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Soil–geomorphology relations in gypsiferous materials of the Tabernas Desert (Almería, SE Spain)

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Abstract

A detailed pedological study in an apparently homogeneous badlands area of gypsiferous mudstones in the Tabernas Desert (Almería, SE Spain), with an annual precipitation of 200 mm, has been shown to be composed of different soil units belonging to different stages of soil development. Twenty-four soil profiles in four topographic transects within a small instrumented catchment have been described and analysed, along with over 100 probings and observations. A complementary approach to ascertain the relationships of soil-units with topography made use of a 1-m resolution digital elevation model (DEM) and derived terrain attributes. Moreover, the relationships with soil cover, surface hydrology and erosion have all contributed to understanding pedogenic and evolutionary processes. The five soil units identified correspond to distinct topographic positions, from steep S-oriented slopes with incipient soil development under bare surfaces (*Epileptic Regosol*), to moderately sloping, N-oriented soils, fairly well developed below a dense cover of annual and perennial plants (*Haplic Calcisol*). Both the spatial distribution and the topographic position of soil units favour gypsum and salt washing processes and gypsum accumulation is restricted to higher positions with very small contributing areas and minimum overland flow and thus reduced leaching. *Gypsic* horizons and *Gypsisols*, while previously described in the area associated to gypseous rock outcrops, are now described associated to gypsiferous mudstones.

Keywords: Gypsic horizon; Semi-arid environment; Badlands; DEM; Terrain attributes; Soil micromorphology; Crusting

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1. Introduction

The differences in soil properties with landscape position are usually attributed to differences in runoff, erosion and deposition processes which affect soil genesis and vegetation development (Birkeland, 1984; Yair, 1990; Dahlgren et al., 1997; Lark, 1999). Several soil studies in arid and semi-arid areas indicate that soils show wide spatial variability resulting from differences in parent material, age of land surface, topography, water distribution, amount and intensity of rainfall and plant heterogeneity (Key et al., 1984; Wierenga et al., 1987; Shmida and Burgess, 1988). Arid soils are characterised by scant moisture availability that limits chemical and physical reactions and soils inherit many characteristics of the parent material (Claridge and Campbell, 1982). Moreover, abrupt, discernible shifts in plant communities and soils occur in relatively small areas in many semi-arid ecosystems, especially badlands (Campbell, 1989). In badlands, where erosion seems to be more important than pedogenesis, soil variability has been little studied, despite the interest, especially for geomorphologists, in understanding the evolution of this type of landscape. It is essential to know the factors controlling soil properties and how they affect soil surface cover, hydrology and erosion. Yaalon (1997) pointed out the need for more data on the nature of present soil resources and a better understanding of soil processes in the various landscapes to be able to face possible future environmental challenges. This need seems especially urgent in badlands where off-site effects might have important environmental impacts (Mathys et al., 1989; Torri and Bryan, 1997), i.e., reservoir silting and deterioration of water quality, especially when the parent material contains significant amounts of salts.

The Tabernas Desert in SE Spain is a very fragile environment over Miocene gypsum-calcareous mudstones, where badlands have developed since at least the early Holocene (Kleverlaan, 1989), making up one of the most extensive badlands in Europe. Field evidence and previous studies (Harvey, 1987; Calvo et al., 1991; Calvo and Harvey, 1996; Solé-Benet et al., 1997; Nogueras et al., 2000; Gallart et al., 2002) reveal that these materials are highly susceptible to erosion though erosion rates over several years of monitoring are only moderate (Cantón et al., 2001a,b). The overall area is composed of a complex mosaic of different types of plant-covered patches and bare ground with contrasting hydrological and erosive behaviour (Cantón et al., 2001a, 2002a). Most studies on the area have dealt with the relationships between geomorphology and vegetation (Alexander and Calvo, 1990; Alexander et al., 1994; Lázaro et al., 2000), vegetation and some soil properties (Lazaro and Puigdefabregas, 1994), geomorphology and soil properties (Alexander et al., 1994), and the hydrological and erosive behaviour of this system together with the contribution of different soil surfaces to the catchment-scale response (Calvo et al., 1991; Solé-Benet et al., 1997; Cantón et al., 2001b, 2002a).

In all those studies, it has been demonstrated that despite the fact that this landscape does not show significant differences in climate or altitude, and is formed over an apparently homogeneous material, there is strong spatial variability in vegetation and soil-surface type causing particular hydrological responses, e.g., the almost bare SW-facing slopes appear to be the main suppliers of water and sediments and the vegetated NE-facing slopes contribute to water storage and deposition on pediments (Solé-Benet et al., 1997;

Cantón, 1999; Cantón et al., 2001b, 2002a). Such spatial variability might also result in different soil types being induced by differential soil development along with contrasting topographical positions.

Although the geomorphology and vegetation in the area have drawn some attention, soils and the processes involved in their evolution have been studied little. Only of certain surface horizons, chemical properties have been studied for their relationships with plant cover (Lázaro, 1995) and a few profiles from dissected pediments of differing age, partially analysed for their relationship with stabilisation mechanisms (Alexander et al., 1994). The most recent general soil survey of the area (Pérez Pujalte and Oyonarte, 1987) was at a scale of 1:100,000, and because of the scale, is not detailed enough to consider the wide diversity of soil-units. The fact that these soils develop over gypsiferous materials and, as a consequence, their development is affected by the dynamics of gypsum and its particular behaviour in dry environments, has received little attention except for inventory or general mapping purposes (Porta and Herrero, 1988). Even Pérez Pujalte and Oyonarte (1987) only found *gypsic* horizons associated to gypseous outcrops and not on gypsiferous mudstones, considering the terms gypseous and gypsiferous as defined by Herrero and Porta (2000).

None of the studies cited have dealt with the morphology, genesis or classification of these soils, nor do they contribute to understanding the relationships observed between the strong variation in soil surface cover and the soils beneath. One of the studies mentioned dealing with soils from surfaces of different ages finds only traces of gypsum (Alexander et al., 1994). Neither is it known whether there are significant differences in the physical and chemical characteristics of soil on north- and south-facing slopes or whether these possible differences could explain the distinct plant cover and contrasting geomorphologic evolution of these slopes.

With this background, this paper aims to: (1) characterise the main soil types in the area; (2) identify the main processes contributing to their genesis and evolution, especially with regard to gypsum depletion and/or accumulation; (3) examine the influence of topography, soil cover, surface hydrology and erosion on soil properties and pedogenesis. An approach using terrain attributes derived from a 1-m resolution digital elevation model (DEM) is applied to integrate the soil study of a small catchment to contribute to understand landscape dynamics.

2. Site description

2.1. Location and geology

The study area is located in the Tabernas Desert, in the province of Almería (SE Spain) (Fig. 1), on the northern versant of El Cautivo cliff, a thick bank of calcaric sandstone, where gullies and erosion on gypsiferous mudstones are more prominent. The Tabernas Desert lies in the Neogene–Quaternary Tabernas depression, partially surrounded by the Betic cordillera. This depression is located south of the Filabres and Nevada ranges and north of the Alhamilla range, which rose during the Miocene, at the same time as the intermountain depression was forming. The Tabernas basin is mainly filled with monotonous

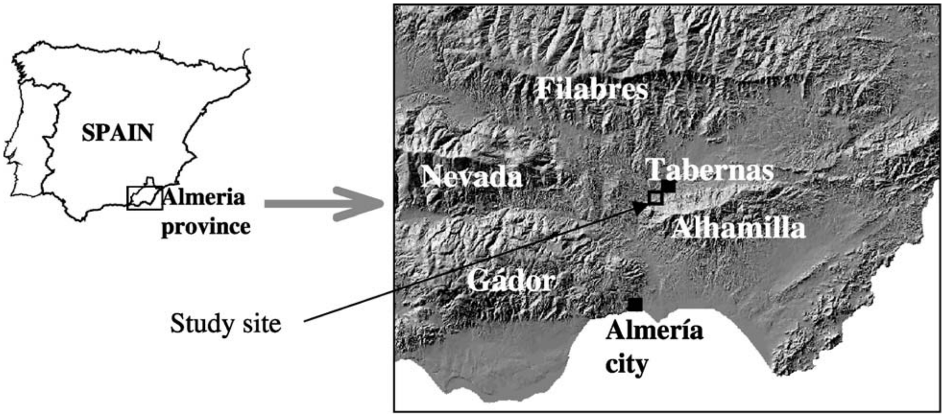

Fig. 1. Location of the study area.

and apparently homogeneous Neogene marine sediments (Kleverlaan, 1989), the more distal being fine-grained (gypsum-calcareous mudstones), and the more proximal turbiditic (alternation of mudstones and calcaric sandstones). Badlands have developed on the highly bioturbated and unclearly stratified gypsum-calcareous mudstones from the Chozas formation (Tortonian age), where the overlying sandstone has been dissected. The average mineralogical composition of these mudstones is muscovite 35%, paragonite 10%, chlorite + smectite 3%, quartz 10%, calcite 20%, dolomite 2% and gypsum 20% (Cantón et al., 2001a).

2.2. Climate

The present climate is semiarid Thermomediterranean (Lázaro and Rey, 1990) with long, dry summers. The average annual temperature is 17.9 °C and the mean annual rainfall is 235 mm (for a 30-year recording period at the nearby Tabernas weather station), mostly in winter. The on-site meteorological station has recorded an average of 200 mm since it was installed in 1991. The distribution of rainfall magnitude between 1991 and 2001, was 1 mm or less in 52% of the events, 3 mm or less in 67%, 9 mm or less in 84%, and only in 2% of the events was 50 mm exceeded. The number of rainy days per year during the study period ranged from 32 to 69 (Cantón et al., 2001b). Annual potential evapotranspiration is around 1500 mm, indicating considerable annual water deficit.

2.3. Geomorphology, vegetation and soils

Badlands from the Tabernas Desert are characterised by narrow valleys mostly dissected in a NW–SE direction, clearly asymmetrical in slope gradient and plant cover (Fig. 2A, Table 1). This basic asymmetry, along with the frequent changes in orientation due to incised gullies, provides a mosaic of surfaces which can be distinguished by their discontinuous perennial plant cover, exiguous annuals, rather abundant lichens and physical soil crusts, and a variety of types of erosion on different slope gradients.

North- to east-facing hillslopes have 10° to 40° gradients and a plant cover of perennials, annuals and lichens. Lichens (mainly *Diploschistes diacapsis*, *Squamarina lentigera* and *Fulgensia fulgida*) mostly covers the upper slope sectors. Annual plants, lichens and sparse shrubs coexist in the intermediate sector. And a mosaic of dense annual herbs (dominated by *Stipa capensis*) over lichens and patches of dwarf and medium shrubs (notably *Helianthemun almeriense*, *Hammada articulata*, *Artemisia barrelieri*, *Salsola genistoides*) cover most of the pediments.

South- to west-facing slopes have gradients of 30° to 77° (average: 40°), and are devoid of vegetation, except limited areas with an incipient or degraded cryptogamic cover and occasional, isolated shrubs of the *S. genistoides* type and the annual *Moricandia foetida* in favourable years.

According to the 1:100,000 soil map of the area (Pérez Pujalte and Oyonarte, 1987), soils are formed by an association of *Orthic Solonchaks and Calcaric Regosols* (FAO,

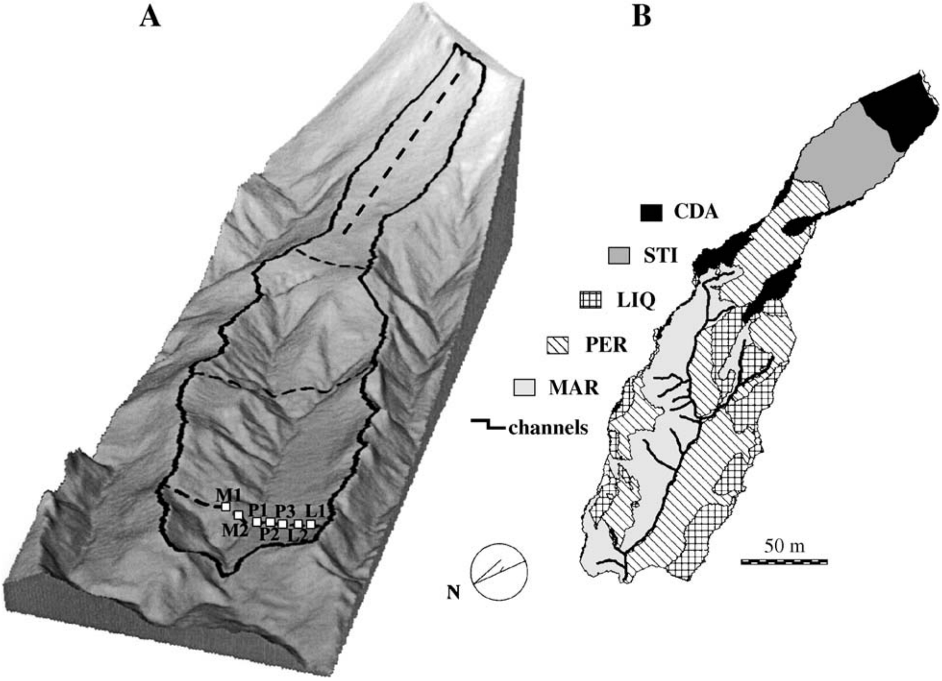

Fig. 2. (A) Tridimensional map of the microcatchment compiled from a digital elevation model at 1 m resolution, with three transverse topographical transects and one longitudinal where soil profiles have been studied (only the soil profiles from the lower transect are marked: L1 = LIQ1, L2 = LIQ2, P1 = PER 1, P2 = PER2, P3 = PER3, M1 = MAR1, M2 = MAR2). (B) Soil map of the same small catchment, with five soil units which are described in Section 4.2.

Table 1
Soil units with their main cover, parent material, topographic position, annual runoff (mm $year^{-1}$) and erosion (g m^{-2} $year^{-1}$) from small plots during 3 years

Unit	Cover	Parent material	Topographic characteristics	Runoff and erosion			
				Hydrological year	Rainfall	Runoff	Erosion
MAR	Bare regolith, small patches covered by a crusted silty layer or degraded lichens	Calcitic–gypsiferous mudstone	SW facing slopes, strong curvature. SLO = 40, ARE = 26, *W* = 1.8, LSF = 11.5	1994/1995	151	23.8 (11.8)	164.8 (155.9)
				1995/1996	197.5	39.8 (32.8)	627.8
				1996/1997	230.5	37.4 (28.9)	131.5
LIQ	Continuous lichen crust and sparse annual and perennial plants	Calcitic–gypsiferous mudstone	Upper part of NE facing slopes, moderate curvature (convex). SLO = 29, ARE = 18, *W* = 2.0, LSF = 7.7	1994/1995	151	28.2	17.0
				1995/1996	197.5	23.2	31.5
				1996/1997	230.5	35.0	15.9
CDA	Lichens and disperse annual and perennial plants	Calcitic–gypsiferous mudstone	Divides, strong curvature (convex) and upper part of the N facing with STI. SLO = 24, ARE = 9, *W* = 2.1, LSF = 6.0	1994/1995	151	–	–
				1995/1996	197.5	13.1	37.7
				1996/1997	230.5	14.0	16.37
STI	Perennial grass (*Stipa tenacissima*) and other perennial plants	Colluvium: mudstone and calcaric sandstone	Old steep slopes at the area's headwaters. Moderate curvature (concave). SLO = 34, ARE = 43, *W* = 2.4, LSF = 12.4	1994/1995	151	10.8	8.6
				1995/1996	197.5	23.5	15.4
				1996/1997	230.5	20.1	1.5
PER	Disperse dwarf shrubs and annual plants	Colluvium of calcitic–gypsiferous mudstone	Pediments at the foot of NE facing slopes. Moderate curvature (concave). SLO = 21, ARE = 32, *W* = 2.9, LSF = 6.4	1994/1995	151	7.7	2.6
				1995/1996	197.5	17.8	3.6
				1996/1997	230.5	8.5	2.0

Numbers enclosed by brackets correspond to rates when the surface is covered by silty deposits. Concave or convex refers to the form transverse to slope, accumulating the higher percentage of pixels.

SLO: slope gradient (°); ARE: specific catchment area (m^2 m^{-1}); LSF: slope length factor; *W*: wetness index.

1974). *Solonchaks* are restricted to the lower parts of the landscape, mostly associated with recent alluvial terraces of present *ramblas* (ephemeral channels), and not present in the area studied, while *Regosols* dominate in intermediate parts and at the headwaters of the landscape over tertiary rock.

The detailed pedological survey was conducted at the El Cautivo experimental field site (Solé-Benet et al., 1997; Cantón et al., 2001a,b, 2002a), an area of about 13 ha, at an altitude of between 247.5 and 382.5 m, representative of the Tabernas Desert, in which a typical microcatchment (Fig. 2) has been instrumented since 1991, including a fully automatic meteorological station, four hydrological gauging stations, and a variety of ongoing hydrological and geomorphological experiments (Cantón et al., 2001b, 2002b). Furthermore, extensive surveys and soil analyses in a larger area have also contributed to pedological knowledge of the area.

3. Methods

Based on the hypothesis that topography might be the main controlling factor in soil development, either directly or through hydrological behaviour or plant development, soils have been studied along four representative topographical transects within the catchment (three crosswise from SW to NE, and one lengthwise from SE to NW) (Fig. 2). A total of 24 soil profiles in the field were described according to the FAO procedure (FAO, 1990). Soil samples collected from different horizons were air-dried, gently crushed and passed through a 2-mm sieve to remove coarse fragments. The following analyses were performed: (a) particle-size distribution was determined by dry sieving and Robinson's pipette method after removal of organic matter with 30% H_2O_2, of sulphate by leaching salts with distilled water, of carbonates with 1 M NaOAC at pH5, and dispersion by agitating the sample in 10 ml of 40% sodium hexametaphosphate (Gee and Bauder, 1986); the sand fraction was separated by wet-sieving, oven-dried and then fractionated by dry sieving; (b) water retention with Richards plates; (c) soil pH was measured in the saturation extract; (d) organic matter content using the Walkley–Black wet digestion method (Nelson and Sommers, 1982); (e) total gypsum by precipitation with $BaCl_2$ (Porta, 1998); (f) calcium carbonate equivalent by the rapid titration method (Puri, 1930); (g) electrical conductivity of the saturation extract; h) soluble Ca^{2+}, Mg^{2+}, Na^+, and K^+ of the saturation extract, by atomic absorption spectrophotometry and soluble SO_4^{-2} by ion chromatography. Thin sections were made of resin-impregnated blocks from undisturbed samples of selected horizons in eight soil profiles and 20 surface horizons, and described according to Bullock et al. (1985). The pore size distribution of the upper 3 cm was evaluated from photographs of selected thin sections (Pagliai et al., 1983) by image analysis with a Quantimet 570. Bulk density measurements were performed in the field by standard coring techniques. Soils were classified according to both the World Reference Base for Soil Resources (WRBSR) (FAO–ISRIC–ISSS, 1998) and the Soil Taxonomy (Soil Survey Staff, 1999).

To study the relationships between soil properties and ground cover, the percentage of stones, mudstone outcrops, silt deposits, litter, lichens, annual plants and perennial plants higher and lower than 35 cm, were measured in 3 random quadrats 1 × 1 m (10-cm mesh) within 3 × 3 m areas surrounding each soil profile.

The soil profiles studied were geo-referenced with a Differential Geopositioning System in order to assess their relationships to the topography. The most important topographical characteristics of each profile were derived from a 1-m resolution digital elevation model (DEM) using *PCRaster* GIS software (Karssenberg, 1996). The terrain attributes extracted were altitude (ALT), slope angle (SLO), slope aspect (ASP), plane curvature (PLN) which yields positive values when the slope segment is concave and negative when convex, profile curvature (PRF) which gives negative values for concave slope segments and positive for convex segments, specific catchment area draining to each cell (ARE) using a single-drainage-direction algorithm (Quinn et al., 1991), wetness index ($W = \ln(\text{ARE}/\tan \text{SLO})$) as developed by Beven and Kirkby (1979), slope length factor, an index for the potential sediment transport using an algorithm derived from the unit stream power theory (Moore and Burch, 1986) ($\text{LSF}=(\text{ARE}/22.13)^n(\sin \text{SLO}/0.0896)^m$, where m and n are constants), and distance to channels (DIST). For each soil profile, terrain attributes were calculated from the averages of nine values obtained from 3 × 3 m windows (3 × 3 pixels).

Hydrological behaviour and erosion of different soil covers was studied in small 0.24-m^2 runoff plots representing the main ground cover types (Cantón et al., 2002b), similar to those used in other studies in similar environments in SE Spain (Cerdá, 1996, 1998, 1999; Solé-Benet et al., 1997). The plots were monitored from May 1994 to June 1997. Total runoff and erosion were sampled after each rainfall event.

To investigate the relationships between soil properties and topographic characteristics, ground cover, runoff and erosion, Pearson correlation analysis and ANOVA were performed.

4. Results

4.1. General characteristics of the soils

The most abundant parent material, when fresh, is a hard, compacted calcitic–gypsiferous mudstone, which upon weathering (wetting–drying and gypsum solubilisation–recrystallization cycles), produces an essentially fine silt that becomes the soil material (Solé-Benet et al., 1997; Cantón et al., 2001a). This rock has also been described as a gypsiferous marl in some papers (Alexander et al., 1994; Harvey, 1982; Calvo et al., 1991) and in the geological map of the area (IGME, 1975), but the term mudstone is preferred to emphasize the always dominant silt fraction (80% silt, 10% clay) in both the total and carbonate-free material, while the amount of carbonates varies (15 to 30%). Soils are in general loamy silts. Coarser textures like sandy loams, appear in the upper part of the catchment, near El Cautivo escarpment (Fig. 2), due to the greater influence of the upper layer, a calcaric sandstone.

In general, soils in the catchment have a weak or moderately fine to medium subangular blocky structure except where the soil is a regolith. Their surface is frequently formed by either physical or biological crusts, with inherent hydrological and pedogenetic consequences: reduced infiltration and limited soil development. Most of the soils are light grey (2.5Y7/2) when dry and greyish brown (2.5Y4/2) when wet. Some of the more developed soils may attain a 10YR hue. Organic matter content is low in horizons near the parent material, from 0.15% to 1.4%, moderate in some surface horizons, from 0.4% to 2.4%, and under perennial plants it may be up to 3.5%. The pH ranges from 6.7 to 8.1.

Electrical conductivity ranges from 0.375 to 19.8 dS m^{-1}, indicating a range from non-saline to highly saline soils. Low values are usually found in most horizons of soils developed on deep colluvia, except in the vicinity of the mudstone. High values are mostly found in soil horizons near the gypsiferous mudstone or in soils from divides. The gypsum content, which is relatively high in the fresh parent material (from 15% to 20%), is relatively low, from 0.5% to 5%, in most surface horizons. Calcium carbonate equivalent ranges from 11% to 30%, with a generalised increase in surface or intermediate horizons, associated with calcic horizons. The most abundant soluble cation is Ca^{2+} (between 0.04 and 9.02 cmol kg^{-1}), followed by Mg^{2+} (between 0.025 and 10 cmol kg^{-1}). The concentration of both cations is higher near the C horizon, and Na and K are less abundant, with a concentration of less than 0.25 cmol kg^{-1}. Carbonate and sulphate are the most abundant anions, chlorides and phosphates being scarce and appearing mainly in C horizons.

In general, in the soils studied, SAR values are low (not over 1), except for some C horizons where SAR values are between 10 and 30, though their electrolyte concentration is also high (EC between 8 and 19.8 dS m^{-1}), resulting in a non-dispersive environment (Imeson et al., 1982).

The micromorphology of shallow soils usually presents surface horizons with both structural and depositional crusts and below a compacted groundmass with vesicular and polyconvex pores. The surface of deep soils presents from poorly developed to moderately developed structural crusts with vesicular pores and below, well-microaggregated material with abundant interconnected pores.

4.2. Soil units

Five different soil types can be distinguished based on horizon development and physicochemical properties.

These soil types have different ground cover, are clearly associated with distinct topographical positions and have different hydrological and erosive behaviour. Table 1 shows their main characteristics (type of groundcover, topography, and hydrology) and Table 2 the cover composition of every soil unit. Selected morphological, physical and chemical properties for the five typical pedons are given in Tables 3 and 4. Main micromorphological characteristics are given in Table 5.

An ANOVA (with the soil properties as dependent variables and soil type as the independent variables) revealed that the five soil types are significantly different ($p=0.00025$, $N=23$) for the average values of every soil property studied.

Fig. 2B shows the spatial distribution of the five soil types in the catchment studied.

4.2.1. MAR

This soil unit, usually devoid of vegetation, is mostly a bare regolith, with a high mudstone fragment content. It is usually covered by a mechanical structural-type crust, sometimes by a depositional crust forming a silty layer of a few millimetres to about 10 cm

Table 2
Ground cover composition for the different soil units

Soil unit	Profile	Bare marl	Crusts	Rock fragment	Lichens	Annuals	Perennials < 35 cm	Perennials >35 cm	Litter
MAR	MAR1	17.83	53.61	1.75	21.22	0.12	1.78	2.66	1.04
	MAR2	96.35	0.66	2.56	0.00	0.00	0.42	0.00	0.02
	MAR3	0.00	85.06	2.92	8.70	0.00	2.35	0.50	0.47
	MAR4	99.83	0.00	0.00	0.00	0.00	0.17	0.00	0.00
	MAR5	94.84	3.40	0.66	0.25	0.01	0.48	0.11	0.25
LIQ	LIQ1	0.00	7.75	3.50	87.70	0.15	0.25	0.00	0.65
	LIQ2	0.00	10.68	9.72	70.16	0.15	1.00	7.56	0.73
	LIQ3	0.00	0.97	0.26	81.37	0.00	14.06	0.00	3.34
	LIQ4	0.00	2.25	0.14	83.34	0.00	10.50	0.00	3.78
	LIQ5	0.00	21.92	3.71	70.65	0.63	2.41	0.00	0.69
CDA	CDA1 (divide)	0.00	7.63	2.32	72.10	5.58	9.64	0.39	2.35
	CDA2 (divide)	0.00	6.75	7.63	66.00	6.13	10.25	0.00	3.25
	CDA3 (divide)	0.00	7.38	2.34	75.86	4.83	6.06	0.63	2.91
	CDA4 (LTE)	0.00	4.11	44.04	29.81	1.03	15.58	2.73	2.71
	CDA5 (LTE)	0.00	2.58	36.33	25.12	0.26	10.04	22.41	3.25
STI	STI1	0.00	12.55	21.65	19.54	0.71	8.20	33.23	4.13
	STI2	0.00	2.00	22.04	22.50	0.25	8.13	37.04	8.04
	STI3	0.00	2.75	21.25	22.25	0.05	7.50	33.70	12.50
PER	PER1	0.00	13.14	0.47	11.33	21.54	8.79	18.65	26.08
	PER2	0.00	19.42	1.09	1.88	10.83	10.75	28.42	27.63
	PER3	0.00	19.71	1.93	4.31	30.75	5.40	1.38	36.53
	PER4	0.00	17.33	1.08	33.58	0.71	24.46	14.33	8.50
	PER5	0.00	18.20	0.86	11.87	13.00	14.41	17.37	24.30
	PER6	0.00	25.32	0.92	15.68	9.29	12.94	17.30	18.54

Values (%) are the averages obtained from three random quadrats (1 m^2) within 3 × 3 m sampling areas. LTE is the upper transect where part of the CDA soil unit is found.

thick, occasionally, by a degraded lichen crust. This unit is found in areas with steep slopes (predominantly southwest facing), having a strong curvature and strong potential for sediment transport (Table 1). Runoff and erosion rates during the monitoring period (1994–1997) are high (Table 1), quite often in form of hyper-concentrated flows and shallow debris-flow type mass movements. The main fine earth particle is fine silt (between 40% and 60% increasing with depth) as can be observed for a representative profile of this soil-unit in Table 4. Coarse silt and clay are the second and third most abundant particles. Water retention in these soils is the lowest of the units studied, ranging between 20% (gravimetric) and 25% at -33 kPa and between 7% and 11% at -1500 kPa. The calcium carbonate content ranges between 21% and 28%. The gypsum content can reach 30% near the mudstone, but is much lower in the surface horizon. The electrical conductivity of these soils ranges between 2.23 and 7.5 dSm^{-1}. SAR readings are somewhat higher in the surface horizon than in similar horizons from the other soil units.

Table 3
Selected morphological properties for the five representative pedons

Horizon	Depth (cm)	Boundary	Dry color	Moist color	Structure	Consistence	Roots	RF (%)	Nodules/ pseudomicellium
MAR									
C1	0–2	gs	2.5Y7/2	2.5Y5/2			1vf	57.10	2 cps
C2	2–20		2.5Y7/2	2.5Y5/2			1vf	77.1	
LIQ									
AC_k	0–2	as	2.5Y7/2	2.5Y4/2	2vfcr	lo lo so po	2vf	13.9	2 cps
C	2–30		2.5Y7/2	2.5Y5/2				71.6	
CDA									
A_k	0–2	aw	5Y6/2	5Y4/3	2fpl	sh fr so po	1f	1.3	
B_y1	2–12	gw	5Y6/2	5Y4/2	1vfcr	so vfr so po	3vf	26.9	3 g
B_y2	12–30	gw	5Y7/2	5Y4/2	1msbk	sh fr so po	1vf	45.5	3 g
C1	30–45		2.5Y6/2	5Y4/2				92.8	–
C2	>45								
STI									
A_k	0–4	aw	2.5Y6/2	2.5Y4/2	1vfsbk	sh fr so po	2vf	43.9[a]	–
C_k1	4–30	as	5Y5/3	5Y4/2	1vfsbk	sh fr so po	2f	40.7[a]	–
C2	30–75	ai	5Y5/3	5Y4/2	M	sh fr so po	1vf	39.3[a]	–
C3	>75								
PER									
A	0–15	gs	5Y6/3	2.5Y4/2	2mcr	sh fr so po	2vf	1.8	–
BC_k	15–34	gw	2.5Y6/3	2.5Y4/2	3csbk	sh fr so po	2vf	6.5	2 cps
C_k1	34–43	gs	2.5Y7/2	2.5Y4/2	M	h fr so po	1f	9.2	2 cn 2 cps
C_k2	43–78	as	2.5Y7/2	2.5Y5/2	M	h fr so po	1vf	15.08	3 cn 2 cps
C3	78–130		2.5Y7/2	2.5Y4/2	2msbk	sh fr so po	1f	47.39	2 cps

Boundary: a = abrupt; g = gradual; s = smooth; w = wavy; i = irregular.
Structure: 1 = weak; 2 = moderate; 3 = strong; M = massive; vf = very fine; f = fine; m = medium; c = coarse; cr = crumby; sbk = subangular blocky; pl = platy structure.
Consistence: (Dry) lo = loose; so = soft; sh = slightly hard; h = hard; (Moist) lo = loose; fr = friable; (wet) so = nonsticky; po = slightly plastic.
Roots: 1 = few; 2 = common; 3 = many; vf = very fine; m = medium; co = coarse.
Nodules and inclusions: 1 = few; 2 = common; 3 = many; cn = carbonate nodule; g = gypsum crystals; cps = carbonate pseudomicelium. RF = rock fragments.

[a] Coarse fragments through this profile are from 2 mm to 30 cm.

Macroporosity in the upper centimetres of this soil is quite high, about 27%, however, the final infiltration rate is very low (Solé-Benet et al., 1997; Cantón et al., 2002a), the opposite of a high runoff rate (Table 1) as a consequence of soil surface sealing processes. In fact, the most abundant macropores (in number) are rounded, between 30 and 200 μm in diameter and most in the upper centimetres are vesicles (Fig. 3A) formed by splash (Moore and Singer, 1990; Zhan and Miller, 1996; Bajracharya and Lal, 1998). However, the highest percentage (80%) of macroporosity is formed by elongated pores, mostly cracks and fissures.

Table 4
Selected physical and chemical properties for five representative pedons of the soil units

Horizon	Depth (cm)	Coarse sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	WHC (%)	OM (%)	pH	EC (dS m^{-1})	Calcium carbonate (%)	Gypsum (%)	SO_4^{2-} (cmol$_c$ kg^{-1})	SAR	Bulk density (mg m^{-3})
MAR															
C1	0–2	2.8	18.9	17.8	42.7	17.9	11.77	1.0	7.6	2.39	27.98	5.41	0.18	1.02	1.20
C2	2–20	12.8	15.0	14.8	45.1	12.3	10.47	0.9	7.4	7.5	23.32	15.19	0.25	11.61	
LIQ															
AC$_k$	0–2	2.3	18.3	17.0	43.2	19.2	18.7	1.2	7.7	2.8	23.91	0.24	0.07	0.75	0.98
C	2–30	5.2	14.9	17.7	42.2	20.0	10.3	0.8	7.6	3.8	14.23	29.71	0.22	3.13	1.38
CDA															
A$_k$	0–2	1.6	14.9	20.8	43.2	19.5	27.0	1.8	7.5	2.7	17.81	1.77	0.15	0.41	1.02
B$_y$1	2–12	0.1	10.2	21.9	44.7	23.1	18.8	0.8	7.7	2.2	11.69	27.52	0.12	0.30	
B$_y$2	12–30	0.4	10.1	21.5	46.3	21.6	17.4	0.9	7.7	2.3	11.22	34.97	0.11	0.31	1.22
C1	30–45	0.3	14.5	20.8	43.9	20.5	19.8	0.7	7.6	1.9	18.47	6.88	0.09	1.55	
C2	>45														
STI															
A$_k$	0–4	3.1	54.0	10.9	19.9	12.0	11.8	1.6	8.0	0.9	20.12	0.10	0.004	0.61	1.257
C$_k$1	4–30	3.9	28.2	14.3	34.4	19.2	17.4	1.2	7.8	0.6	24.05	0.19	0.01	0.89	1.236
C2	30–75	1.8	54.5	10.9	20.8	12.0	12.6	1.5	7.8	1.3	17.93	0.08	0.05	1.55	
PER															
A	0–15	0.60	35.1	19.3	28.2	16.8	21.6	2.0	7.9	1.1	18.96	0.28	0.28	0.34	1.15
BC$_k$	15–34	0.50	28.1	16.3	33.3	21.8	23.1	1.6	7.8	0.5	21.73	0.40	0.13	0.57	1.21
C$_k$1	34–43	0.52	26.0	17.3	35.5	20.8	24.6	0.6	8.1	0.9	26.63	0.09	0.01	0.92	1.29
C$_k$2	43–78	0.35	10.8	20.5	45.2	23.1	27.3	0.5	7.5	3.1	27.36	0.21	0.08	4.43	1.31
C3	78–130	1.16	11.4	22.4	44.8	20.3	22.0	0.9	7.3	9.1	15.54	12.1	0.21	9.12	1.00

WHC: water holding capacity (gravimetric), OM: organic matter, EC: electrical conductivity, SAR: sodium absorption ratio.

Table 5
Selected micromorphological characteristics of the surface horizon five soil units

Horizon	MAR	LIQ	CDA	STI	PER
Surface horizon (upper mm)	Structural and depositional crusts, and marl fragments, rare vertical planar voids	Crustaceous lichens (50%) and structural crusts (among lichen-covered areas) with rare vertical planar voids	Structural crust (50%) with abundant vesicles	Rare physical and biological crusts, vertical and sub-vertical planar voids	Structural and biological crusts with few vesicules and some vertical and sub-vertical planar voids
Surface horizon (below upper mm)	Only marl fragments with bridged grain structure, porosity decreasing downward	Granular to sub-angular blocky microstructure with compound packing voids	Platy microstructure with some polyconvex pores containing gypsum crystals	Good micro-aggregated structure with abundant and interconnected polyconvex voids	Banded distribution of buried depositional and biological crusts; few aggregates
Sub-surface horizon	Only marl fragments with very few fine earth, only cracks and fissures	Only marl fragments with very few fine earth, only cracks and fissures	Compacted groundmass, many polyconvex pores with gypsic lenticular crystals	Good micro-aggregated structure with abundant and interconnected polyconvex pores	Good micro-aggregated structure with abundant and interconnected pores

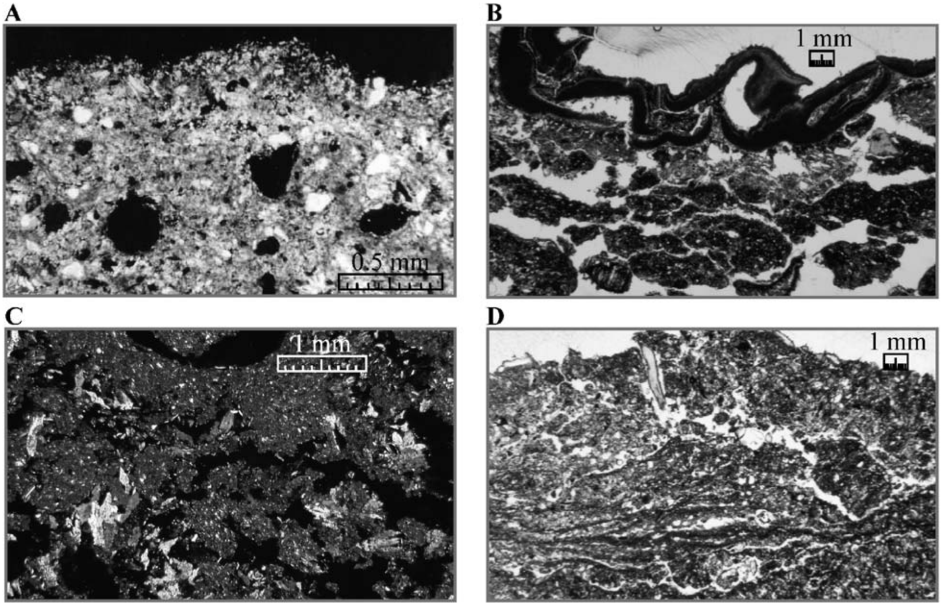

Fig. 3. Micrographs of some representative horizons: (A) surface of MAR showing a thick structural crust with vesicles, XPL; (B) surface of LIQ with abundant elongated pores below the liquen, PPL; (C) gypsic horizon of CDA with many intergrown gypsum crystals; (D) surface of PER with a structural crust at the surface and a layering below formed by depositional crusts, XPL.

This soil-unit is classified as an *Epileptic Regosol* (WRBSR) or *Lithic Torriorthent* (Soil Taxonomy).

4.2.2. LIQ

LIQ is found in areas with intermediate slopes and medium sediment transport capacity. It is characterised by small contributing areas where slope shape is convex in the direction of the slope (Table 1). The ground cover consists of lichens carpeting about 80% of the surface along with a sparse cover of annual and perennial plants (Table 2). This unit has high runoff rates, but little erosion (Table 1). Soil development is considerably reduced. Soils are shallow, about 30 cm, and only the top 5 cm have a moderately developed subangular blocky structure. The rest of the profile is formed by a regolith similar to the MAR soil-unit. Fine silt and clay are the most abundant particles at all depths and the water retention capacity is slightly higher than in MAR. Although the bulk density is very low in the first 5 cm, it increases further down. This is explained by the macroporosity of the first centimetres (between 22% and 37.1%), found under lichen, and having large elongated pores observable with the naked eye (Fig. 3B, Table 5), whereas below that, the soil appears to be more compact.

An increase in the calcium carbonate content can also be noticed at the surface, whereas the inverse trend is observed in gypsum (Table 4). The electrical conductivity increases with depth. The soil in this unit is classified as an *Endoleptic Regosol* (WRBSR) or *Lithic–xeric Torriorthent* (Soil Taxonomy).

4.2.3. CDA

This soil unit is found in two locations: (a) divides with low slope gradients, convex curvature, having quite small contributing areas and receiving water only from precipitation, with low runoff and erosion rates (Table 1), covered mostly by lichens and scattered annual and perennial plants; (b) at the top of north-facing steeply sloping and reduced contributing areas (Fig. 4), the parent material being a mixed colluvium including gypsiferous mudstones and calcaric sandstones. This soil-unit has a much greater infiltration capacity (Table 1) and better soil development than *LIQ*, and soil depth can be up to 50 cm in divides and 70 cm at the top of steep slopes. Better developed subangular blocky structure than previous soil-unit. Texture varies from silty (divides) to sandy loam (steep slopes). Water retention ranges between 36% and 26% at − 33 kPa and at − 1500 kPa, between 15% and 9%, the highest of all soil-units, due to a higher soil gypsum content, as described by Eswaran and Zi-Tong (1991). The most interesting feature of these soils is the gypsum accumulation in a sub-surface horizon (upper boundary between 5 and 20 cm of the soil surface) meeting the requirements for a *gypsic* horizon. The most typical form of gypsum accumulation is named according the micromorphological classification proposed by Stoops and Poch (1994) as *Gypsic lenticular* (mostly idiomorphic lenticular gypsum in channels, chambers and fissures and also in the

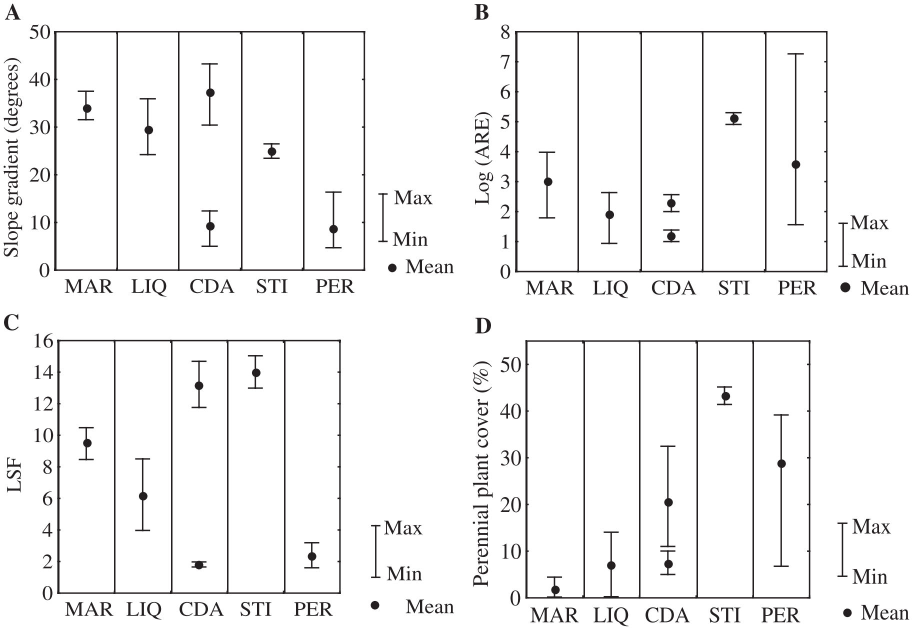

Fig. 4. Mean, maximum and minimum values of slope gradient (A), specific catchment area (B), length slope factor (C) and perennial plant cover (D) for all studied profiles of the five soil units. Soil types on the *X*-axis are in order of increasing thickness. For CDA, mean, maximum and minimum values are presented in two groups because they represent two topographic positions. In panel (B), the logarithm of ARE is presented for better visualisation.

groundmass) (Fig. 3C). Thin section analysis reveals a macroporosity of about 18% in the upper 3 cm, the elongated pores being the most representative.

Calcium carbonate is less abundant in these soils, representing only between 11% and 21.7%. Electric conductivity ranges from 0.02 to 0.035 Sm^{-1}. An accumulation of soluble salts can sometimes be observed on the surface horizon (Table 4).

This soil unit is classified as *Eutric Gypsisol* according to the WRBSR or either *Lithic Haplogypsid* (in divides) or *Leptic Haplogypsid* (in upper slopes), according to the Soil Taxonomy.

4.2.4. STI

This soil unit, developed on a mixed coluvial material (sandstone and mudstone), while located at the bottom of quite steep north-facing slopes with high potential for sediment transport, has relatively deep soils (>90 cm) with coarser textures and medium water-holding capacity and supports a relatively dense annual and perennial plant cover, dominated by *Stipa tenacissima*.

This soil unit is a *Calcaric Regosol* (WRBSR) or a *Xeric Torriorthent* (Soil Taxonomy). In this soil, electric conductivity and soluble salts are lower than in the rest of the soils in the study area. The influence of calcaric sandstone is revealed in the amount of fine sand which is the most abundant particle size (up to 62%). The colluvial nature of the soil is also seen in the discontinuities in particle size distribution with depth. Water retention is lower than in soils near the top due to greater sand content. It is very low in gypsum (less than 1%). Calcium carbonate (between 15.61% and 24%), while higher than at the top, is still lower than for the rest of the soils in the area. Soil macroporosity ranges between 20% and 30% for the upper horizon.

4.2.5. PER

Usually found on pediments, PER is characterised by low slope gradients, relatively large contributing areas with concave curvature, where soil water storage is favoured and sediment transport potential is low. Usually covered by annual and perennial plants, infiltration is relatively high and erosion is low (Table 1). Soils are usually thicker and more developed compared to other units. They are relatively deep (from 1 to 1.8 m) with a well-developed structure type. Their texture and chemical properties show discontinuous patterns at some depth. Fine silt is the most abundant fraction (between 35% and 40%), followed by fine sand and clay. The water-holding capacity is the highest of the study area (Table 4) and is quite constant throughout the profile: water retained at -33 kPa ranges from 25% and 33%, and at -1500 kPa between 6% and 9%. Macroporosity in the first 3 cm is reduced (about 14%) as a consequence of surface crusting caused by rainfall impact (Fig. 3D). The latter figure shows a platy microstructure from the upper horizon in an inter-plant area and a banded distribution indicating cycles of upslope colluviation. However, soil sealing only affects bare inter-plant areas and this soil-unit absorbs rainfall better than others due to stem flow from the relatively more abundant vegetation.

Organic matter content is highest in the area, ranging from 1% to 2.4% at the surface. Calcium carbonate ranges between 15.5% and 33.4%, being lower within surface horizons and higher in subsurface horizons, with the presence of a *calcic* horizon with pseudomycellium (Table 4). In some profiles, notable amounts of gypsum are present in or near the C horizon, while the rest of the profile is practically gypsum-free.

The soil in this unit is a *Haplic Calcisol* (WRBSR) or *Xeric Haplocalcid* (Soil Taxonomy).

4.3. Relationships among soil properties, topography, ground cover, runoff and erosion

Fig. 4 shows some of the differences in topography and groundcover between the soils units.

Table 6 gives the correlation matrix between selected soil properties (the most variable of the soil types), topographical characteristics, groundcover, runoff and erosion. Averages weighted for horizon thickness were used as input data.

Altitude (ALT) is positively correlated with sand content and negatively correlated with silt and clay. A negative correlation exists between elevation and SAR values: indeed, the soil-units that are the least saline and the least susceptible to dispersion in the catchment are the STI unit (*Calcaric Regosol*) located at the headwater of the catchment (Fig. 3) and PER unit (*Haplic calcisol*) that can also be found on old, truncated pediments and in the highest part of the catchment.

The higher the slope gradient, the shallower the soil (see Fig. 4 where soil types on the X-axis are in the order of increasing thickness) and the lower the water retention capacity; soils on steep slopes, like MAR, have a low water-holding capacity. The wetness index (W) shows an inverse correlation with soil properties, positively correlated with both the soil water-holding capacity and with soil depth, but negatively correlated with gypsum content. This last is attributed to the fact that a high W corresponds to low gradient areas, where infiltration rates are highest in the area and salt leaching in soils is favoured, as in the case of PER and STI (despite a higher slope gradient, drained areas per surface unit are quite extensive, along with a coarser soil favouring infiltration and salt leaching).

Length slope factor (LSF) is positively correlated to the sand content and negatively correlated to silt and clay: as LSF is related to sediment transport capacity, the higher the transport capacity, the higher the removal of finer particles, and the higher the sand content.

Plane curvature and profile curvature are correlated to the organic matter content: the larger the concavity, the higher the organic content gets. This can be attributed to the accumulation of water and consequently, of vegetation in concave areas, which increases the organic matter in soil.

When the correlation analysis takes only the soil properties of the top 10 cm of all soil profiles into account, instead of the averages for the entire profile, new significant relationships appear: W is positively correlated with the organic content and negatively correlated with the electric conductivity of the saturation extract.

As might be expected, soil depth is positively related to perennial plant cover and litter. The water-holding capacity also shows a positive correlation with perennial and annual plant cover and with litter cover. In contrast, soil depth is negatively correlated with lichen and bare mudstone cover: indeed, soils with a dominant lichen cover (LIQ and CDA) or areas where the bare regolith appears at the surface (MAR) are always shallow. Water-holding capacity is also negatively related to bare marl cover.

Table 6

Pearson correlation coefficients between topographic characteristics, ground cover, runoff and erosion and some selected soil properties

	Topographic characteristics								Ground cover							Runoff	Erosion
	ALT	SLO	ARE	*W*	DIST	LSF	PLN	PRF	Bare marl	Crusts	Stones	Lichens	Annuals	Perennials	Litter		
Depth	0.18	− **0.55**	**0.44**	**0.85**	− 0.05	− 0.27	− 0.03	0.21	− **0.43**	0.13	0.08	− **0.41**	0.38	**0.76**	**0.60**	− **0.76**	− **0.49**
Sand	**0.43**	0.07	0.05	0.17	0.15	**0.50**	0.17	0.23	− 0.08	− 0.27	**0.58**	− 0.21	− 0.10	**0.58**	0.00	− 0.34	− 0.21
Silt	− **0.45**	− 0.03	− 0.04	− 0.22	− 0.09	− **0.47**	− 0.17	− 0.25	0.09	0.20	− **0.52**	0.24	0.06	− **0.62**	− 0.04	0.38	0.18
Clay	− **0.43**	− 0.17	− 0.04	0.00	− 0.26	− **0.44**	− 0.12	− 0.10	0.04	0.37	− **0.57**	0.07	0.18	− 0.33	0.11	0.15	0.21
O.M.	− 0.32	− 0.06	0.03	0.20	− 0.27	0.16	**0.44**	− **0.44**	0.13	0.34	− 0.15	− **0.61**	0.01	0.33	0.16	− 0.04	0.30
E.C.	− **0.52**	− 0.02	− 0.05	− 0.13	− 0.40	− 0.30	0.04	− 0.32	0.07	**0.42**	− 0.37	− 0.22	0.16	− 0.33	0.06	0.21	0.26
Carbonates	− 0.35	− 0.08	− 0.02	0.10	− 0.17	− 0.17	0.26	− 0.36	0.24	0.32	− 0.25	− **0.56**	0.25	0.01	0.32	0.00	0.25
Gypsum	0.04	0.28	− 0.24	− **0.55**	0.12	− 0.04	− 0.08	− 0.07	0.13	− 0.20	− 0.02	**0.61**	− 0.42	− **0.67**	− **0.63**	0.03	0.15
WHC	0.27	−**0.60**	0.27	**0.66**	−0.02	−0.31	−0.21	**0.45**	−**0.45**	−0.16	0.15	−0.22	**0.52**	**0.81**	**0.67**	−**0.75**	−**0.55**
SAR	− **0.51**	− 0.08	− 0.01	0.03	− 0.35	− 0.24	0.24	− **0.45**	0.09	**0.56**	− **0.37**	− **0.41**	0.22	− 0.24	0.17	0.15	0.34

ALT: altitude; ARE: specific catchment area; *W*: wetness index; DIST: distance to channels; LSF: length slope factor; PLN: plan curvature, yielding positive values when slope segments are concave and negative ones when convex; PRF: profile curvature, yielding negative values when slope segments are concave and positive ones when convex; WHC: water holding capacity.

Bold-type numbers are statistically significant ($p < 0.05$).

A positive correlation between both sand content and stone cover and sand content and perennial cover is also observed, whereas silt content shows an opposite relationship: this is because in PER and STI soils units (*Haplic Calcisol and Eutric Regosol*), both with either important plant or stone cover, the sand content is higher than in the rest of soils.

Gypsum is positively correlated with the lichen cover (all soils with gypsic horizon have a lichen cover) and negatively correlated with perennial plant cover and litter.

SAR and electric conductivity show positive correlations to the relative surface occupied by soil crusts. Many authors have described the relationships of mycrophytes and soil salinity, and have indicated that many lichens and cyanobacteria occur in saline soils, some of which may even require sodium for optimal growth (Shubert and Starks, 1985; Starks and Shubert, 1982; West, 1990).

4.4. Transects

In order to visualize the spatial variability of soil properties, soil profile data were plotted following the transects in Fig. 1: a general NW–SE transect (Fig. 5) and a representative NE–SW transect (Fig. 6). Data from the NW–SE transect were obtained from the weighted (depth) average data of every soil profile from all NE–SW transect, and from the average data of the longitudinal transect (Fig. 2) at the upper part of the catchment. For some soil properties, significant trends can be observed.

A general decrease in sand is observed to the northwest, from the upper to the lower part of the catchment (Fig. 5). Conversely, silt content increases downward. These trends are interpreted as both a decreasing influence of the calcaric sandstone outcrop in the upper part of the catchment, and erosion–deposition processes in which finer particles are transported over longer distances. The third point downward in the NW–SE transect has somewhat less sand and more silt than the lowest point in the transect because the corresponding NE–SW transect has steeper slopes and consequently, more erosion, providing added silt from the mudstone.

In the typical NE–SW transect (Fig. 6), across the main valley, the silt fraction decreases downslope while sand increases, deeper at the pediments with lower slope gradients (profiles PER1, PER2 and PER3) due to the inheritance of fine sand transported from the highest part of the catchment. Sand and silt from LIQ and MAR soil units show an opposite pattern compared to that in PER, because these units are on more recent surfaces, with steeper slopes and higher erosion, and consequently bear characteristics more similar to the parent material (the gypsiferous mudstone).

Gypsum and carbonates in NW–SE transects also show a contrasting trend, with high carbonate and low gypsum content in pediments where slope gradient is low (PER profiles) and the opposite trend in adjacent slopes (LIQ and MAR profiles). Within most profiles at the centre of the transverse transects, calcium carbonate concentrates in intermediate, calcic horizons.

Along the NE–SW transect, gypsum from subsurface horizons decreases downwards considerably, suggesting partial loss, probably during the transport of the sediments accumulating in the lower parts of the catchment. However, calcium carbonate increases slightly towards the bottom of the toposequence.

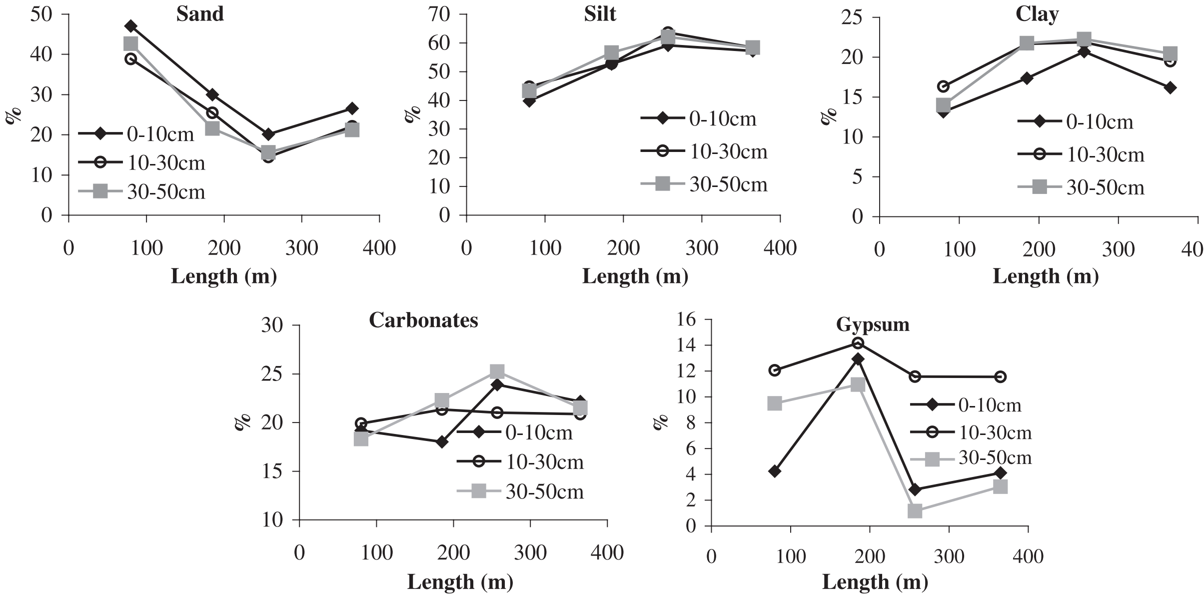

Fig. 5. Spatial representation of sand, silt, clay, carbonates and gypsum (obtained from the weighted average data of every soil profile) along the general SE–NW, top to bottom, longitudinal transect (left to right) of the whole small catchment.

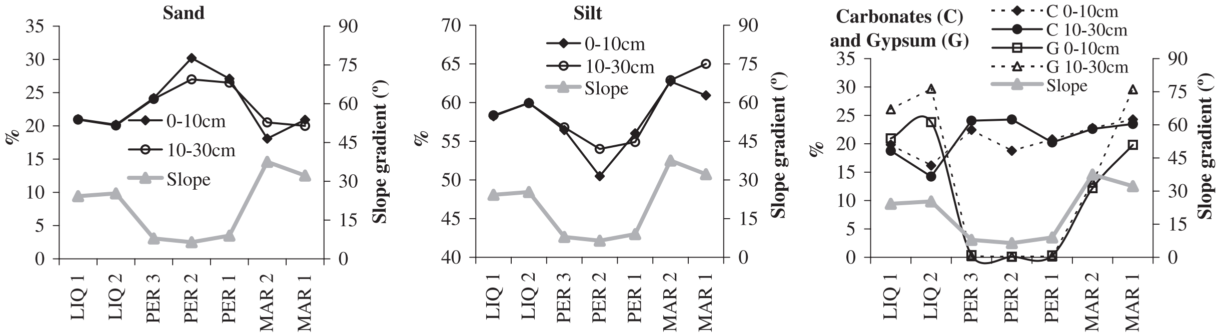

Fig. 6. Spatial representation of sand, silt, carbonates and gypsum along the lower NE–SW, transversal transect (Fig. 2), and corresponding slope gradients.

5. Discussion and conclusions

5.1. Weathering and soil characteristics

Weathering and soil development in the Tabernas Desert would be expected to be, a priori, very limited due to the low annual precipitation and the shallow infiltration fronts restricting soil moisture. The scant soil moisture is explained, apart from shallow profiles with an unfavourable texture, a poor structure, and low water retention capacity, by well-developed surface crusts.

However, the relatively large number of rainfall events, around 50 days, explains why wetting–drying cycles in the upper millimetres of the outcropping mudstones can frequently occur (Cantón et al., 2001a), even though limited in depth by the slight infiltration (Solé-Benet et al., 1997). In wet years, with one or two rainfall events of over 20 mm (Cantón et al., 2001b), infiltration fronts can penetrate deeper and therefore have a greater weathering impact. As the parent material is rich in gypsum and soluble salts, the combined effects of moisture cycling and salt dissolution–precipitation constitutes an important weathering process (Cantón et al., 2001a).

A logical consequence of the dominance of steep slopes in badlands, is the relatively rapid erosion. Weathering can barely keep up with the rate of erosion, mostly resulting in shallow, weathering-limited soils (Yaalon, 1997). This fact is particularly marked in the MAR soil unit (*Epileptic Regosol*), where local conditions are harsh enough to restrict the establishment of vegetation. Therefore, plant cover that would otherwise favour soil development and protect it against erosion is lacking. Moreover, erosion and runoff processes are linked by a feedback mechanism that also limits soil development.

Because of their limited development, many properties of these soils are inherited from the parent material, like particle size distribution and some chemical characteristics. MAR (*Epileptic Regosol*) and LIQ (*Endoleptic Regosols*) soil units have a texture dominated by fine silt and most of their properties coincide with those encountered in the fresh mudstone, such as strong electric conductivity, high content of carbonates and gypsum (the last in subsurface horizons), with Ca^{2+} the dominant exchangeable cation followed by Na^{+} and Mg^{2+} (Cantón et al., 2001a). The few clay in these soils also reveals their reduced pedogenesis. However, at the catchment headwaters (Fig. 2), the mudstone is covered by a calcaric sandstone colluvium and the incidence of sandy soils (STI) is the result of the erosion and transport of that rock. In most of the catchment, sharp changes in particle size distribution occur along soil profiles due to the colluvial nature of these soils.

In general, soil salinity is relatively high and this produces volumetric changes in the soil mass (Imeson et al., 1982) which, along with the few organic matter, does not favour aggregate stability. The repeated cycles of salt dissolution–crystallisation during wetting–drying processes also affect soil structure, making the soil less resistant to erosion. The increase in salinity with depth is not gradual, specifically in PER and STI, and sharp increases are recorded in some cases, e.g. in PER soil salinity increases quickly from 0.9 dS m^{-1} in horizon C_k1 to 3.1 dS m^{-1} in C_k2 (Table 4).

The soil chemistry does not suggest that crusting is associated with the chemical dispersion of the soils. Crusting is primarily the result of the physical disintegration produced by raindrop impact as indicated by the presence of vesicles (Fig. 3A).

5.2. Effect of surface crusting

A general characteristic of all the soils in this area is the presence of surface crusts, whether biotic or physical (structural or depositional), one to several millimetres thick, with a platy structure and dominant vesicular pores. These crusts hinder infiltration (Morin et al., 1981; Helalia et al., 1988; Mualem and Assouline, 1996) in most of the soil-units and thereby soil development. The MAR soil unit, *Epileptic Regosol*, is always covered by either structural crusts—where the regolith outcrops—or depositional crusts—where the regolith is overlaid by silty deposits. LIQ and CDA soil units are covered by a nearly continuous lichen crust, while PER and STI inter-shrub areas are covered by both physical and lichenic crusts. Physical crusts promote increased runoff and sediment yield and account for most of the runoff and sediment yield in the whole catchment (Cantón et al., 2001b), as is the case in other arid and semi-arid ecosystems (Rushforth and Brotherson, 1982; Mücher et al., 1988; Harper and Marble, 1988; Campbell, 1989; West, 1990; St. Clair and Johansen, 1993; Slattery and Bryan, 1994; Williams et al., 1995; Bajracharya and Lal, 1998).

However, cryptogamic crusts have varying effects on infiltration, and it is unclear whether they improve or worsen water relationships in the soil. Numerous authors think that cryptogamic crusts have some negative influence on infiltration (Rogers, 1977; Danin, 1978; Stanley, 1983; Wood, 1988; Solé-Benet et al., 1997; Kidron et al., 1999; Cantón et al., 2002a), as in the study area, where high runoff rates were recorded on LIQ (*Endoleptic Regosol*), with dominant lichen cover, despite the high macroporosity found under the lichen crust (Fig. 3B).

In less developed soils, conditions are harsh and only lichens are successful in colonising these environments. Lichen cover certainly plays an important role. On one hand, their influence on infiltration is negative, because such crusts are relatively impermeable (Solé-Benet et al., 1997). On the other hand, erosion is reduced (Table 1). This is also in agreement with the findings of other authors (Rushforth and Brotherson, 1982; Mücher et al., 1988; Harper and Marble, 1988; Campbell, 1989; West, 1990). It is well known that lichen crusts improve soil fertility by increasing the organic carbon content and nitrogen fixation of the soils they cover (St. Clair and Johansen, 1993; Jeffries et al., 1992; Klubek and Skujins, 1980). Cryptogamic crusts also significantly increase the availability of essential minerals for higher plants (Harper and Pendleton, 1993), and also improve soil development as revealed in some spots in the study area, e.g., in the LIQ soil-unit, where there is an increase in perennial plant cover, the A horizon is 10 to 15 cm thick and contains more organic matter.

SEM observations of lichen crusts and the soil below show how fungus hyphae aggregate soil particles through the production of extracellular polysaccharides (Fig. 7), as described by Bailey et al. (1973) and Lynch and Bragg (1985) among other authors, and demonstrate the positive influence of lichen on soil development.

5.3. Influence of topography

Not only do topographic factors directly influence pedogenic processes, e.g., by their effect on particle stability (Beckett and Webster, 1971) or surface water distribution (Moore

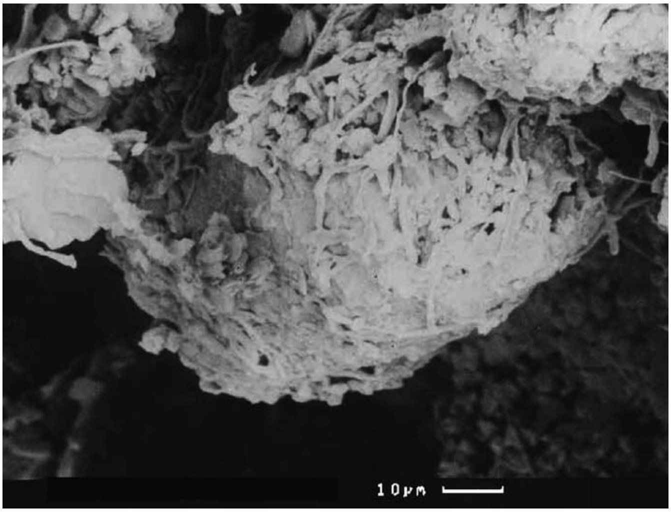

Fig. 7. SEM micrograph of a soil aggregate where fungi hiphae from lichens contribute to soil structure. Individual fine silt particles can also be observed.

et al., 1993), but variations in landform may reflect underlying changes in parent material and differences in age of the soil profile. In the study area, strong interrelationships have been found between topographic characteristics (slope gradient, contribution area) and soil development (Fig. 4) amongst others, like topography and hydrological and erosive behaviour. From upper to downslope positions, soil development as well as plant cover increase. Pearson correlation analyses between soil properties and terrain attributes have also shown significant relationships (Table 6): differences in soil properties are due largely to the topographic variability, which influences water redistribution within soil units, being overland flow the main agent for water redistribution, erosion and deposition in arid environments (Yair, 1990).

Leaching processes are facilitated where water accumulation is favoured: in such locations gypsum is almost absent, while carbonates accumulate at depth forming calcic horizons, as what occurs in PER (Table 4). Moreover, the spatial distribution of soil units play a crucial role: in PER surface leaching of gypsum and other soluble salts is favoured by the hydrological behaviour of the soil units upslope, i.e. LIQ. LIQ produces high runoff rates and subsurface drainage has been detected during 17 days in 1 year (Cantón et al., submitted for publication a). LIQ is one of the most important sources of runoff in the studied microcatchment, but most runoff is infiltrated in PER (Cantón et al., 2002a).

In general, leaching of gypsum and soluble salts is observed in most soils. However, a concentration of salts in the surface horizon of better-developed soil-units (PER, STI and CDA) has been observed. Increases in salinity from upper layers may result from shallow water penetration during rainfall (depth of infiltration fronts between 10 and 12 cm over the same surfaces, Solé-Benet et al., 1997), followed by upward capillary movement due to high evaporation rates. This capillary rise apparently results in a concentration of soluble salts in the top layer as Zaidenberg et al. (1982) explain for aridic soils in Samaria. However, in the LIQ and especially in MAR soil units, this concentration of salts in the upper layer is not often observed, because in these soils water penetration and capillary rise is more limited and also because enhanced runoff washes gypsum and salts from soil surface.

The more poorly developed soils, MAR (*Epileptic Regosols*), appear on bare hillslopes with topographic features favouring high erosion rates (highest SLO and LSF) (Fig. 4, Table 1). The characteristics of these young soils are very similar to the parent material, with large amounts of gypsum and other soluble salts.

The next step in soil development is found in the LIQ soil unit (*Endoleptic Regosols*), where the lower slope gradients and, in general, the smoother topography allow an incipient soil with a moderately crumbled structure and better water-holding capacity than for MAR to exist, though still high in salt content.

CDA (*Eutric Gypsisols*) are found on specific topographical positions with very small contributing areas, which do not allow significant overland flow nor gypsum leaching. Their infiltration capacity is high but infiltration fronts rarely exceeds 11 cm (Solé-Benet et al., 1997), favouring gypsum accumulation. The presence of gypsic horizons is also evidence that there is not much erosion (Wieder et al., 1985).

CDA and STI soil-units (*Haplic Gypsisols* and *Calcaric Regosols*, respectively) appear on the oldest geomorphic surface (Harvey, 1987; Calvo et al., 1991 Alexander et al., 1994), upslope in the catchment. These steep north-facing slopes, below the protective bank of calcaric sandstones, receive low incident radiation (Cantón et al., submitted for publication b) and consequently, favour less soil moisture loss from evapotranspiration. Moreover, a considerable cover of rock fragments in STI (Table 2) reduces overland runoff, increasing infiltration and protect the soil from erosion (Poesen et al., 1990; Bunte and Poesen, 1994; Poesen and Lavee, 1994). All these features have favoured the development of the soil, notwithstanding a strong potential for erosion because of the steep slope gradients. Moreover, these hillslopes, especially near the bottom (STI soil-unit), have vast contribution areas that favour salt washing processes.

The PER (*Haplic Calcisols*) soil unit is found in pediments, with low slope gradients, over colluvial material and wide contributing areas, low LSF (Fig. 4) and good infiltration. All these features favour weathering, leaching and soil development, allowing scattered shrub cover with a positive feedback on the soil. Soils on stable landscape surfaces and under good plant cover conditions may improve with time by accumulating organic material, enhancing soil aggregate stability, increasing infiltration capacity and decreasing erosion potential (Trimble, 1990; Kosmas et al., 2000).

5.4. Dynamics of gypsum and soil classification

This landscape is controlled mostly by weathering and by the movement of gypsum along slopes, as summarised by Porta and Herrero (1990) for non-leaching environments with gypsiferous rocks. The occurrence and distribution of gypsum-affected soils in this landscape is similar to other gypsiferous soils in similar environments elsewhere, though the smaller size of the field site studied makes the variety of soils found in it quite unique. In very small areas, the gypsum dynamics is quite different and leaching and accumulation vary depending on both slope gradient and soil thickness. Though the present environmental conditions, climate and parent material, are very appropriate for production of *Gypsisols* or *Haplogypsids*, the role of two other factors, i.e., time and topography, restrict their development to only favourable positions.

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