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Aggregate stability in range sandy loam soils Relationships with runoff and erosion

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ABSTRACT

The spatial variability of soil aggregate stability and its relationship to runoff and soil erosion were examined in a catena of soils and vegetation in a semiarid environment at the Rambla Honda field site (Tabernas, Almería, SE Spain) to evaluate the validity of structural stability as a soil erosion indicator in sandy loam range soils. The influence of soil properties and topography on the variability of aggregate stability was also examined. Methods include: 1) aggregate stability assessment at 12 sites (3 repetitions per site) on the hillslope by two methods: a) aggregate size distribution by dry sieving b) water drop test; 2) soil organic carbon content; 3) particle size distribution determination; 4) terrain attributes derived from a digital elevation model (1-m resolution); 5) monitoring runoff and erosion for nearly 3 years in eight (10 × 2 m) plots distributed over the hillslope. Results: 41% of the average soil mass is formed by >2-mm aggregates. However, wet aggregate stability is poor, with a mean (of a total of 1440 aggregates) of only 26 drop impacts necessary to break up a wet aggregate (pF = 1). Significant relationships were found in the number of water drops required for aggregate breakdown and runoff and erosion rates. However, no significant relationships between the mean weight diameter of aggregates under dry conditions and runoff or erosion rates were observed. The relationships of aggregates with other soil properties, hillslope position and proximity to plants are also analysed. The most significant correlation found was between the number of drop impacts and soil organic matter content. The stability of topsoil aggregates seems to be a valuable indicator of field-assessed runoff and inter-rill erosion of sandy loam range soils under semiarid conditions.

1. Introduction

Although no single simple measurable soil property can fully represent the integral response that constitutes soil erodibility (Lal, 1990), in practice, a few properties, particularly soil aggregation, dominate soil erosion response (Bryan, 2000). Aggregate stability is considered to be one of the main soil properties regulating soil erodibility (De Ploey and Poesen, 1985; Cerdá, 1998) in semiarid environments (Dunne et al., 1991). Numerous studies describe the relationships between aggregate stability indexes and soil erosion (Imeson and Vis, 1984; De Ploey and Poesen, 1985; Le Bissonnais, 1996; Cammeraat and Imeson, 1998; Cerdá, 1998). Field evaluation of soil susceptibility to water erosion is often expensive and time-consuming. Determination of its relationship to soil aggregate stability is easier and cheaper and would enable soil aggregation characterisation to be extended to evaluation of this susceptibility (Barthès et al., 2000; Barthès and Roose, 2002).

Most work on this topic has been done on agricultural land in temperate climates, but relatively few studies have focused on semiarid environments. Nevertheless, results presently available confirm that aggregate stability is a relevant indicator of soil erodibility and runoff, especially in Mediterranean areas where intense storms are frequent (Cammeraat and Imeson, 1998; Barthès and Roose, 2002). Moreover, there are very few studies in which aggregate stability is compared to water erosion and runoff rates found under natural rainfall conditions to validate the suitability of aggregate stability as an indicator of runoff and erosion.

At the Rambla Honda field site, located in Almería (SE Spain), hillslope hydrology and erosion have been monitored at different spatial and temporal scales over the last 15 years, so an ample database is available and can be used to evaluate the importance of aggregate stability as an indicator of runoff and erosion in this type of soils. At the same time, structural stability analysis could help to interpret runoff and erosion rates in the study area.

The objectives of this paper are to: 1) analyse the spatial heterogeneity of aggregate stability over a catena of soils and vegetation;

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2) examine the influence of other soil properties and topography on aggregate stability and 3) analyse the relationships of aggregate stability to runoff and soil erosion to check its validity as an erodibility indicator.

2. Field site and methods

2.1. Study site

The Rambla Honda field site is located near Tabernas, in Almería Province, SE Spain (37° 8'N, 2° 22'W), on the southern slope of Filabres Mountain Range (Fig. 1), which is mainly Pre-Cambrian to Triassic metamorphic rock. Precipitation in this semiarid climate falls mainly in winter, with a dry period from June to September. The mean annual precipitation is 235 mm in Tabernas (10 km from the site), where data have been recorded over a period of 30 years (1967–97) (Lázaro et al., 2001), and 265 mm at the instrumented site, where records are for 18 years (1988 to 2007). The mean annual temperature is 17.8 °C. Prevailing winds come mostly from the N, NW and SE through the Rambla Honda Valley. The wind speed is over 5 m s^{-1} for only 1% of the year (Puigdefábregas et al., 1996). The main bedrock is a highly convoluted and fractured, dark grey, fine-grained, Devonian–Carboniferous slaty micha schist with graphite and garnets, crossed by abundant quartz veins alternating with thin phyllite layers (Nicolau et al., 1996).

Field work was conducted on an 18-hectare sector of hillslope, which stretches from the dry bed of an ephemeral river (Rambla Honda) at 630 m altitude to the water divide at 770 m, with a median slope angle of 40%. The hillslope surface is a catena of soils and associated vegetation types. Soils show little development of pedogenic horizons, and are mostly loamy sands and fine sandy loams (with low proportions of silt and clay). At the top of the hillslope, soils (Typic Torriorthents) lie on mica schists and the vegetation is dominated by *Stipa tenacissima L.* tussocks. On the Typic Torrifluvents in the alluvial fan, the shrub *Anthyllis cytisoides* L. predominates at the upper part, and *Retamasphaerocarpa* (L.) Boiss is predominant at the lower part. *Retama* is also abundant in the dry stream bed. *S. tenacissima* on the upper slopes used to be harvested for cellulose, while the footslope sedimentary fill was cultivated with rainfed cereals. Both types of land use were discontinued about 45 years ago (Puigdefábregas et al., 1999). For a detailed description of the site, see Puigdefábregas et al. (1996, 1999).

2.2. Data acquisition

2.2.1. Soil aggregation characteristics

Based on the hypothesis that topography might be an indirect factor controlling aggregate stability through its influence on other soil properties like soil organic matter (SOM), texture and plant development, aggregates were studied in representative topographical transects on the hillslope (from about 630 m to 770 m altitude and 550 m in length). 12 sampling sites (about 30 m × 5 m) were selected with 3 micro sampling areas (0.25 m^2), 15 m apart from each other, in each (36 micro sampling areas total). Eight of the sampling sites are near (less than 1 m away) erosion plots. Soil samples were collected from the surface layer (1–3 cm), which is affected by natural rainfall and is crucial to erosion processes (Cerdá, 1998). Litter, rock fragment cover and surface crusts, when present, were removed prior to sampling. The aggregates were deposited in rigid cardboard boxes to keep them undisturbed till reaching the laboratory. All the samples were taken in open areas (in the centre of an open area or near the plant but outside the canopy structure), because the erosion plots involved in this work are predominantly open areas covered by annuals and rather limited shrub cover (Puigdefábregas et al., 1996). A detailed description of the soil surface conditions, vegetation, stone cover, etc., was made of each sampling point, and georeferenced using a differential GPS.

Soil aggregation parameters were found by two methods: 1) Dry sieving and 2) Water-drop test (CND).

1) Dry aggregate size distribution was determined after air drying by mechanical sieving (Kemper and Chepil, 1965) into different size fractions (>8 mm, 4–8 mm; 2–4 mm; 1–2 mm; 0.5–1 mm; 0.25–0.5 mm and <0.25 mm). Stones and litter >2 mm were removed. The percentage by weight of aggregates in each fraction and the Mean Weight Diameter index (MWD) were calculated (Chaney and Swift, 1984).
2) Wet aggregate stability was determined by the single water-drop test (Imeson and Vis, 1984) on 4-mm to 4.8-mm-diameter

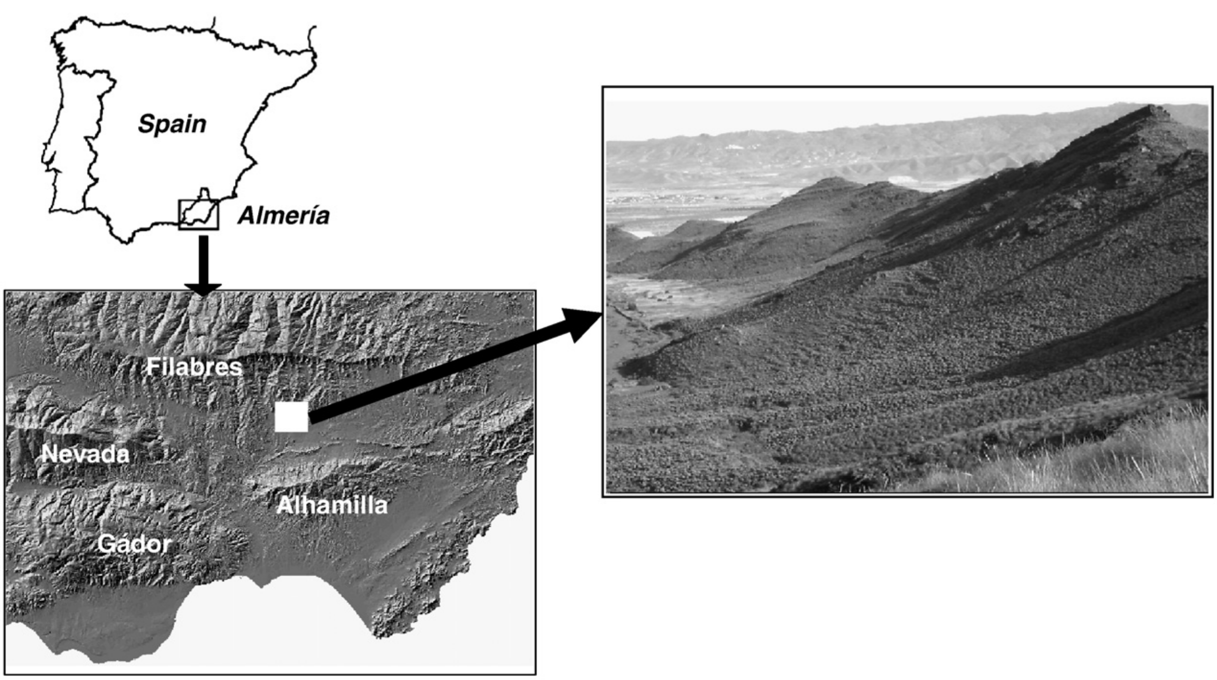

Fig. 1. Field site location and general view.

Table 1
Basic characteristics of the runoff and erosion plot

Plots	Slope (%)	Plant cover (%)	Shrubs (%)	Rock fragments (%)	Crust (%)
P1	12	40	5	80	10
P2	21	65	5	90	5
P3	27	20	15	80	20
P4	29	40	15	50	40
P5	33	70	5	60	10
P6	28	70	5	80	20
P7	35	80	10	30	2
P8	45	80	25	45	4

aggregates which had been moistened for 24 h with distilled water to standardised moisture conditions (pF 1) to prevent slaking on abrupt wetting (Emerson, 1983; Le Bissonnais et al., 1989). 4.0 and 4.8-mm aperture sieves were used to separate the required sizes. 0.1-g (5.8-mm diameter) water drops were allowed to fall 1 m through a 15-cm-diameter polythene pipe onto aggregates placed on a 2.8-mm metal sieve (Imeson and Vis, 1984). The number of drops necessary to disrupt the aggregates was counted and used as a stability index. Other authors have used the same aggregate sizes for Mediterranean soils (Imeson and Verstraten, 1985; Lavee et al., 1991, 1996; Boix et al., 1995; Cerdá, 1996) mainly due to the size of the drops used in the drop-test. 40 single aggregates were taken from each soil sample, for a total of 1440 aggregates for all of the samples. Aggregate stability (number of drops required to destroy an aggregate up to a maximum of 100 drops) was expressed as the mean of the 40 aggregates per soil sample. The CND test was chosen from among the standard methods for assessing aggregate stability, because, due to its simplicity, it can be used with many samples, as in this case. The aggregate pre-treatment and size standardisations adopted by Imeson and Vis (1984), and applied by numerous other authors (Cerdá, 1998, 2000; Sarah, 2005), were used in this paper.

2.2.2. Soil properties

Soil samples were air-dried, gently crushed and passed through a 2-mm sieve to remove coarse fragments. SOM content was then determined using the Walkley–Black wet digestion method (Nelson and Sommers, 1982). Particle-size distribution was assessed by dry sieving and Robinson's pipette method after removal of organic matter with 30% H_2O_2 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.

2.2.3. Rainfall, runoff and erosion measures

Rainfall volume and intensity were recorded by rain gauges distributed along the hillslope. Intensity was measured by automatic tipping-bucket gauges (0.24-mm resolution) connected to the general data acquisition and transmission system (Puigdefábregas et al., 1996, 1999). In addition, each runoff plot was provided with a rain gauge for measuring total precipitation per event.

Surface runoff and sediment yield were measured in 8 enclosed runoff plots (8×2 m) distributed over the hillslope to collect information on the role of old abandoned fields with low perennial plant cover and different gradients as potential sources of runoff and sediment. The main characteristics of the plots are presented in Table 1. Each plot is provided with two 200-litre collector tanks. When the first overflows, 1/10 of the stream flows on to the second through a slot. Readings were made after each rain event and samples were taken for sediment determinations. The events during a period of 2 years and 8 months were used for this work. The relationships between aggregation parameters and runoff and erosion rates were analysed using the average aggregation parameters of 3 sampling areas close to every plot and the total runoff and erosion rates for the entire period.

2.2.4. Terrain attributes

To analyse the influence of topography on soil aggregate stability, the following terrain attributes were derived from a 1-m-resolution digital elevation model (DEM) using PC-Raster and IDRISI software: a) Slope angle (SLO), b) Slope aspect (ASP) and an insolation index, c) Slope profile curvature (PRF), which is negative for concave slope segments and positive for convex segments, d) Plane curvature (PLN) which is positive when the slope segment is concave and negative when convex, e) Distance to the nearest stream (DIST), g) Contributing area (ARE); h) Topographic wetness index (W) (Beven and Kirby,

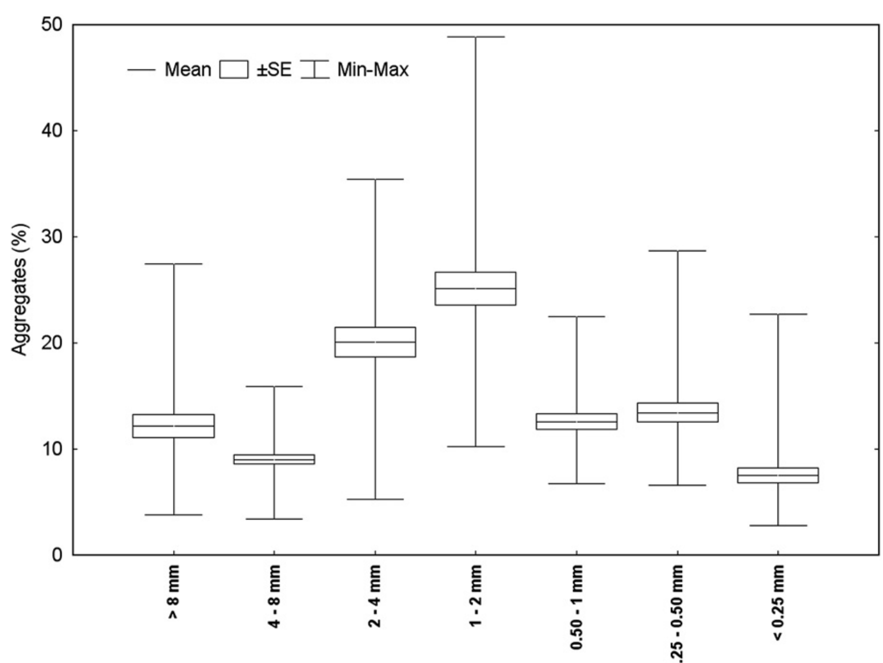

Fig. 2. Size aggregate distribution.

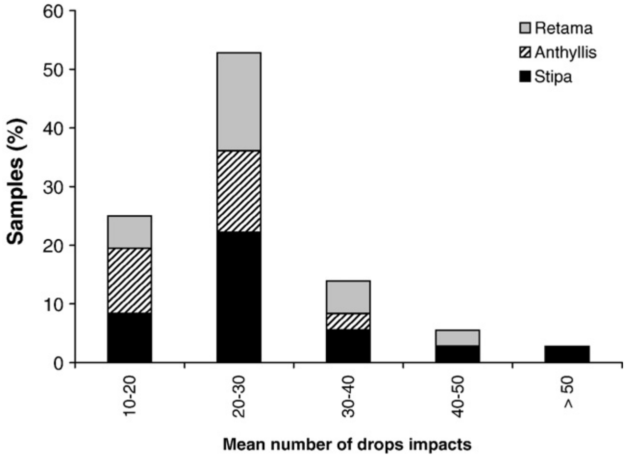

Fig. 3. Distribution of the mean number of drops necessary to break one aggregate under the influence of different vegetation type.

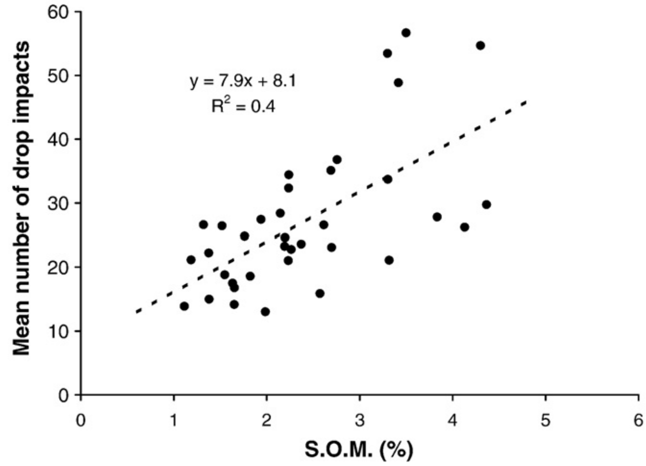

Fig. 4. Relationship between the soil organic matter (S.O.M.) content and the mean number of drop impacts necessary to break one aggregate (4.0–4.8 mm) for the 36 studied areas.

1979), and i) Length slope factor (LSF) as defined by Moore and Burch (1986). Terrain attributes were calculated from the average of nine values from 3×3-m windows (3×3 pixels) for each aggregate sample. The relationships between aggregate stability indexes and terrain attributes were examined by Pearson correlation analysis.

2.2.5. Statistical analysis

Differences in vegetation types with respect to aggregate size distribution, macro-aggregate stability and soil properties were analysed using one-way ANOVA. The samples were grouped by the predominant shrub (*Stipa*, *Retama*, *Anthyllis*) in the sampling area. Relationships between aggregate stability and erosion and runoff rates were found by fitting exponential or lineal equations. Statistica 6.0 software was used, and the significance level was p equal or smaller than 0.05 in all statistical analyses.

3. Results

3.1. Aggregate size distribution and macro-aggregate stability on the hillslope

There are not many large-sized aggregates (>8 mm and 4–8 mm) in any of the samples, as may be observed in Fig. 2, where only an average of 12% of aggregates is over 8 mm and 21% of aggregates are larger than 4 mm. Moreover, the mean of 26 drop impacts (for 1440 aggregates) necessary to break up an aggregate under wet conditions (pF=1) means wet aggregate stability is poor. CND test results range from 13 to 55, and in 97% of the samples a mean of less than 50 drop impacts was necessary to break up 4 to 4.8-mm aggregates. In 52% of the samples, 20 to 30 drop impacts were enough to break up the aggregates (Fig. 3). In the most stable samples, when aggregates had moss and/or small roots, some aggregate CND results were over 100, though the average of the 40 sample aggregates was below 56.

To analyse the influence of vegetation types (*Stipa*, *Anthyllis* and *Retama*) on aggregate size distribution, the samples were grouped according to the predominant plant cover in the sampling areas. No statistically significant differences were found in vegetation types for the mean weight diameter (MWD) or percentage of >8-mm and 2–4-mm aggregates, whilst the number of 4–8-mm aggregates is significantly related to vegetation type (Table 2). Statistically significant differences were also found for 1–2-mm, 0.5–1-mm, 0.25–0.5-mm and <0.25-mm aggregates (Table 2). There were no significant differences in CND values for the three main types of plant communities on the hillslope (Table 2).

The influence of the proximity of the soil sample to any individual perennial plant was also analysed by comparing the aggregate size distribution and wet aggregate stability in both open areas over 0.5 m from individual plants, and near them, but remaining outside their canopies. Although larger aggregates were associated with positions near a plant as reflected by the MWDs and percentages of >2-mm, >8-mm, 4-8-mm and 2–4-mm aggregates (Table 2), these differences are only significant for the percentage of >8-mm aggregates, MWD and >2-mm aggregates ($p<0.1$ for the last two variables). The mean number of drop impacts necessary to break up the aggregates (4–4.8 mm) was significantly higher for samples near perennial plants (36.7) than for samples in open areas (23.9).

3.2. Influence of other soil properties and topography on aggregate size distribution and wet aggregate stability

SOM content ranges from 1.1% to 4.4% in the 36 samples analysed. Nevertheless, in 42% of them, it was below 2%. No significant

Table 2
Mean values of soil aggregate parameters and soil properties under the influence of different vegetation types and position respect shrubs

Data Group	No. sampling areas	Percentage of aggregate sizes								MWD (mm)	N.D.	S.O.M. (%)	Sand (%)	Silt + Clay (%)
Vegetation type		>8	4–8	2–4	1–2	0.5–1	0.25–0.5	<0.25	>2					
Stipa	14	11.2	10.2a	21.4	22.1a	13.0a	13.9ab	8.1a	42.7	2.6	30.9	2.5	75.5a	24.5a
Anthyllis	11	12.8	9.2ab	19.3	20.9a	14.4a	15.4a	7.9a	41.4	2.8	22.0	2.1	77.1a	22.9a
Retama	11	14.2	7.4b	20.9	32.7b	9.6b	10.2b	5.0b	42.5	2.6	27.2	2.6	82.7b	17.3b
Position respect the shrub														
Open area	27	10.5a	8.9	19.8	25.7	13.0	14.2	7.9	39.2a*	2.5a*	23.9a	2.2a	77.6	22.4
Near the shrub	9	17.1b	9.6	20.8	23.4	11.3	11.2	6.5	47.5b*	2.9b*	36.7b	2.9b	74.9	25.1

Statistical differences ($p<0.05$) between groups are marked with different letters, * indicates $p<0.1$. Aggregates sizes are expressed in mm. MWD = mean weight diameter in mm. ND = number of drop impact per aggregate.

Table 3
Correlation coefficients (r) between topographic attributes and aggregate stability under dry conditions (mean weight diameter index (MWD) and size distribution of aggregates) and wet (number of drop impacts per aggregate)

Variable	Elev	Slo	Ins.	Prf	Pln	Are	W	LSF	Dist
No. drop/aggr	0.08	−0.03	0.05	**0.35**	0.09	−0.22	0.14	−0.14	−0.02
MWD (mm)	0.01	0.21	0.19	0.03	−0.09	−0.08	−0.26	0.04	−0.02
>8 mm	−0.15	−0.07	**0.34**	0.04	−0.11	−0.13	−0.32	−0.20	−0.15
4–8 mm	**0.43**	**0.40**	−0.26	−0.05	−0.10	−0.02	0.02	0.32	**0.39**
2–4 mm	0.14	0.17	0.12	−0.02	0.15	0.14	0.03	0.25	−0.02
1–2 mm	−0.32	−0.30	−0.19	−0.05	**0.39**	0.32	0.17	0.07	−0.29
0.5–1 mm	0.11	0.08	−0.03	0.06	−0.31	−0.23	−0.01	−0.15	0.18
0.25–0.5 mm	0.12	0.07	−0.05	0.04	−0.32	−0.26	−0.05	−0.19	0.20

relationships were found between SOM content and aggregate size distribution (or with MWD or aggregate size classes). However, wet aggregate (4–4.8 mm) stability increased significantly ($p = 0.00004$) with SOM content (Fig. 4). There were no significant differences in SOM among vegetation types (Table 2), however, it was significantly higher in samples taken near the plant than from bare areas (Table 2).

As may be observed in Table 2, sand is the major fraction in these soils, representing 71.2% to 83.5%. Clay content ranges from 0% to 8.5%. The analysis of relationships between soil particle size (sand, silt, clay, silt + clay) and aggregation parameters (mean number of drop impacts necessary to break up aggregates, MWD and percentage of aggregates of different sizes) indicates that particle size does not play a determining role in either wet aggregate stability or aggregate size distribution. Only the relationships between soil particle size and 4–8-mm aggregates and 1–2-mm aggregates are significant. A higher percentage of 4–8-mm aggregates was found when the silt + clay content increased (4–8-mm aggregates (%) = 0.38 * silt (%) + clay (%) + 0.76; $r^2 = 0.3$, $p < 0.02$), and the opposite relationship was found for sand content (4–8-mm aggregates (%) = −0.38 * sand (%) + 38.9; $r^2 = 0.3$, $p < 0.01$). For the 1–2-mm aggregate class the relationship to particle size is the opposite of the 4–8-mm aggregate class.

The average silt + clay content is significantly higher where there is *Stipa* than *Anthyllis* and much more than *Retama*, and obviously the sand content follows the opposite trend. Although the silt + clay content is higher near the plant than in open areas, this difference is not statistically significant (Table 2).

Few significant correlations were found among terrain attributes and aggregate size distribution or CND values (Table 3), for example, the mean number of drop impacts necessary to break up 4–4.8-mm aggregates was positively correlated with profile curvature (the more convex the more drops). The 4–8-mm aggregate class was positively correlated with altitude, slope gradient and distance to channels. No significant correlations were found when terrain attributes were compared with particle size composition or SOM.

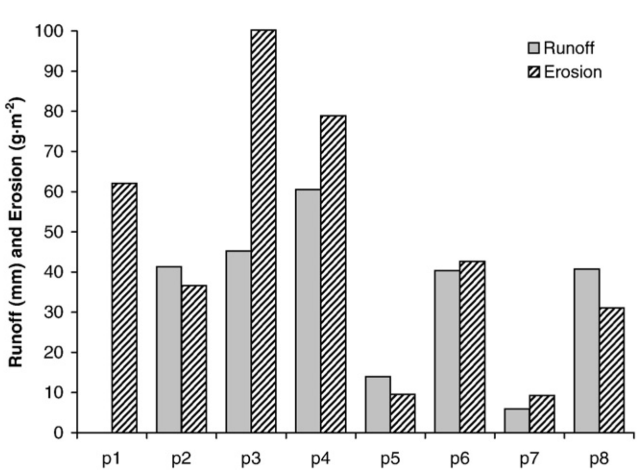

Fig. 5. Total runoff and erosion rates in the 8 plots monitored during 2 years and 8 months.

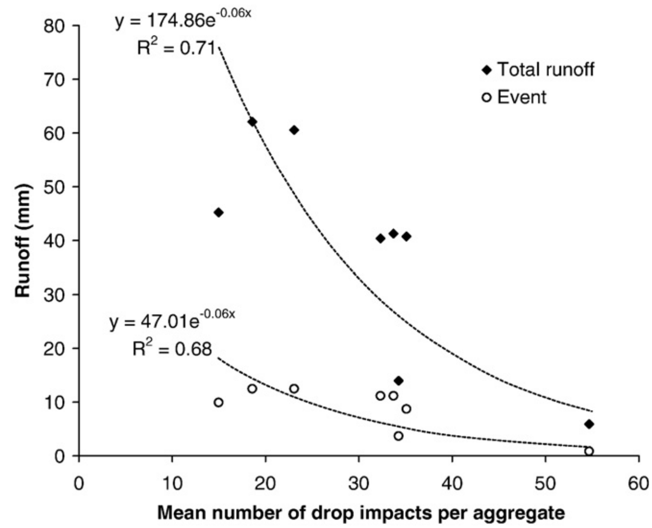

Fig. 6. Relationship between total and maximum runoff recorded in one event in all the field plots and the mean number of drop impacts necessary to break one aggregate of soil in the corresponding part of the catena.

3.3. Relationships with runoff and erosion

Fig. 5 shows runoff and erosion rates recorded in the 8 plots during the study period, in which 25 runoff events occurred. There is not much erosion on the hillslope; the highest erosion rate after 2 years and 8 months was less than 100 g/m^{-2}. It may be observed that the highest erosion rates were recorded in the alluvial fans (Plots p3 and p4). Total erosion rates are positively and linearly related, though not significantly, with total runoff rates, and for total and maximum rates recorded in one event. This weak relationship can be attributed to the short monitoring period.

The mean number of drop impacts necessary to break up 4–4.8-mm aggregates had a significant negative exponential relationship with total runoff (Fig. 6), and also with the maximum runoff rate recorded in a single event (P = 41 mm a maximum $I_{10\ min} = 120\ mm \cdot h^{-1}$). There is also a significant negative logarithmic function between the mean number of

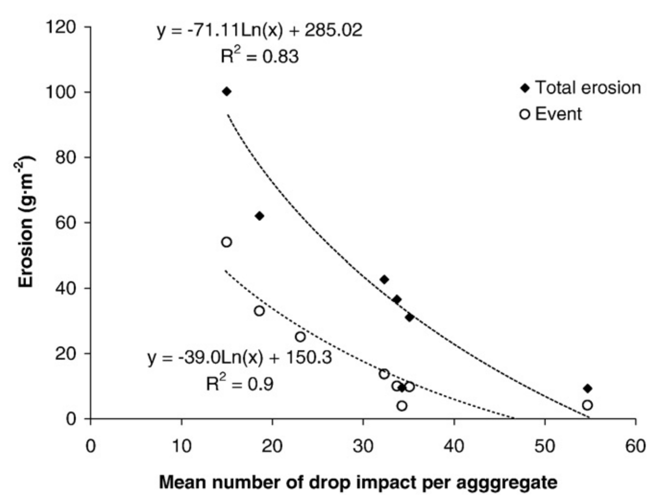

Fig. 7. Relationship between total and maximum erosion recorded in one event in all the field plots and the mean number of drop impacts necessary to break one aggregate of soil in the corresponding part of the catena.

drop impacts and the total (over the monitoring period) and maximum erosion rates in a single event (Fig. 7). The mean number of drop impacts necessary to break up 4–4.8-mm aggregates increased as runoff and erosion rates decreased.

No significant relationships were found between MWD values and runoff and erosion rates or between the different aggregate size classes and runoff and erosion.

4. Discussion

4.1. Aggregate size distribution and macroaggregate stability on the hillslope

Soil aggregation in sandy loam soils from micaschists is relatively high (e.g., >2-mm aggregates represent an average of about 41% of all samples) despite the particle size distribution and other properties of these soils: about 80% sand, very low clay content, near absence of calcium carbonate, relatively low SOM, low CEC (<10 $\mathrm{cmol \cdot kg^{-1}}$) (Puigdefábregas et al., 1999). Nevertheless, large aggregates (>8 mm) are not very abundant in most samples and in general the most abundant aggregates are in the 1 to 4-mm classes. As several works have shown that aggregation and the proportion of large aggregates decrease with aridity (Lavee et al., 1996; Cerdá, 1998), because soil conditions are more favourable for aggregation in humid areas, a smaller proportion of large aggregates was expected in the study area (mean annual rainfall of 235 mm). However, other studies in arid areas, and also in Southeast Spain (Alicante), have found more abundance of large aggregates, e.g., Boix-Fayos et al. (2001) analysed soil aggregation in a climatological transect, from semiarid to subhumid conditions, finding the highest proportions of large aggregates (>10, 5–10, 2–5 mm) in the most arid part of the areas studied, associated with more biological activity in these soils due to low-intensity land use. In Rambla Honda, there is very little biological activity, as shown by Puigdefábregas et al. (1996, 1999) from micromorphological soil observations, despite the fact that these soils have not been farmed for over 40 years. However, the soil properties are very different from those of the soils studied by Boix-Fayos et al. (2001), where more than 50% are fine silt + clay, SOM is over 5% and calcium carbonate is much higher.

Despite the relative abundance of macroaggregates on the hillslope in Rambla Honda, the stability of 4–4.8-mm aggregates to drop impacts is poor compared to the values found by others authors. Cerdá (1998), in a study on soils on limestone in eastern Spain found, for the same initial conditions (pF = 1), that a mean of 162 drop impacts was necessary to break up an aggregate (4–4.8 mm).

Although there were only 5 to 12% of 4–4.8-mm aggregates in the soil samples studied, and the most representative size is actually 1–2 mm (Fig. 2), we decided to apply the standardised CND test (Imeson and Vis, 1984) to 4–4.8-mm aggregates so that results would be comparable to those of other authors in semiarid areas like Boix-Fayos et al. (1998), Sarah (2005) and Cerdá (1996, 1998, 2000) among others, who applied the CND test to the same size aggregates under similar conditions (water-drop weight and fall height, etc.). Nevertheless, very similar results were found using >2-mm-diameter aggregates with no variation in drop weight. For 200 >2-mm aggregates from a mixed sample from different positions on the hillslope, a mean of 31 water drop impacts were necessary to break up an aggregate.

Other authors (Cerdá, 1998; Caravaca et al., 2005) have pointed out the influence of vegetation type on aggregate stability. However, the results presented here do not support their findings. This may be because, contrary to other studies, the samples in this study were always taken in open areas, near a plant, but never under the canopy as in other studies, thus limiting the influence of the plant. In fact, we did not find any significant difference in SOM content among the three hillslope sectors (by type of predominant vegetation, different in each), though previous studies in the same area (Nicolau et al., 1996; Puigdefábregas et al., 1996) found that SOM content from the soil surface horizon increased upslope, also coinciding with larger amounts of litter under *Stipa*, followed by *Anthyllis* and finally *Retama*.

The main differences among the types of perennial vegetation affected the distribution of 4–8-mm and <2-mm aggregate classes, the abundance of larger aggregates coincided with a relatively higher content of silt + clay (upper sector of hillslope covered by *Stipa*), and the opposite was true for <2-mm aggregates. In previous work done at the site, the more abundant fine fractions at the upper sector of the hillslope was explained by frequent rock outcrops on the upper hillslope, which retain silt and clay upslope above the alluvial fans (Puigdefábregas et al., 1999). Cammeraat and Imeson (1998), analysing aggregate size distribution of Leptosols and Regosols in Murcia under different types of plant cover, found that coarser fractions were also more abundant under *S. tenacissima*, though this was not related to higher SOM.

It seems that perennial plant proximity exerts some influence on the mean number of drop impacts necessary to break up an aggregate (4–4.8 mm), and the proportion of coarser aggregates is larger nearer the plant than farther away from it (Table 2). Though the aggregates near the plant have a higher SOM and fine silt + clay content, these differences are not statistically significant. Other conditions, like soil water content, higher in areas close to the plant than farther from it, as demonstrated in a nearby field site in Tabernas (Cantón et al., 2004), and better soil temperature regime, would probably play a significant role in this sense, by improving soil biological activity (Imeson et al., 1996). Pugnaire and Haase (1996) in their work, also done in the Rambla Honda, found that the SOM content (about 3.9 ± 0.7%) was higher under *R. sphaerocarpa* than in open areas (1.4%) and texture improved, with a higher silt + clay content under *Retama* (15.6 ± 0.2%) than outside the canopy (9.6 ± 0.1%). Most authors (Cammeraat and Imeson, 1998; Cerdá, 1998, 2000; Li and Sarah, 2003; Sarah and Rodeh, 2004) also found differences between open areas and under the plant).

4.2. Influence of other soil properties and topography

Many authors have demonstrated that SOM content is one of the most important factors determining aggregate stability in soil (Tisdall and Oades, 1982; Metzger et al., 1987; Roberson et al., 1991; Boix-Fayos et al., 1998; Cerdá, 1998, 2000; Martí et al., 2001; Castro-Filho et al., 2002; Sarah, 2005; Le Bissonnais et al., 2007). Our results agree, as SOM shows a positive linear relationship with the number of water drops necessary to break up aggregates (Fig. 4). Taking into account that 2% of SOM content constitutes an important threshold of soil aggregate stability (Oades, 1988; Cerdá, 1998), the fact that 42% of the soil samples studied had less than 2% SOM content also explains the relatively poor aggregate stability of these soils.

SOM seems not to be an important factor in the formation of coarser aggregates in the Rambla Honda because no significant relationships were found between MWD and SOM, and although coarser aggregates are positively related to SOM and smaller aggregates are negatively related, the relationships are not significant. Boix-Fayos et al. (2001) and later Sarah and Rodeh (2004) did not find statistically significant relationships between SOM content and MWD index or the aggregates size distribution either, whereas other authors (Tisdall and Oades, 1982; Roberson et al., 1991) found that MWD increased with increasing SOM. Castro-Filho et al. (2002) showed that the MWD index was 50% higher in the first 20 cm of soil where SOM was also higher. Other authors have not found a relationship between >2-mm aggregates and SOM, although they have with very small aggregates, i.e., aggregates smaller than 0.105 mm (Unger 1997; Boix-Fayos et al., 2001). Nevertheless, in other works, the abundance of macroaggregates was significantly related to SOM content (Ternan et al., 1996; Cerdá, 1998; Martí et al., 2001).

The role of soil texture in wet aggregate stability is not as influential as the SOM content in these soils, which coincides with the findings of other researchers in different places (Tisdall and Oades, 1982; Metzger et al., 1987; Roberson et al., 1991). Rambla Honda soil has a very low clay content (less than 8.5% in all the samples analysed), and as clay is the most important fraction controlling structural stability (Gollany et al., 1991; Payne, 1992), this could explain the slight effect of texture on macroaggregate stability. Rather unstable soil aggregates over 4 mm, though not very frequent, might also be explained, apart from the presence of SOM, by the fact that a large percentage of the mineral grains are micas (mainly muscovite, paragonite and biotite) with different degrees of weathering, and therefore have some negative charge, which might contribute to bonding with both SOM and Fe oxihydroxides, which are also present due to garnet weathering, determined from the reddish colour of weathering rinds in mica schist rock fragments. Thus the influence of texture becomes apparent in the abundance of 4–8 mm and 1–2 mm aggregates. As expected, the abundance of coarse aggregates (4–8 mm) increased with silt + clay content and decreased with sand content, coinciding with the results of Boix-Fayos et al. (2001), and the other way round for 1–2-mm aggregates.

Topography does not significantly affect macroaggregate stability or aggregate size distribution. This is consistent with the fact that topography showed no significant relationships with SOM content or particle sizes. Only some relationships, like the positive correlation between aggregate stability to drop impact and convexity were significant. Flow velocity and erosive potential are reduced on convex hillslope segments, allowing more stable aggregates to form (Meyer and Martínez-Casasnovas, 1999). The positive correlation between the proportion of large aggregates (4–8 mm) and altitude, slope gradient and channel distance (Table 3) can be explained by the higher fine-particle content at the upper sector of the hillslope (with steeper slope gradients and farther from channel).

4.3. Relationships to runoff and erosion

Neither the aggregate size distribution nor the MWD index is of value as an indicator of susceptibility to runoff and erosion in Rambla Honda soils. In fact, other authors have pointed out that both indices are mainly related to wind erosion (Unger, 1997). Abu-Hamdeh et al. (2005) found that detachment rates increased and inter-aggregate tensile strength decreased as clod size increased and that final splash loss rates from the largest clods were higher than from the smaller ones.

Our results confirm the validity of wet aggregate stability determined by the CND test as an indicator of soil susceptibility to runoff and erosion as reported in previous publications (Cammeraat and Imeson, 1998; Barthès and Roose, 2002). Barthès and Roose (2002), using different methods, found that topsoil aggregate stability was closely related to runoff and soil erosion assessed in the field at several scales (from 1 m^2 microplot to hillslope). As in our case, other authors have found significant negative relationships between aggregate stability and soil erodibility and susceptibility to runoff (Reichert and Norton, 1994; Amezketa et al., 1996). However, in most studies on aggregate stability, soil erosion was determined by rainfall simulation on disturbed samples in the laboratory or performed on microplots in the field with rainfall simulators (Valentin and Janeau, 1989; Van Dijk et al., 1996; Boix-Fayos et al., 1998), but only a few studies have evaluated runoff and soil erosion under natural rainfall on erosion plots (Quantin and Combeau, 1962; Barthès et al., 2000; Barthès and Roose, 2002). This paper demonstrates the value of using macroaggregate stability assessed under natural rainfall on runoff-erosion plots as an indicator of runoff and soil erosion in sandy loam soil in a semiarid environment.

5. Conclusions

1. Wet aggregate stability of sandy loam soil in the Rambla Honda is poor. 97% of the samples studied required less than 50 drop impacts to cause the disintegration of 4–4.8-mm aggregates.
2. The SOM content has been found to be one of the main factors controlling the wet aggregate stability in these soils, however no significant relationships were found between the organic matter content and the aggregate size distribution.
3. As clay content in this soil is very low (<8.5%), the influence of texture on aggregate size distribution and wet aggregate stability is of little significance, even considering that the silt fraction, especially the finest, might contribute slightly to aggregation.
4. No significant differences were found in wet aggregate stability in open areas among the three hillslope sectors, each of which had a different predominant vegetation type (*Retama*, *Anthyllis* and *Stipa*). However, significant differences were found in aggregate size distribution among the three vegetation types, with more large-size aggregates (4–8 mm) in the areas of influence of *Stipa* and *Anthyllis*. Moreover, the sampling site position with respect to perennial plants affects aggregate stability, with a higher mean number of drop impacts necessary to break up aggregates and a higher proportion of macroaggregates (>8 mm) near the plant.
5. Terrain attributes do not play a significant role in soil aggregate stability, nor does topography exert much control on the spatial distribution of either soil organic matter or texture. However, it is worth while highlighting the significant relationship between wet aggregate stability and profile curvature, indicating that more stable aggregates are found on convex areas where flow velocity and potential erosion are lower.
6. The wet stability of topsoil aggregates as determined by a CND test is a valuable indicator of runoff and erosion measured in the field under natural rainfall conditions in sandy–loam soil. Thus, a simple laboratory assay, such as the CND test, could provide results significantly correlated with field data which are much more expensive and time-consuming to acquire.

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References

Abu-Hamdeh, N.H., Abo-Qudais, S.A., Othman, A.M., 2005. Effect of soil aggregate size on infiltration and erosion characteristics. European Journal of Soil Science 57 (5), 609–616.
Amezketa, E., Singer, M.J., Le Bissonnais, Y., 1996. Testing a new procedure for measuring water-stable aggregation. Soil Science Society of America Journal 60, 888–894.
Barthès, B., Roose, E., 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena 47, 133–149.
Barthès, B., Azontonde, A., Boli, B.Z., Prat, C., Roose, E., 2000. Field-scale aggregate stability in three tropical regions (Benin, Cameroon, México). European Journal of Soil Science 51, 485–495.
Beven, K.J., Kirby, M.J., 1979. A physically based, variable contribution area model of basin hydrology. Hydrological Science Bulletin des Sciences Hydrologiques 24, 43–69.
Boix, C., Calvo, A., Imeson, A.C., Soriano, M.D., 1995. Climatic and altitudinal effects on soil aggregation in slopes of Mediterranean environment. Physics and Chemistry of the Earth 203 (4), 287–292.
Boix-Fayos, C., Calvo-Cases, A., Imeson, A.C., Soriano-Soto, M.D., Tiemessen, I.R., 1998. Spatial and short-term temporal variations in runoff, soil aggregation and other soil properties along a mediterranean climatological gradient. Catena 33, 123–138.
Boix-Fayos, C., Calvo-Cases, A., Imeson, A.C., Soriano-Soto, M.D., 2001. Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. Catena 44, 47–67.
Bryan, R.B., 2000. Soil erodibility and processes of water erosion on hillslope. Geomorphology 32, 385–415.

Cammeraat, L.H., Imeson, A.C., 1998. Deriving indicators of soil degradation from soil aggregation studies in southeastern Spain and southern France. Geomorphology 23, 307–321.
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.
Caravaca, F., Alguacil, M.M., Torres, P., Roldán, A., 2005. Plant type mediates rhizospheric microbial activities and soil aggregation in a semiarid Mediterranean salt marsh. Geoderma 124 (3–4), 375–382.
Castro-Filho, C., Lourenço, A., Guimaraes, M.F., Fonseca, I.C.B., 2002. Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil. Soil and Tillage Research 65, 45–51.
Cerdá, A., 1996. Soil aggregate stability in three Mediterranean environments. Soil Technology 9, 133–140.
Cerdá, A., 1998. Soil aggregate stability under different Mediterranean vegetation types. Catena 32, 73–86.
Cerdá, A., 2000. Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia. Soil & Tillage Research 57, 159–166.
Chaney, K., Swift, R.S., 1984. The influence of organic matter on aggregate stability in some British soils. Journal of Soil Science 35, 223–230.
De Ploey, J., Poesen, J., 1985. Aggregate stability, runoff generation and interrill erosion. In: Richards, K.S., Arnett, R.R., Ellis, S. (Eds.), Geomorphology and Soils. George Allen & Unwin, London, pp. 99–120.
Dunne, T., Zhang, W., Aubry, B.F., 1991. Effects of rainfall, vegetation and microtopography on infiltration and runoff. Water Resources Research 27, 2271–2285.
Emerson, W.W., 1983. Inter-particle Bonding. Soils: An Australian Viewpoint. Division of Soils, CSIRO. CSIRO. Academic Press, Melbourne, pp. 477–498.
Gee, G.W., Bauder, J.W., 1986. Particle-size analysis, In: Klute, A. (Ed.), Methods of Soil Anlysis, part I. Physical and Mineralogical Methods, 2nd edition. Agronomy, vol. 9. American Society of Agronomy, Madison, Wi, pp. 383–411.
Gollany, H.T., Schumacher, T.E., Evenson, P.D., Lindstrom, M.J., Lemme, G.D., 1991. Aggregate stability of an eroded and desurfaced Typic Argiustoll. Soil Science Society of America Journal 55, 811–816.
Imeson, A.C., Verstraten, J.M., 1985. The erodibility of highly calcareous soil material from Southern Spain. Catena 12, 291–306.
Imeson, A.C., Vis, M., 1984. Assessing soil aggregate stability by ultrasonic dispersion and water-drop impact. Geoderma 34, 185–200.
Imeson, A.C., Pérez-Trejo, F., Cammeraat, L.H., 1996. The response of landscape-units to desertification. In: Brandt, C.J., Thornes, J.B. (Eds.), Mediterranean Desertification and Land Use. Wiley, London, pp. 447–469.
Kemper, W.D., Chepil, W.S., 1965. Size distribution of aggregates. In: Black, C.A. (Ed.), Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurements and Sampling, Agronomy, vol. 9. Am. Soc. Agr. Inc.Publ., Madison, WI, pp. 499–510.
Lal, R., 1990. Soil Erosion in the Tropics. Principles and Management. McGraw-Hill, New York.
Lavee, H., Imeson, A.C., Pariente, S., Benyamini, Y., 1991. The response of soils to simulated rainfall along a climatological gradient in an arid and semiarid region. Catena Supplement 19, 19–37.
Lavee, H., Sarah, P., Imeson, A.C., 1996. Aggregate stability dynamics as affected by soil temperature and moisture regimes. Geografiska Annales 78, 73–82.
Lázaro, R., Rodrigo, F.S., Gutierrez Carretero, L., Domingo, F., Puigdefábregas, J., 2001. Analysis of a 30-year rainfall record (1967–1997) in semi-arid SE Spain for implications on vegetation. Journal of Arid Environments 48, 373–395.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. European Journal of Soil Science 47, 425–437.
Le Bissonnais, Y., Bruand, A., Jamagne, M., 1989. Laboratory experimental study of soil crusting: relation between aggregate breakdown mechanisms and crust structure. Catena 16, 377–392.
Le Bissonnais, Y., Blavet, D., De Noni, G., Laurent, J.Y., Asseline, J., Chenu, C., 2007. Erodibility of Mediterranean vineyard soils: relevant aggregate stability methods and significant soil variables. European Journal of Soil Science 58, 188–195.
Li, X., Sarah, P., 2003. Arylsulfatase activity of soil microbial biomass along a Mediterranean-arid transect. Soil Biology & Biochemistry 35, 925–934.
Martí, C., Badía, D., Buesa, M.A., 2001. Determinación de la estabilidad estructural de suelos del Alto Aragón por tamizado en húmedo y lluvia simulada (In Spanish) Edafología 8 (2), 21–30.
Metzger, L., Levanon, D., Mingelgrin, U., 1987. The effect of sewage sludge on soil structural stability: microbiological aspects. Soil Science Society of America Journal 51, 346–351.
Meyer, A., Martínez-Casasnovas, J.A., 1999. Prediction of existing gully erosion in vineyard parcels of the NE Spain: a logistic modelling approach. Soil & Tillage Research 50, 319–331.
Moore, I.D., Burch, G.J., 1986. Physical basis of the legth-slope. Factor in the universal soil loss equations. Soil Science Society of America Journal 50, 1294–1298.
Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter, In: Page, L.A., Miller, R.H., Kenney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Methods, 2nd edition. American Society of Agronomy, Madison, Wi, pp. 539–579.
Nicolau, J.M., Solé-Benet, A., Puigdefábregas, J., Gutiérrez, L., 1996. Effects of soil and vegetation on runoff along a catena in semi-arid Spain. Geomorphology 14, 297–309.
Oades, J.M., 1988. The retention of organic matter in soils. Biogeochemistry 5, 35–70.
Payne, D., 1992. Estructura del suelo, laboreo y comportamiento mecánico. In: Urbano, P., Rojo, C. (Eds.), Condiciones del suelo y desarrollo de las plantas según Russell. Ediciones Mundi-Prensa, Madrid, pp. 395–430 (In Spanish).
Pugnaire, F.I., Haase, P., 1996. Facilitation between higher plant species in a semiarid environment. Ecology 77 (5), 1420–1426.
Puigdefábregas, J., Alonso, J.M., Delgado, L., Domingo, F., Cueto, M., Gutiérrez, L., Lázaro, R., Nicolau, J.M., Sánchez, G., Solé, A., Vidal, S., Aguilera, C., Bremner, A., Clarks, S., Incoll, L., 1996. The Rambla Honda field site: interactions of soil and vegetation along a catena in semiarid southeast Spain. In: Brandt, J., Thornes, J.B. (Eds.), Mediterranean Desertification and Land use. J. Wiley & sons, Chinchester, England, pp. 137–167.
Puigdefábregas, J., Solé, A., Gutiérrez, L., Del Barrio, G., Boer, M., 1999. Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in southeast Spain. Earth-Science Reviews 48, 39–70.
Quantin, P., Combeau, A., 1962. Relation entre érosion et stabilité structurale du sol. Comptes Rendus de l'Académie des Sciences 254, 1855–1857.
Reichert, J.M., Norton, L.D., 1994. Aggregate stability and rain-impacted sheet erosion of air-dried and prewetted clayey surface soils under intense rain. Soil Science 158, 159–169.
Roberson, E.B., Sarig, S., Firestone, M.K., 1991. Cover crop management of polysaccharides-mediated aggregation in an orchard soil. Soil Science Society of America Journal 55, 734–739.
Sarah, P., 2005. Soil aggregation response to long- and short-term differences in rainfall amount Ander arid and Mediterranean climate conditions. Geomorphology 70, 1–11.
Sarah, P., Rodeh, Y., 2004. Soil structure variations under manipulations of water and vegetation. Journal of Arid Environment 58, 43–57.
Ternan, J.L., Williams, A.G., Elmes, A., Hartley, R., 1996. Aggregate stability in Central Spain and the role of land management. Earth Surface Processes and Landforms 21, 181–193.
Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33, 141–163.
Unger, P.W., 1997. Aggregate and organic carbon concentration interrelationships of a Torrertic Paleustoll. Soil & Tillage Research 42, 95–113.
Valentin, C., Janeau, J.L., 1989. Les risques de dégradation de la surface des sols en savane humide (Côte d'Ivoire). Cahiers-ORSTOM. Série Pédologie 25, 41–52.
Van Dijk, P.M., Van der Zijp, M., Kwaad, F.J.P.M., 1996. Soil erodibility parameters under various cropping systems of maize. Hydrological Processes 10, 1061–1067.