p < 0.01$, August: $F_{1,40} = 26.28$; $P < 0.01$, Fig. 4b and d). These differences were especially remarkable for mid-day leaf water potential.

4.2.2. *M. sativa* plant spatial distribution

In the most densely rilled slopes (slopes 1 and 2), the abundance of *M. sativa* plants showed a negative correlation with plant centrality on interrill areas (Table 2). Thus, in these slopes the abundance of growing alfalfa plants is higher on interrill borders, close to the rills, and decrease towards the middle of interrill areas. On the other hand, no significant correlation between plant abundance and relative plant position was found in slopes 3 and 4, where rill networks are discontinuously structured.

4.2.3. Potential germination of *M. sativa* seeds on field conditions

Data from the germination experiment under controlled conditions evidenced a significant effect of water potential on germination rate of *M. sativa* seeds (Fig. 5). Germination rate decreased sharply at water potential values ranging from -0.20 MPa to -0.60 MPa (Fig. 5a). For higher values seed germination was almost complete (circa 90%) while below it was almost negligible (c. 0%). These absolute rates of germination were obtained in a period of time ranging from 15 to 25 days from the start of the experiment (Fig. 5b). Water potential values defining the obtained experimental threshold for seed germination (-0.20 MPa and -0.60 MPa) correspond respectively to 16.76% (S.D. 1.56%) and 13.23% (S.D. 1.38%) volumetric soil moisture values. These values are reasonably homogeneous between the analyzed soil samples of the five experimental slopes, as no differences of soil moisture between slopes were detected at these pressure values ($\Psi = -0.20 \text{ MPa}$: $F_{4,20} = 0.90$, $P = 0.48$, $\Psi = -0.60 \text{ MPa}$: $F_{4,20} = 0.78$, $P = 0.55$).

The 2005–06 hydrological year was fairly humid as total precipitation was 615 mm (about 32% above the annual average). Daily mean air temperature remained below $10 \text{ }^\circ\text{C}$ during late autumn and winter (from early November to late March; Fig. 6a). Thus, throughout this period potential seed germination in the five slopes was constrained because of temperature limitations, according to Brar et al. (1991) and Fombellida (2001). Before this period, soil moisture at 5 cm depth reached values higher or equal to soil water potential levels of -0.20 MPa for more than 20 days in slopes 4 and 5. In the most eroded slopes (slopes 1, 2 and 3) these moisture values were reached only occasionally; nevertheless the -0.60 MPa water potential threshold was surpassed for a long period (Fig. 6a). Moisture dynamics, after air temperature exceeded $10 \text{ }^\circ\text{C}$ in spring, followed a similar pattern to early autumn (Fig. 6a): soil moisture in the uneroded slope (slope 5) surpassed the -0.20 MPa water potential threshold for a long time (more than 40 days), while soil moisture in the eroded slopes (slopes 1, 2, 3 and 4) remained between -0.20 and -0.60 MPa water potential range values for about two months. Thus, field conditions for *M. sativa* seed germination during this humid year were very favorable in the uneroded slope (slope 5). In highly and medium eroded slopes (slopes 1, 2, 3 and 4) field conditions were less favorable and probably allowed a limited seed germination and seedling recruitment.

The 1989–90 hydrological year was markedly drier, with a total precipitation of 270 mm (Nicolau, 2002), a 42% below annual average.

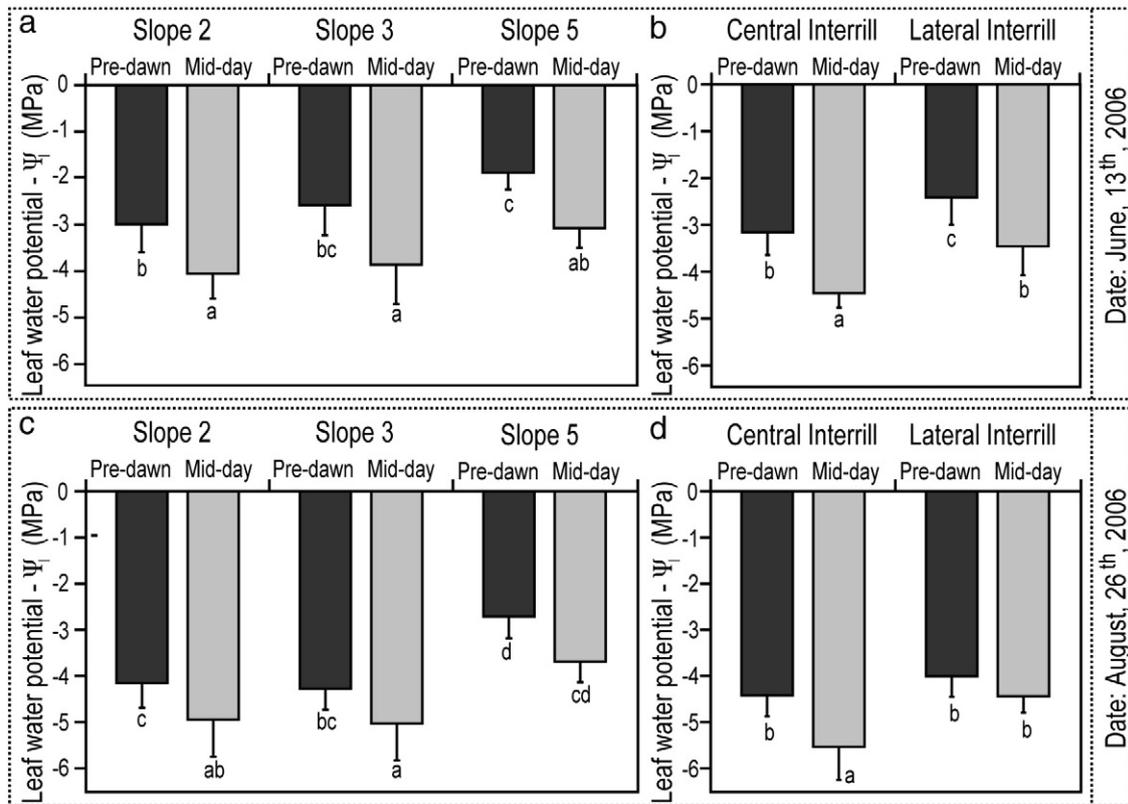


Fig. 4. *Medicago sativa* leaf water potential values (bars represent mean values and whiskers the standard deviation) obtained during the two measurement campaigns (mid June and late August). Left-side graphs (a and c) represent differences between slopes; right-side graphs (b and d) represent differences related to intertill plant position on the rilled slopes (slopes 2 and 3). Different lowercase letters (a–d) indicate significant differences in Tukey post-hoc tests ($P < 0.05$).

Soil moisture in the monitored slope (slope 2) only exceeded the -0.60 MPa water potential threshold during winter (from mid November to mid February) when air temperature remained below 10 °C (Fig. 6b). Thus, potential *M. sativa* seed germination was notably constrained in this highly eroded slope along this dry year.

4.2.4. Relation between soil erosion and slope scale plant community attributes

The analyzed plant community attributes were strongly related to the intensity of the rill erosion processes acting in the experimental slopes since their construction, indicating non-linear decreases of species richness and aboveground biomass with increasing soil erosion (Fig. 7). In fact, contrasting with the productive and diverse vegetation developed on the uneroded slope (slope 5: Biomass = 240 g m^{-2} ; $S = 37$ species), both ecological attributes showed very low values in the most eroded slopes (slopes 1 and 2: Biomass = $10\text{--}30 \text{ g m}^{-2}$; $S = 5\text{--}12$ species).

5. Discussion

Soil moisture dynamics in our reclaimed coal-mining slopes reveals an important influence of soil erosion processes on water

Table 2
Spearman's R correlation coefficients between *Medicago sativa* plant abundance and plant centrality on intertill for the studied rilled slopes (slope 5 is void of rills).

	Spearman's R	P
Slope 1	−0.331	0.000
Slope 2	−0.324	0.000
Slope 3	−0.073	0.272
Slope 4	−0.100	0.145

availability and spatial distribution of soil moisture, with important consequences for long-term vegetation performance and structure.

The emergence of a general geomorphic pattern constituted by rill and intertill units that conditions water availability for vegetation is an elemental process structuring water resources at the slope scale (Fig. 2). This effect is especially evident in the case of the most eroded slopes (slopes 1 and 2; rill erosion rate $>40 \text{ t ha}^{-1} \text{ year}^{-1}$). There, soil moisture penetration in intertill areas (where vegetation development is not hampered by the mechanical disturbance caused by concentrated water flows) is severely limited, while water resources are concentrated along the rill networks. This distribution is expected in highly eroded landscapes, where moisture penetration is usually shallow and generally patterned by the presence of runoff routing channeling forms which, at the same time, drive important amounts of water resources out of the slope system (van den Elsen et al., 2003; Cantón et al., 2004; Biemelt et al., 2005). In accordance, previous works carried out in this experimental site (Moreno-de las Heras et al., 2009, 2010) indicated that the pattern of generation and circulation of water flows in these highly eroded slopes (slopes 1 and 2) leads to an acute loss of precipitation during 2005–06 hydrological year in 15 m long plots, Table 1). These losses are ruled by the lack of vegetation influence on soil conditions, which limits infiltration capacity on intertills (Intertill f_c circa 10 mm h^{-1} , Table 1), as well as the high runoff connectivity imposed by the dense rill networks (rill density $0.8\text{--}1 \text{ m m}^{-2}$), which severely constrains runoff re-infiltration processes down the slope (2005–06 $R_{i-15 \text{ m plots}} < 30\%$, Table 1). This situation markedly contrasts with the unrilled slope (slope 5), where vegetation is discontinuously developed (c. 60% cover) and runoff (as sheet flow) is widely redistributed down the slope (2005–06 $R_{i-15 \text{ m plots}}$ c. 80%, Table 1), limiting the losses of water resources by surface runoff at about 5% of precipitation in 15 m long plots.

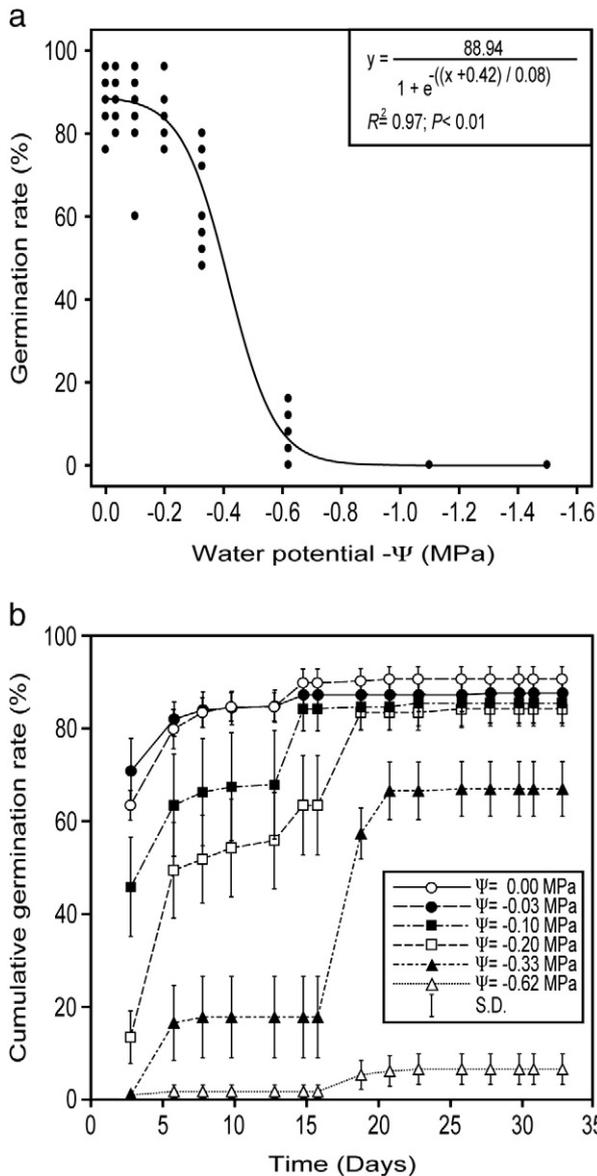


Fig. 5. Diagrams representing the relation between (a) *Medicago sativa* seed germination rate and water potential, and (b) *Medicago sativa* cumulative seed germination rate and experimental time (days).

The ecological consequences of the soil erosion processes acting in the studied Mediterranean-dry environment are led by the increase of water stress related to the associated loss of water resources. We observed higher levels of plant water stress in the eroded slopes along the drought period (late spring and summer, Fig. 4), as well as a non-linear decline in aboveground biomass parallel to the erosion related water availability reduction (Figs. 3 and 7). These outcomes are comparable with the general results obtained in cropping systems and rangelands affected by accelerated erosion processes, which point at an accentuation of water stress and productivity decline associated to the loss of water by surface runoff (Pimentel et al., 1995; Lal, 1998; Illius and O'Connor, 1999).

It is not by chance that vegetation composition in the most eroded analyzed slopes (slopes 1 and 2) is almost restricted to *M. sativa* species (more than 75% of total cover, Table 1), as this perennial legume has demonstrated a special ability to resist very intense periods of water deficit (Bell et al., 2007). Nevertheless, we have observed the lack of alfalfa recruitment in these highly eroded slopes, although some alfalfa seeds can actually be found on the soil seed bank (Espigares et al., in

press). Indeed, our results suggest that field conditions related to water availability in the eroded slopes show important restrictions for the germination of alfalfa seeds, possibly limiting plant recruitment (Fig. 6). Furthermore, these conditions could limit natural colonization by other species, since successful natural colonizing species of human-made slopes in Mediterranean-dry Spain generally show water potential based critical thresholds for seed germination (between -0.05 and -0.35 MPa, Bochet et al., 2007) more restrictive than those we obtained for alfalfa seeds (between -0.20 and -0.60 MPa). In fact, previous evidences have demonstrated that plant recruitment and natural colonization in these highly eroded slopes are seriously constrained by the accumulated impact of water scarcity in seedling emergence, survival, and in seed production, leading to a species-poor community dominated by some aged drought-tolerant alfalfa plants (Moreno-de las Heras et al., 2008; Espigares et al., in press). Accordingly, previous results obtained in highly eroded Mediterranean rangelands have documented very acute species losses leading to impoverished plant communities, generally dominated by few species especially drought-resistant (Guerrero-Campo and Montserrat-Martí, 2004).

The spatial organization of these simple alfalfa communities is conditioned by the consolidation of the interrill-rill pattern of soil moisture distribution. In the most eroded conditions, we observed a preferential distribution of alfalfa plants close to the edge of interrill areas (Table 2), where they have to face a less intense water stress (Fig. 4b and d) probably thanks to the deep intake of water resources around rill beds. Simultaneously, plants in these microsites are safe from the mechanical disturbance associated to concentrated water flows that are routed by the rills. The emergence of such vegetation pattern, formed by downward spots and stripes adjacent to the flow channeling forms, has been explained in water-restricted environments by the long-term interaction of the patterns of plant growth and senescence with the spatial distribution of both soil moisture and mechanical disturbance (Puigdefábregas and Sánchez, 1996; Saco et al., 2007). As Puigdefábregas et al. (1999) asserted, this vegetation pattern shows an exceptional incapacity to control runoff and sediment flows, probably reinforcing the degradation trend through the intensification of the loss of water and soil resources from the slope.

The configuration of this plant distribution pattern disappears in the medium eroded slopes (slopes 3 and 4: rill erosion rate $8\text{--}17\text{ t ha}^{-1}\text{ year}^{-1}$), where rill networks are spatially discontinuous and less densely developed (rill density $0.3\text{--}0.6\text{ m m}^{-2}$), and soil moisture differences between geomorphic units (rills and interrills) are attenuated (Fig. 2). In these slopes, the presence of spotted splays where rills break off could influence vegetation structure and distribution, since this kind of flow discontinuity provides localized areas where vegetation can be favored by the accumulation of water and soil resources (Wainwright et al., 2002). In fact, several perennial grasses (*Lolium perenne*, *Elymus hispidus* and *Dactylis glomerata*) are widely established in these areas where runoff is discharged and sedimentation occurs (Moreno-de las Heras, 2009), limiting the dominance of alfalfa plants in vegetation composition (*M. sativa* relative abundance: 20–40%, Table 1) and deleting the downward aligned pattern of plant distribution.

Both types of plant communities (*M. sativa* type and the more complex ones enriched by perennial grasses) are linked to the gradient of vegetation structure simplification promoted by rill erosion processes acting in the reclaimed slopes since their construction. In this way, the impact of such processes in plant community attributes (diversity and biomass) showed a characteristic non-linear trend (exponential negative, Fig. 7), as could be expected given the previous insights on the ecological effects of soil erosion (Thornes, 2004; Zehe and Sivapalan, 2009). Such non-linear relationships are distinctive expressions for the identification of critical degradation thresholds in water-limited landscapes, where feedbacks between biotic factors and abiotic processes can accelerate and make irreversible ecosystem transitions

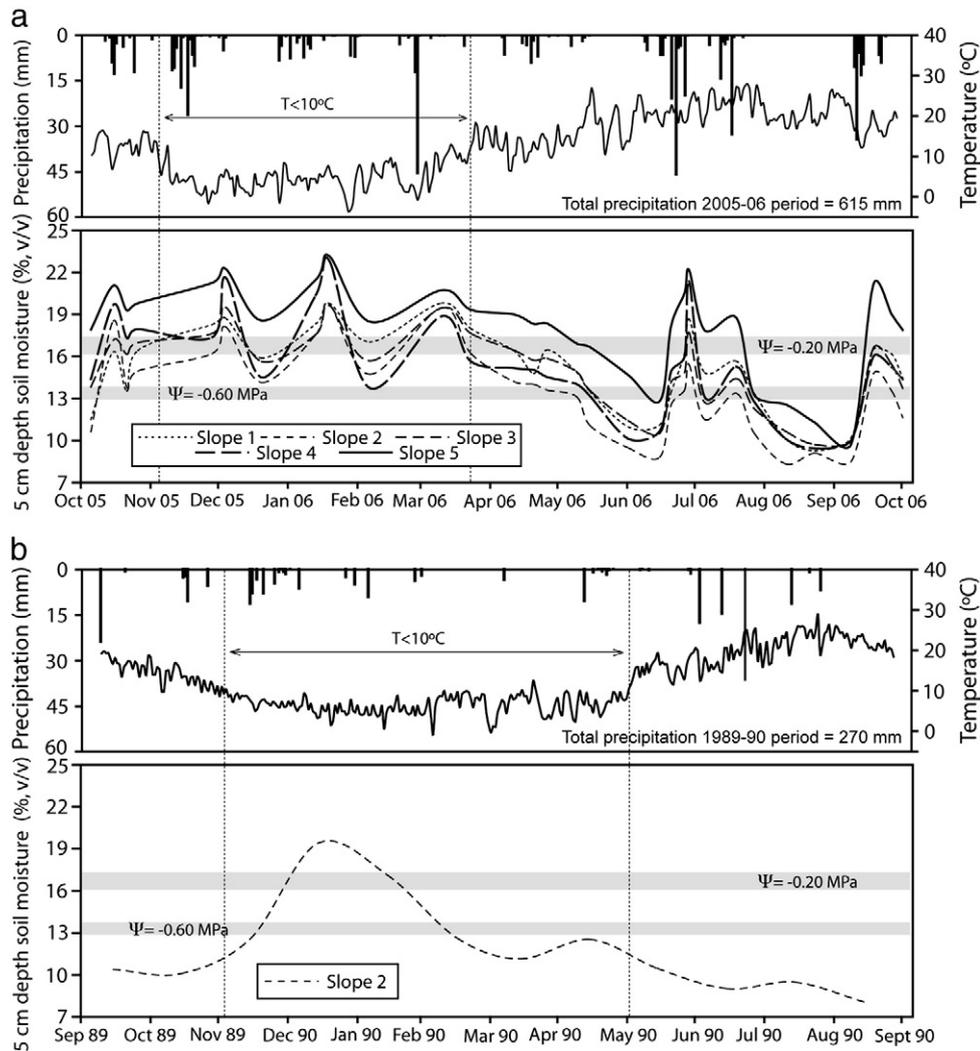


Fig. 6. Diagrams representing field conditions (air temperature and volumetric soil moisture at 5 cm depth) for *Medicago sativa* seed germination along (a) 2005–06 (all slopes included) and (b) 1989–90 (only slope 2 available, data from Nicolau, 2002). Critical air temperature threshold for seed germination is delimited by vertical dotted lines: below 10°C seed germination is unlikely, according to Brar et al. (1991) and Fombellida (2001). The obtained critical water potential threshold values for seed germination (over -0.20 MPa seed germination is successful, while below -0.60 MPa is negligible) are represented by horizontal grey bars (mean \pm SD).

(Suding et al., 2004; Solé, 2007; Okin et al., 2009). A degradation threshold in these reclaimed systems might exist at a rill erosion rate between 17 and 45 t ha⁻¹ year⁻¹, leading to a very impoverished and water-stressed ecosystem state where plant recruitment and colonization are severely constrained (i.e. the simple *M. sativa* plant communities). This agrees with previous findings obtained in heavily rilled reclaimed coal-mining slopes at the Mediterranean-dry regional scale, where an extensive human intervention designed to destroy or reduce the connectivity of the rill networks is required to set back the reduction of plant available water caused by the erosion process, hence facilitating vegetation recovery (Moreno-de las Heras et al., 2008; Espigares et al., in press).

More research is required to test the general applicability of the described interactions in other systems. Water scarcity has been argued as a common phenomenon explaining the lack of vegetation establishment in intensively rilled roadslopes under Mediterranean-dry climate (Bochet and García-Fayos, 2004; Bochet et al., 2007) which, together with our results, suggests the occurrence of a common mechanism of interaction between the rill erosion processes and vegetation dynamics in water-limited reclaimed slope ecosystems. More intricate might result the application of our findings in natural hillslopes. In fact, complex local variations of slope steepness and

aspect in long natural hillslopes can lead to important changes on the spacing and organization of the rill networks, conditioning the routing of the surface water fluxes as well as the spatial distribution of soil moisture, possibly obscuring the relationships described in this work.

6. Conclusions

Our results showed that the development of soil erosion processes with rill formation has a major role on the ecohydrological relations of Mediterranean-dry reclaimed sloping systems, by conditioning the availability and spatial distribution of water resources. As a result of the loss of water caused by the draining effect of rill networks, water stress increases in growing vegetation and, in addition, unfavorable conditions for plant recruitment and colonization occur, causing a non-linear decline of species richness and biomass at the slope scale level. In the long term, when dense rill networks are developed, soil erosion consequences result in an irreversible ecosystem change leading to a low productive and species-poor plant community spatially arranged by the rill-interrill geomorphic pattern of soil moisture and mechanical disturbance distribution. Reclamation strategies in drylands should especially take into account the non-linear nature of the vegetation–erosion relationships, preventing or

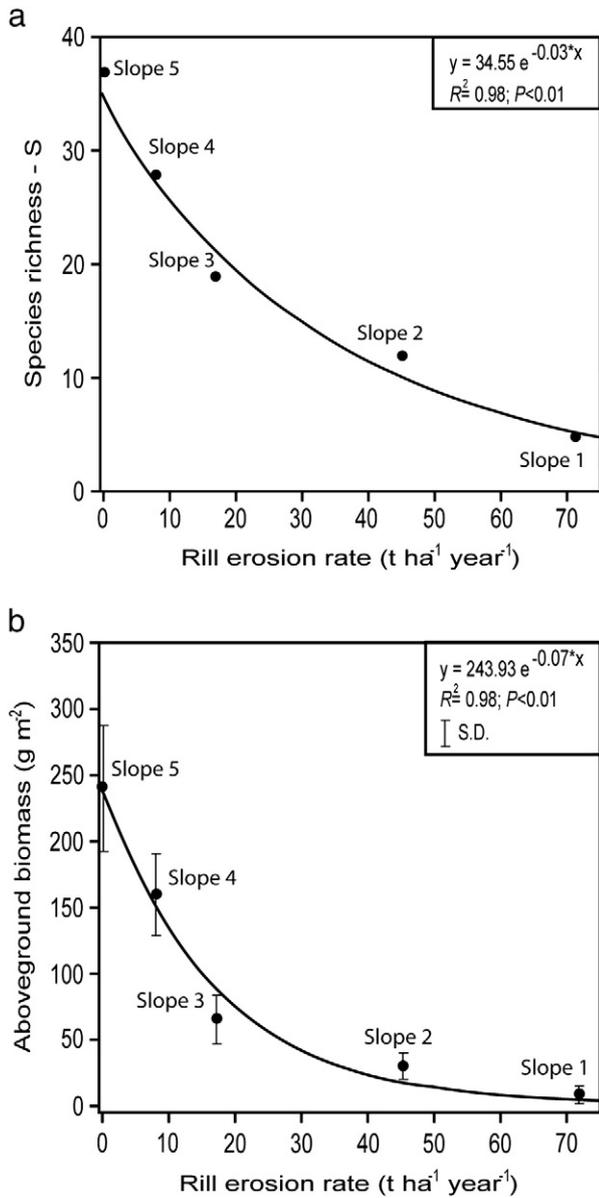


Fig. 7. Diagrams representing the relations between the soil erosion rates of the slopes and slope scale (a) species richness and (b) aboveground biomass (g m⁻²).

disrupting critical abiotic feedback loops which could promote irreversible ecosystem transitions (i.e. loss of water resources by rill networks).

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References

Bell, L.W., Williams, A.H., Ryan, M.H., Ewing, M.A., 2007. Water relations and adaptations to increasing water deficit in three perennial legumes, *Medicago sativa*, *Dorycnium hirsutum* and *Dorycnium rectum*. *Plant Soil* 290, 231–243.

- Biemelt, D., Schapp, A., Kleeberg, A., Grünwald, U., 2005. Overland flow, erosion, and related phosphorous and iron fluxes at plot scale: a case study from a non-vegetated lignite mining dump in Lusatia. *Geoderma* 129, 4–18.
- Bochet, E., García-Fayos, P., 2004. Factors controlling vegetation establishment and water erosion on motorway slopes in Valencia, Spain. *Restoration Ecology* 12, 166–174.
- Bochet, E., García-Fayos, P., Alborch, B., Tormo, J., 2007. Soil water availability effects on seed germination account for species segregation in semiarid roadslopes. *Plant Soil* 295, 179–191.
- Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes* 21, 1749–1763.
- Brar, G.S., Gomez, J.F., McMichael, B.L., Matches, A.G., Taylor, T.H., 1991. Germination of twenty forage legumes as influenced by temperature. *Agronomy Journal* 83, 173–175.
- Brown, P.W., Tanner, C.B., 1981. Alfalfa water potential measurement: a comparison of the pressure chamber and leaf dew-point hygrometers. *Crop Science* 21, 240–244.
- Cantón, Y., Solé-Benet, A., Domingo, F., 2004. Temporal and spatial patterns of soil moisture in semiarid badlands of SE Spain. *Journal of Hydrology* 285, 199–214.
- Cassel, D.K., Kachanoski, R.G., Topp, G.C., 1994. Practical considerations for using TDR cable tester. *Soil Technology* 7, 113–126.
- Espigares, T., Moreno-de las Heras, M., Nicolau, J. M. In press. Performance of vegetation in reclaimed slopes affected by soil erosion. *Restoration Ecology*. [doi: 10.1111/j.1526-100X.2009.00546.x].
- Fombellida, A. 2001. Variabilidad del ecotipo de alfalfa Tierra de Campos (*Medicago sativa* L.). Ph.D. thesis. ETSI Agrónomos, Universidad Politécnica de Madrid, Madrid, Spain.
- Guerrero-Campo, J., Monserrat-Martí, G., 2004. Comparison of floristic changes on vegetation affected by different levels of soil erosion in Miocene clays and Eocene marls from Northeast Spain. *Plant Ecology* 173, 83–93.
- Hancock, G.R., Willgoose, G.R., 2004. An experimental and computer simulation study of erosion on a mine tailings dam wall. *Earth Surface Processes and Landforms* 29, 457–475.
- Illius, A.W., O'Connor, T.G., 1999. On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. *Ecological Applications* 9, 798–813.
- Jiao, J., Zou, H., Jia, Y., Wang, N., 2009. Research progress on the effects of soil erosion on vegetation. *Acta Ecologica Sinica* 29, 85–91.
- Klute, A., 1986. Water retention: laboratory methods. *Methods of Soil Analysis, Part I, Physical and Mineralogical Methods*. Agronomy Monograph N° 9. American Society of Agronomy, Soil Science Society of America, Madison, USA, pp. 635–662.
- Lal, R., 1998. Soil erosion impact on agronomic productivity and environment quality. *Critical Reviews in Plant Sciences* 17, 319–464.
- Loch, R.J., 2000. Using rainfall simulation to guide planning and management of rehabilitated areas. Part 1: experimental methods and results from a study at the Northpakes mine, Australia. *Land Degradation and Development* 11, 221–240.
- Michel, B.E., 1983. Evaluation of the water potentials of solutions of Polyethylene Glycol 8000 both in the absence and presence of other solutes. *Plant Physiology* 72, 66–70.
- Moreno-de las Heras, M., 2009. Development of soil physical structure and biological functionality in mining spoils affected by soil erosion in a Mediterranean-Continental environment. *Geoderma* 149, 249–256.
- Moreno-de las Heras, M., Nicolau, J.M., Espigares, T., 2008. Vegetation succession in reclaimed coal mining slopes in a Mediterranean-dry environment. *Ecological Engineering* 34, 168–178.
- Moreno-de las Heras, M., Merino-Martín, L., Nicolau, J.M., 2009. Effect of vegetation cover on the hydrology of reclaimed mining soils under Mediterranean-Continental climate. *Catena* 77, 39–47.
- Moreno-de las Heras, M., Nicolau, J.M., Merino-Martín, L., Wilcox, B.P., 2010. Plot-scale effects on runoff and erosion along a slope degradation gradient. *Water Resources Research* 46, W04503.
- Morgan, R.P.C., 1995. Measurement of soil erosion. In: Morgan, R.P.C. (Ed.), *Soil Erosion and Conservation*, 2nd Edition. Longman, Essex, UK, pp. 84–95.
- Nicolau, J.M., 2002. Runoff generation and routing on artificial slopes in a Mediterranean-continental environment: The Teruel coalfield, Spain. *Hydrological Processes* 16, 631–647.
- Nicolau, J.M., 2003. Trends in relief design and construction in opencast mining reclamation. *Land Degradation and Development* 14, 215–226.
- Okin, G.S., Parsons, A.J., Wainwright, J., Herrick, J.E., Bestelmeyer, B.T., Peters, D.C., Fredrickson, E.L., 2009. Do changes in connectivity explain desertification? *Bioscience* 59, 237–244.
- Papadakis, J., 1966. *Climates of the World and Their Agricultural Potentialities*. Buenos Aires, Argentina.
- Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267, 1117–1123.
- Puigdefábregas, J., 2005. The role of vegetation patterns in structuring runoff and sediment fluxes in drylands. *Earth Surface Processes and Landforms* 30, 133–147.
- Puigdefábregas, J., Sánchez, G., 1996. Geomorphological implications of vegetation patchiness on semi-arid slopes. In: Anderson, M.A., Brooks, S.M. (Eds.), *Advances in Hillslope Processes*, Volume 2. John Wiley and Sons Ltd, Chichester, UK, pp. 1027–1060.
- Puigdefábregas, J., Sole, A., Gutiérrez, L., del Barrio, G., Boer, M., 1999. Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda site in SE Spain. *Earth-Science Reviews* 48, 39–70.
- Saco, P.M., Willgoose, G.R., Hancock, G.R., 2007. Eco-geomorphology of banded vegetation patterns in arid and semi-arid regions. *Hydrology and Earth System Sciences* 11, 1717–1730.
- Solé, R., 2007. Scaling laws in the drier. *Nature* 449, 151–153.
- Statsoft, 2001. STATISTICA version 6. Data Analysis Software System. Statsoft Inc., Tulsa, Oklahoma, USA.
- Suding, K.N., Gross, K.L., Houseman, G.R., 2004. Alternative states and positive feedbacks in restoration ecology. *Trends in Ecology and Evolution* 19, 46–53.

- Thornes, J.B., 1985. The ecology of erosion. *Geography* 70, 222–235.
- Thornes, J.B., 2004. Stability and instability in the management of Mediterranean desertification. In: Wainwright, J., Mulligan, M. (Eds.), *Environmental Modelling: Finding Simplicity in Complexity*. John Wiley and Sons, Chichester, UK, pp. 303–315.
- Tormo, J., Bochet, E., García-Fayos, P., 2006. Is seed availability enough to ensure colonization success? An experimental study in road embankments. *Ecological Engineering* 26, 224–230.
- Tutin, T.G., Heywood, V.H., Walters, S.M., Webb, D.A., 1964–1980. *Flora Europaea*. Vols 1–5. Cambridge University Press, Cambridge, UK.
- van den Elsen, E., Xie, Y., Liu, B., Stolte, J., Wu, Y., Trouwborst, K., Ritsema, C.J., 2003. Intensive water content and discharge measurement system in a hillslope gully in China. *Catena* 54, 93–115.
- van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44, 892–898.
- Wainwright, J., Parsons, A.J., 2010. Classics in physical geography revisited, Thornes, J.B. 1985: The ecology of erosion (*Geography* 70, 222–235). *Progress in Physical Geography* 34, 399–408.
- Wainwright, J., Parsons, A.J., Schlesinger, W.H., Abrahams, A.D., 2002. Hydrology vegetation interactions in areas of discontinuous flow on a semi-arid bajada, southern New Mexico. *Journal of Arid Environments* 51, 319–338.
- Wilcox, B.P., Newman, B.D., 2005. Ecohydrology of semiarid landscapes. *Ecology* 86, 275–276.
- Wilcox, B.P., Breshears, D.D., Allen, C.D., 2003. Ecohydrology of a resource-conserving semiarid woodland: effects of scale and disturbance. *Ecological Monographs* 73, 223–239.
- Zehe, E., Sivapalan, M., 2009. Threshold behaviour in hydrological systems as (human) geo-ecosystems: manifestations, controls, implications. *Hydrology and Earth System Sciences* 13, 1273–1297.