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Variation of rock fragment cover and size along semiarid hillslopes: a case-study from southeast Spain

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Abstract

The spatial variation of rock fragment cover (Rc) and rock fragment size (Rs) along semiarid hillslopes and transects in the Mediterranean is largely controlled by hillslope gradient. Total rock fragment cover (Rc > 5 mm) often increases in a convex upward curve with hillslope gradient while the D_{50} of the surface rock fragments > 5 mm increases linearly with hillslope gradient. On south-facing slopes, Rc > 5 mm is slightly higher than on north-facing slopes. Lithology controls the size distribution of the stone pavement rather than its cover percentage. Spatial variation of rock fragment cover reflects spatial variation in past erosion and deposition rates. Hillslope sections that are steep, south-facing, or have been abandoned a long time ago have undergone intense interrill and rill erosion, and thus have high rock fragment covers. Tillage erosion leads to high rock fragment covers on convex hillslopes in intensively cultivated areas. Thus, using information on hillslope gradient, aspect, lithology and landuse, we have been able to describe the spatial variation of rock fragment cover and size along semiarid hillslopes in southeast Spain. Such information is crucial for understanding and modelling the spatial variation of the hydrological and erosion response of semiarid hillslopes under environmental change, especially in semiarid environments of the Mediterranean where vegetation cover is predicted to decrease due to climatic or landuse changes and rock fragments at the surface become the only soil surface stabilisers. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: rock fragments; lithology; hillslope; gradient; aspect; Mediterranean; water erosion; tillage erosion

1. Introduction

Over the past decade there has been a growing interest in understanding the spatial pattern of top soil horizon attributes such as A horizon thickness, organic matter content, amorphous Fe, electrical conductivity, pH, extractable plant nutrients, texture, soil water content and aggregate stability at the hillslope scale (e.g., Miller et al., 1988; Pierson and Mulla, 1990; Brubaker et al., 1993, 1994; Moore et al., 1993; Tomer and Anderson, 1995). Such information is crucial for understanding for instance the variation in soil erosion and in soil water availability for plants along the hillslopes, both of which control the spatial patterns of biomass production.

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In most semiarid and arid environments, topsoils contain significant amounts of rock fragments. Rock fragment cover (Rc) and size (Rs) affect the intensity of various hydrological and soil degradation processes such as surface sealing, infiltration, evaporation, runoff generation, runoff energy dissipation and erosion by water (Abrahams and Parsons, 1994; Brakensiek and Rawls, 1994; Poesen and Lavee, 1994; Poesen et al., 1994; Valentin, 1994; van Wesemael et al., 1995, 1996). Rock fragment content has also been reported to favour soil productivity especially in semiarid and arid regions (Kosmas et al., 1993; Poesen and Lavee, 1994). Until now, most studies have dealt with rock fragment cover effects on the intensity of earth surface processes operating at the plot scale. However, few quantitative data are available on the distribution of rock fragment cover along entire semiarid and arid hillslopes. Such information is crucial for understanding the vulnerability of hillslope sections to land degradation and for modelling overland flow, erosion and deposition along such hillslopes (Lane et al., 1995; Thornes et al., 1996).

Several studies in semiarid and arid environments have pointed to the existence of a positive relation between hillslope gradient and surface rock fragment cover (e.g., Yair and Klein, 1973; Martinez et al., 1979; Abrahams and Parsons, 1991; Cooke et al., 1993; Simanton et al., 1994; Simanton and Toy, 1994). Others also reported a positive relation between slope and surface rock fragment size (e.g., Carson and Kirkby, 1972; Abrahams et al., 1985; Parsons and Abrahams, 1987; Le Roux and Vrahimis, 1987). Only a few studies have quantified the relationship between slope and Rc along specific hillslopes. Simanton et al. (1994) and Simanton and Toy (1994) found a logarithmic increase of Rc with slope for hillslopes formed in weakly consolidated coarse Quaternary alluvium in semiarid rangelands of Arizona (USA). But it is unknown whether the same relation between hillslope gradient and Rc or Rs holds true for semiarid environments in the Mediterranean where shallow soils are often developed over more resistant bedrock. Therefore, a field study was set up to investigate how topography (hillslope gradient and aspect) and lithology influence the rock fragment cover and size in rangelands of the semiarid part of the Mediterranean. Currently, this area is threatened by desertification processes which are being investigated within the framework of an interdisciplinary research project, MEDALUS (MEditerranean Desertification And Land USe; Brandt and Thornes, 1996). In order to better understand how hydrology and soil erosion affect Mediterranean hillslopes, the following objectives were pursued:

1. To describe and to explain the spatial variation of Rc and Rs along Mediterranean hillslopes under rangeland conditions;
2. To discuss the implications of the spatial patterns of Rc in assessing the desertification risk and for modelling runoff, erosion and deposition in Mediterranean environments.

This study focuses on southeast Spain, the driest area of Mediterranean Europe. Vegetation cover is low during summer and surface rock fragments are very important in stabilising the soil surface and therefore play a crucial role in the response of the hillslopes to environmental change.

2. Study area

The study area in the Almeria Province (southeast Spain; Fig. 1) has a typical basin and range topography. The rocks are of Palaeozoic and Cenozoic age and consist mainly of micaschist, andesite and conglomerate (Delgado Castilla, 1974; IGME, 1985). Seven hillslopes ranging from 150 to 650 m length and with a local slope range of 4 to 66% were selected in order to cover different lithologies and different aspects (Fig. 1, Table 1). The hillslopes typically have convex–straight–concave profiles and run from the top of low mountain ridges to alluvial fans (Figs. 2 and 3). These fans are thin or poorly developed in the Gergal area (hillslopes 1, 2, 3 and 7) but thick and well developed at the foot of the Sierra de Gata (hillslopes 4 and 5; Harvey, 1987). Soils are well-drained, gravelly, calcareous loam to loamy sand with an erosion pavement on top (Fig. 4): the rock fragment content of the 3–4 cm thick top soil is higher than that immediately below. Although there are different explanations for the formation of a stone pavement (e.g., Cooke et al., 1993, pp. 68–76), the selective removal of fines by overland flow is the most probable cause in this study area. On the hillslopes, this process might have been

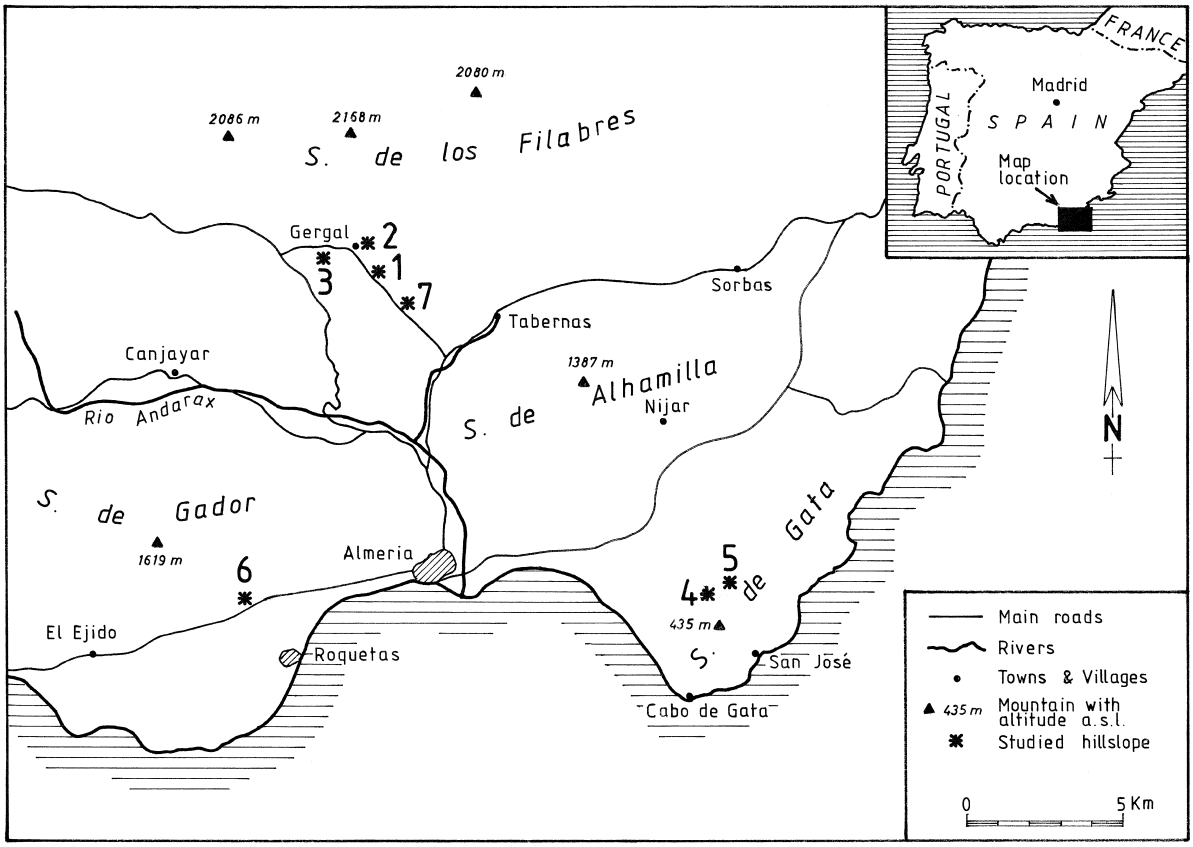

Fig. 1. Location of the hillslopes in southeast Spain.

enhanced by bioturbation: e.g., by burrowing (ants, scorpions), by trampling (sheep and goats) and by digging and wallowing (wild boar). The soils are generally thin on the steeper slope sections (Eutric Leptosol; FAO, 1994) and better developed on the footslopes (Calcic Luvisol; FAO, 1994), although in this latter section effective soil depth is often limited by the presence of calcrete at shallow depth.

Table 1
Characteristics of the studied hillslopes in Almeria Province

Hillslope	Lithology	Aspect	Slope range (%)	Length (m)	Soil depth* (cm)	Veg. cover** (%)
1	micaschist	NW	5–57	600	10–15	11–18
2	micaschist	SW	12–40	350	15–> 100	6–12
3	micaschist	NE	5–61	150	25–70	4–9
4	andesite	NW	5–48	690	25–40	5–30
5	andesite	SW	4–66	460	25–30	14–26
6	conglomerate	SW	11–46	380	13–30	9–22
7	micaschist	SE	12–48	350	25	8–23

*Depth to bedrock or petrocalcic horizon.
**The vegetation cover varies throughout the year. The values listed were determined in October and are minima.
For location, see Fig. 1.

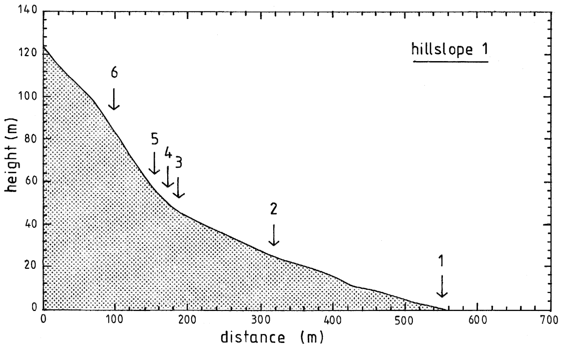

Fig. 2. Typical hillslope profile with segments where rock fragment cover was sampled.

By the end of the summer, vegetation cover is usually less than 30% (Table 1). The dominant species on the upper part of the slopes are *Stipa tenacissima* (perennials) and *Brachypodium distachyon* (annuals) and on the lower part of the slopes *Plantago albicans* and *Anthyllis cytisoides* (perennials) and *Plantago ovata* and *Aegilops geniculata* (annuals). The hillslopes used to be cultivated for wheat production. Cultivation ceased on the upper parts of the hillslopes in the late 1940s, whereas the lower parts remained cultivated until the early 1960s. The present landuse is grazing by sheep and goats. Three climatic stations were used to characterise mean annual temperature (T) and mean annual precipitation (P) of the hillslopes (Fig. 1): (a) Gergal with a T of 16.3°C and a P of 250 mm for hillslopes 1, 2, 3 and 7; (b) Cabo de Gata with a T of 18.6°C and a P of 122 mm for hillslopes 4 and 5; and (c) El Ejido with a T of 18.2°C and a P of 266 mm for hillslope 6 (INM, 1986). Rainfall is concentrated from late September to May.

In addition to the individual hillslopes, Rc was also measured on several straight slope segments along a 12-km long transect in the Sierra de la Torrecilla (Guadalentin basin, 100 km northeast of the town of Almeria, Murcia Region). This low mountain range consists of greywackes, slates, conglomerates and quartzites of Palaeozoic, Mesozoic or Cenozoic age. A dense drainage network created steep and V-shaped valleys. Landuse is mainly dry farming cropland (40%; mainly almond groves), scrubland (32%) and forest (21%). Soils are well-drained calcareous loams with a depth ranging from 10 cm on the convexities to more than 2 m in the valley bottoms. The main soil types are Eutric Leptosols and Calcaric Cambisols (ICONA, 1993). The slope segments were selected to cover the most common combinations of hillslope gradient, lithology and landuse. The two climatic stations that best represent mean annual temperature and rainfall in this area are Puerto Lumbreras (17.2°C, 270 mm) and Embalse de Puentes (17.6°C, 278 mm) (Poesen et al., 1997).

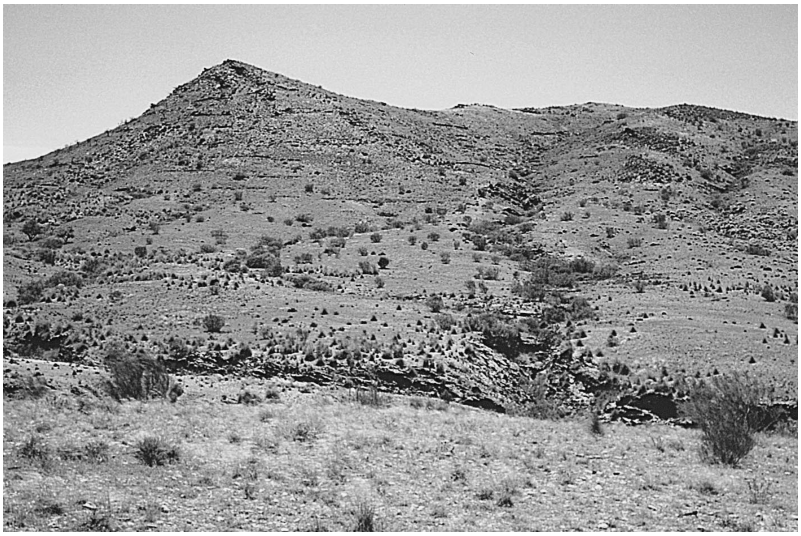

Fig. 3. View on hillslope 1 (Gergal, see Fig. 1).

3. Methods

The profiles of the seven hillslopes (e.g., Fig. 2) were recorded using a clinometer and a tape measure. For each hillslope, between 6 and 30 slope segments with uniform gradients were delineated between the foot of the hillslope and the steepest hillslope section (Fig. 2). Within each of these segments a representative interrill area of approximately 100 m^2 was selected and within this area, orthogonal photographic slides of the soil surface were taken at six unvegetated, randomly chosen sites of ca. 0.5 m^2 (e.g., Fig. 4a, b). A similar procedure was followed for the transect study in the Murcia region. Rc was calculated by projecting the slides onto a grid of 140 nodes (point-count method). The use of a centimeter-scale on the projected slides enabled us to distinguish between the following rock fragment size classes: uncovered (i.e., < 5 mm), 5–25 mm, 25–75 mm, 75–150 mm and 150–300 mm. Mineral particles < 5 mm were considered to be part of the fine earth fraction of the soil since they are easily trans-

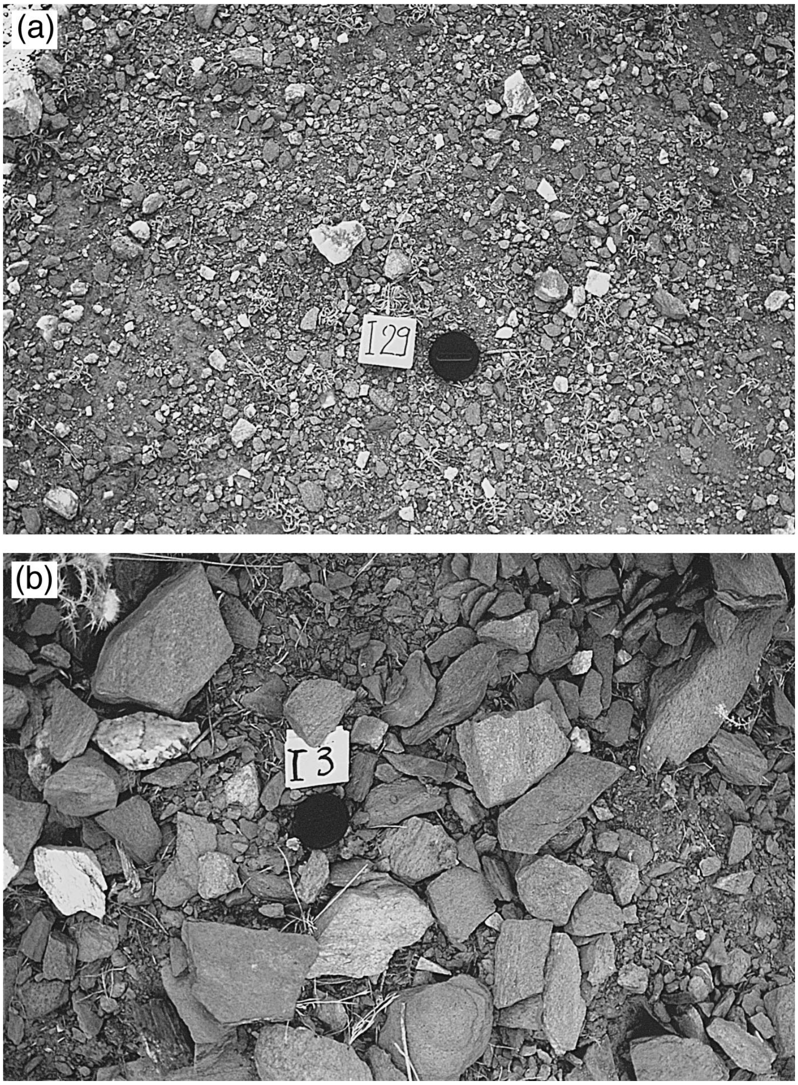

Fig. 4. Detail of soil surface at segment 2 (a) and at segment 6 (b) of hillslope 1. Lens cap is 5 cm in diameter.

ported by interrill flow, while rock fragments > 5 mm were considered to behave as relatively immobile particles on the interrill areas where they form erosion pavements (Poesen, 1987). Rock fragments were then further differentiated in size between the total areal rock fragment cover percentage (Rc > 5 mm) and the cover percentage of large rock fragments (Rc > 25 mm) which cannot be transported by ordinary interrill flow. The median diameter (D_{50}) of the rock fragments > 5 mm was calculated as well. Since measurements were repeated at six neighbouring sites within each hillslope segment, all reported data refer to mean values obtained from six repetitions. At hillslope 1 and 5 it was found by the transect method that only 13 to 20% of all surface rock fragments (at each investigated hillslope segment) were well embedded into the soil surface.

Regression analysis was used to find the best-fit relationships between both Rc and Rs and hillslope gradient. Four types of regression functions were tested for a best-fit: linear, logarithmic, power and exponential. The function that yielded the lowest standard error of Y estimates (of the non-transformed variable) was selected to predict Rc and Rs for a given hillslope gradient at a particular hillslope segment.

4. Results and discussion

4.1. Slope–Rc and slope–Rs relations for hillslopes in the Almeria province

A typical example of the relation between total rock fragment cover percentage (Rc > 5 mm) and hillslope gradient as well as cover percentage of large rock fragments (Rc > 25 mm) and hillslope gradient is shown for hillslope 1 in Fig. 5. Although there is some local variation in rock fragment cover percent for each hillslope segment (as indicated by the standard deviation in Fig. 5), both total rock fragment cover (Rc > 5 mm) and cover of large rock fragments (Rc > 25 mm) increase with hillslope gradient. Regression equations for the relation between hillslope gradient and rock fragment cover percent for the seven hillslopes in the Almeria province are given in Tables 2 and 3.

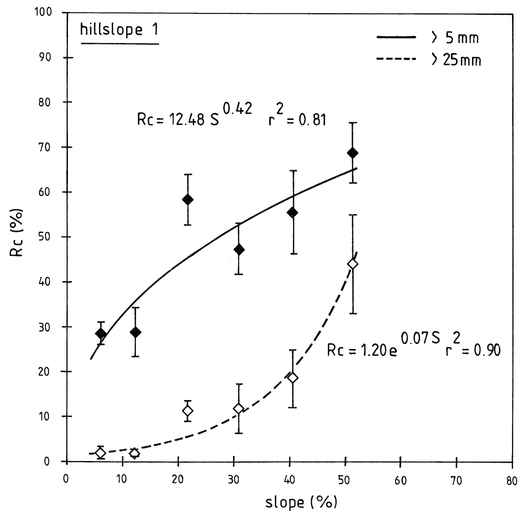

Fig. 5. Example of relation between hillslope gradient and cover of rock fragments > 5 mm and > 25 mm for hillslope 1. Mean and standard deviation of the six repeated measurements are shown for each of the six hillslope segments. For location of the individual hillslope segments, see Fig. 2.

For most of the hillslopes, the increase in total rock fragment cover percent (Rc > 5 mm) tapers off at the steep, upper parts of the slopes (Fig. 6), and this is reflected by the mostly logarithmic regression functions showing a convex upward shape (Table 2). Logarithmic regression functions were also obtained by Simanton et al. (1994) for hillslopes developed on weakly consolidated alluvium in the semiarid region of Arizona (USA) with an annual precipitation of 300 mm. An exception from these logarithmic regression functions is hillslope 6 in the Almeria province, and this hillslope is formed on a substrate

Table 2
Relations between hillslope gradient (S, in %) and total cover percentage of rock fragments larger than 5 mm (Rc, in %) for the studied hillslopes in southeast Spain

Hillslope	Best fit	R^2	n	SE
1	$Rc = 12.48\ S^{0.42}$	0.81	6	8.21
2	$Rc = -14.98 + 25.94 \ln(S)$	0.86	6	5.30
3	$Rc = -26.82 + 21.84 \ln(S)$	0.96	6	3.61
4	$Rc = -16.38 + 21.39 \ln(S)$	0.87	7	7.98
5	$Rc = -21.17 + 24.98 \ln(S)$	0.86	8	9.36
6	$Rc = 25.73\ e^{0.01\ S}$	0.98	6	1.09
7	$Rc = -45.31 + 30.99 \ln(S)$	0.54	30	12.56

SE = standard error of Y-estimates.

Table 3
Relations between hillslope gradient (S, in %) and cover percentage of rock fragments larger than 25 mm (Rc, in %) for the studied hillslopes in southeast Spain

Hillslope	Best fit	R^2	n	SE
1	$Rc = 1.20\ e^{0.07\ S}$	0.90	6	3.59
2	$Rc = 3.29\ e^{0.067\ S}$	0.84	6	3.56
3	$Rc = -1.49 + 0.60\ S$	0.78	6	4.83
4	$Rc = 2.69 + 0.99\ S$	0.90	7	6.03
5	$Rc = -41.47 + 23.75\ \ln(S)$	0.87	8	8.64
6	$Rc = 7.44\ e^{0.02\ S}$	0.72	6	2.83
7	$Rc = -47.44 + 18.99\ \ln(S)$	0.67	28	5.40

SE = standard error of Y-estimates.

of conglomerates. Here, total rock fragment cover continues to increase with progressively steeper rates, up to the steepest parts of the hillslope. This indicates that lithology might play a role in the relation between hillslope gradient and total rock fragment cover percentage. However, there is no general difference for hillslopes developed on micaschists (hillslopes 1, 2, 3 and 7), and andesite (hillslopes 4 and 5). On these micaschist and andesite hillslopes, hillslope aspect seems to have an effect, yielding higher percentages of total rock fragment cover (Rc > 5 mm of 70–80%) on steep hillslopes (40–50% gradient) that face in southerly directions. For the same range of hillslope gradients, northerly facing hillslopes have a total rock fragment cover of only 50–60%. For lack of data, we cannot evaluate the effect of aspect on conglomerate hillslopes, but the one southerly facing hillslope on conglomerates does not group with the other south-facing hillslopes on andesite and micaschist.

Lithology and aspect also control the cover percentage of large rock fragments (Rc > 25 mm) (Fig. 7). Andesite hillslopes (numbers 4 and 5) tend to have the highest cover percentage of large rock fragments. Slopes on micaschist spread over a large range of rock fragment cover percentages, and the apparent grouping within the four micaschist hillslopes suggests that other factors have an effect on rock fragment cover as well. The hillslope 6 on conglomerates has a relative low cover percentage of large rock fragments. Within one lithology, and within one group of data, south-facing slopes always have higher rock fragment covers than north-facing slopes.

The lithological difference between rock fragment covers becomes especially apparent when comparing the D_{50} of rock fragment sizes. While the andesite hillslopes show a steep increase of rock fragment size with hillslope gradient, rock fragment sizes on

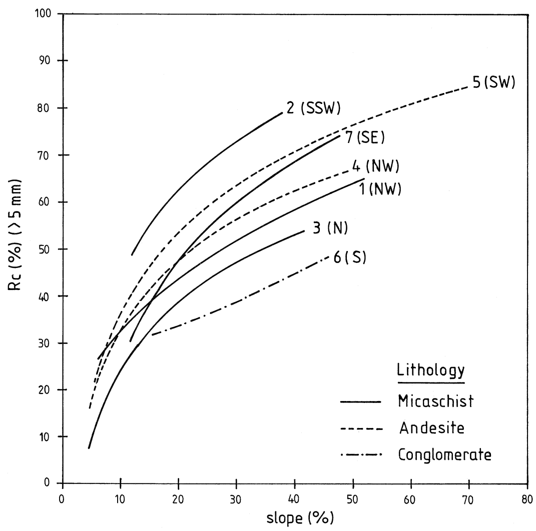

Fig. 6. Relations between hillslope gradient and total cover percentage of rock fragments > 5 mm for the seven hillslopes with different aspects and lithology. See Fig. 1 for location of hillslopes, and Table 1 for hillslope characteristics.

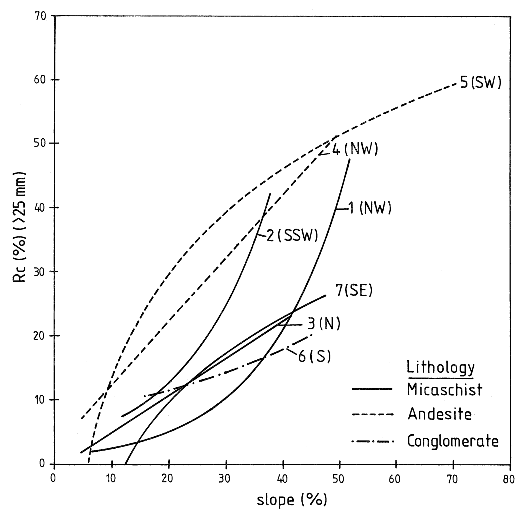

Fig. 7. Relations between hillslope gradient and cover percentage of large rock fragments > 25 mm for the seven hillslopes with different aspects and lithology.

micaschist slopes are only about half as large as those on andesite hillslopes (Fig. 8). There was hardly any systematic variation of rock fragment size with hillslope gradient along the hillslope on conglomerates.

The general increase of rock fragment cover with hillslope gradient (Figs. 6 and 7) is attributed to the erosion and deposition processes by water occurring along the sparsely vegetated hillslopes (Simanton et al., 1994). On steep slopes, selective erosion of the fine earth and possibly very small rock fragments results in a well-developed erosion pavement with a high D_{50}. Such armouring processes have been successfully modelled by the MEDALUS hillslope model on stony hillslopes in central Spain (Thornes et al., 1996). Further downslope, where slopes become more gentle, erosion by water is less intense, resulting in a poorly developed pavement with low rock fragment cover. In addition, fine earth and small rock fragments eroded on upper slope segments are likely to be deposited at the soil surface in this area yielding a lower D_{50} (Fig. 8). Also, it is well possible that arable soils on gentle slopes were reclaimed by removing the largest rock fragments—a common practice in the Mediterranean—resulting in a low cover of large rock fragments (e.g., Fig. 5). Another factor contributing to the high Rc on the steepest slope segments is that these parts of the hillslope were the first to be abandoned from agricultural use. This longer period since abandonment allowed selective erosion to occur on the steepest segments over longer time spans than on the less steep hillslope segments.

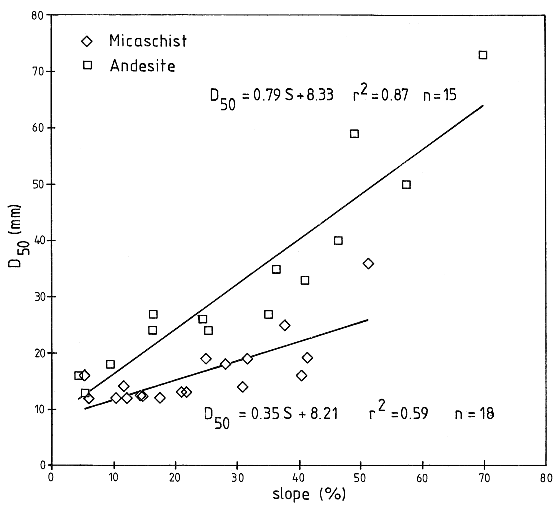

Fig. 8. Relation between hillslope gradient and median diameter (D_{50}) of the surface rock fragments (> 5 mm).

The higher total rock fragment covers (Rc > 5 mm) on south- compared to north-facing slopes are explained by different rates of water erosion. In general, south-facing slopes have lower vegetation cover due to the larger plant water stress, resulting in higher erosion rates by rain and runoff. This, in turn, leads to a more developed erosion pavement on south-facing slopes. Similar observations of aspect-controlled erosion rates were reported by Marques and Mora (1992) in northeastern Spain.

Rock fragment size is obviously controlled by lithology because different rock types have different weathering rates. In the study area, the dense andesite fragments with abundant medium size phenocrystals (pyroxenes and plagioclases) and with an equant or prolate shape are relatively more resistant to weathering than the planar shaped micaschist fragments which are fine-grained schistose rocks (with foliated structure), rich in graphite and garnets. The presence of sand-sized garnets in the micaschists favours their weathering. Hence, the clast size at the soil surface of the andesite hillslopes is larger than that on the micaschist hillslopes. This is best seen when comparing the relation between slope and Rc > 25 mm (Fig. 7) or D_{50} (Fig. 8) for both lithologies. Since the weathering of the conglomerates produces a uniform rock fragment size distribution along the entire hillslope, the relation between slope and Rc > 5 mm or Rc > 25 mm is less pronounced (Figs. 6 and 7). In addition, being rounded these clasts roll very easily downslope when entrained by erosion or trampling, thus creating a more even distribution along the hillslope.

4.2. Slope–Rc relations for hillslopes in other areas

Few authors have published data on the relation between hillslope gradient and rock fragment cover. Only Simanton et al. (1994) and Simanton and Toy (1994) showed that slope was positively and logarithmically related to Rc for hillslopes formed in weakly consolidated coarse Quaternary alluvium in

Table 4
Relations between hillslope gradient (S, in %) and total cover percentage of rock fragments (Rc, in %) for other hillslopes in semiarid and arid environments

Location and lithology	Slope range (%)	Best fit	R^2	n	SE	Source
Turkey, Çanakli, limestone (> 5 mm)	4–56	$Rc = -37.27 + 25.68 \ln(S)$	0.80	9	11.82	Poesen and Bunte (1996)
Israel, Avdat, limestone (> 2 mm)	3–52	$Rc = -4.93 + 20.32 \ln(S)$	0.74	10	12.47	Lee (1988)
USA, Arizona, Quaternary alluvium (> 2 mm)	3–60	$Rc = 2.32 + 16.21 \ln(S)$	0.74	61	8.84	Simanton et al. (1994)
USA, Arizona, basalt (> 25 mm)	18–70	$Rc = 16.93 + 0.81\ S$	0.48	9	19.74	Kirkby and Kirkby (1974)
USA, Arizona, schist (> 25 mm)	18–55	$Rc = -41.55 + 18.89 \ln(S)$	0.43	8	10.11	Kirkby and Kirkby (1974)
USA, Arizona, granite (> 25 mm)	3–44	$Rc = 3.31 + 1.04\ S$	0.97	6	4.23	Kirkby and Kirkby (1974)

The calculations are based on data from various sources.
SE = standard error of Y-estimates.

semiarid rangeland of Arizona (USA). Others have reported field observations from other semiarid and arid environments which allow one to establish a relationship between slope and Rc for hillslopes on limestone (Lee, 1988; Poesen and Bunte, 1996), basalt, schist and granite (Kirkby and Kirkby, 1974). Details on these hillslopes and the established relations between slope and Rc are shown in Table 4. In agreement with our results, most relations in Table 4 show a progressively slower rate of increase of Rc with increasing slope. In four out of six hillslopes, the best fit regression was logarithmic.

4.3. Slope–Rc relations along a transect in the Guadalentin basin

A unique logarithmic relation between hillslope gradient and the total cover percentage of rock fragments (Rc > 5 mm), as well as the cover percentage of large rock fragments (Rc > 25 mm) was also found for individual hillslope sections along a 12 km long transect in the Sierra de la Torrecilla in the Guadalentin basin near Murcia (Fig. 9). Each of these hillslope sections had an even hillslope gradient, without convexities or concavities. The scatter of the data in Fig. 9 might reflect the different lithologies (i.e., marls, greywackes, slates, phyllites, and quartzites), different land uses (cultivated for wheat and almonds, as well as abandoned), and different aspects of these slope segments.

Although logarithmic relations between hillslope gradient and rock fragment cover percentage were established for many individual hillslopes, as well as for slope segments with neither concave or convex profiles, a logarithmic relation between hillslope gradient and rock fragment cover does not hold true in all cases.

A closer look at individual hillslopes in the Sierra de la Torrecilla reveals that the intensively cultivated convex hilltops, which have gentle hillslope gradients, usually have the highest Rc-values (Poesen et al., 1997). Similar observations were made in intensively cultivated hilly areas on micaschists in the Alentejo region in southeast Portugal (Fig. 10a), on shales–sandstones in the Thiva region in central Greece (Fig. 10b), and in the Larissa region in northern Greece (Danalatos, 1993). This high rock fragment cover percentage on the gentle-sloped convex hill tops in Mediterranean landscapes can be

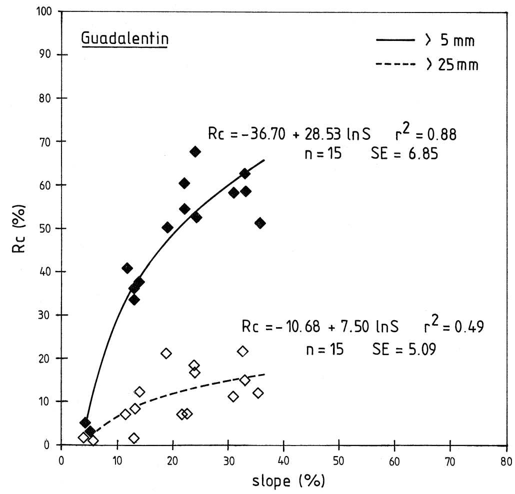

Fig. 9. Relation between hillslope gradient and cover of rock fragments > 5 mm and > 25 mm along a 12 km long transect in the Sierra de la Torrecilla (Guadalentin basin, SE Spain).

attributed to tillage erosion which causes a rapid net removal of topsoil, resulting in thin soils and exposure of the weathered bedrock (Poesen and Lavee, 1994; Poesen et al., 1997).

If stoniness is highest along the convex upper parts of the slopes, the relation between hillslope gradient and rock fragment cover becomes non-monotonic, yielding a sharp increase of rock fragment cover percentage for increasing hillslope gradients, and a gradual decrease of stoniness along the steeper parts of the slope. This is depicted in Fig. 11, using the data from southeast Portugal and central Greece. Hence, the logarithmic relations between hillslope gradient and rock fragment cover found along abandoned slopes with concave profiles in the Almeria province and the Guadalentin do not hold for intensively cultivated, convex hillslopes in Mediterranean landscapes.

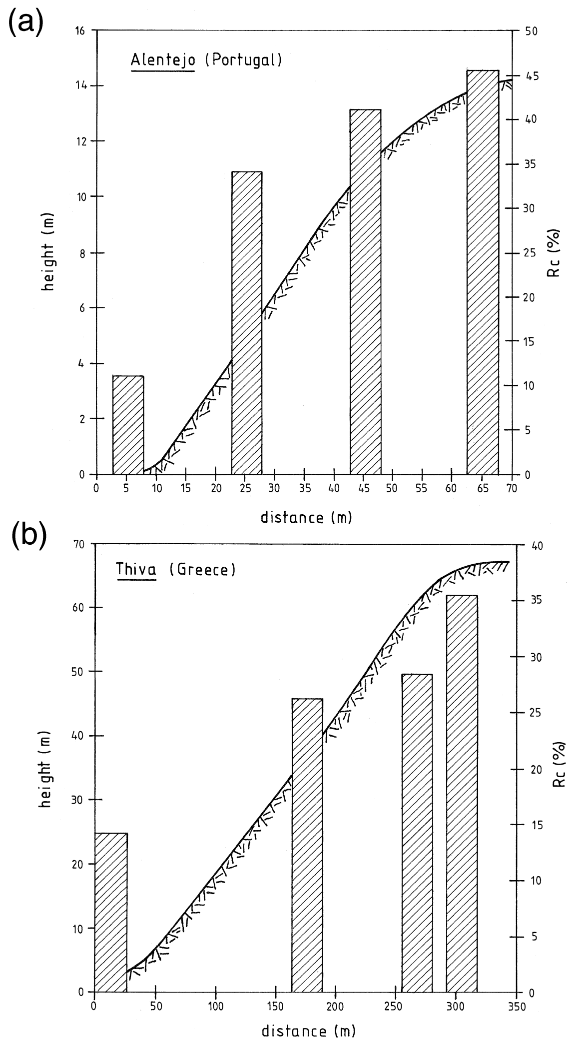

Fig. 10. Representative hillslope profile and spatial variation of total percentage cover of rock fragments > 5 mm (as indicated by vertical bars) in typical intensively cultivated areas of the Mediterranean: (a) Alentejo, southeast Portugal and (b) Thiva, central Greece.

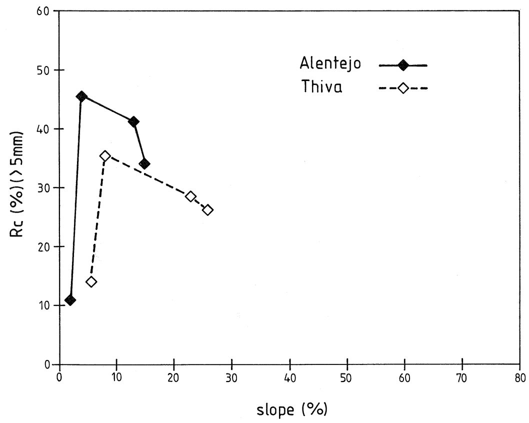

Fig. 11. Relation between hillslope gradient and total percentage cover of rock fragments > 5 mm for typical intensively cultivated convex hillslopes of the Mediterranean: Alentejo (southeast Portugal) and Thiva (central Greece).

5. Implications

Both cover and size of surface rock fragments control the intensity of a series of hydrological and soil degradation processes such as surface sealing, infiltration, evaporation, runoff generation, runoff energy dissipation and erosion by water. Hence, the observed relationships between slope and Rc, as well as between slope and Rs, help understanding the spatial pattern of the intensity of these processes along hillslopes in the Mediterranean.

In order to illustrate this, the observed rock fragment cover distribution along hillslope 1 (Figs. 2 and 5) is used to predict the relation between hillslope gradient and soil loss by interrill and rill erosion. The relationship between slope (θ, in degrees) and relative soil loss by interrill and rill erosion (RSL) for a soil without rock fragments can be represented by the slope factor of the USLE (Wischmeier and Smith, 1978; Fig. 12):

$$\mathrm{RSL} = 65.41 \sin^2(\theta) + 4.56 \sin(\theta) + 0.065 \qquad (1)$$

RSL (dimensionless) is expressed relative to soil loss for a standard plot which has a 9% slope and is 22.1 m long.In the case of hillslope 1, $\mathrm{Rc} > 5$ mm increases with slope (S, in %) according to the equation (Table 2, Fig. 5):

$$\mathrm{Rc} = 12.48\, S^{0.42} \qquad (2)$$

From an extensive literature review, Poesen et al. (1994) found that relative soil loss by interrill and rill erosion decreased exponentially with Rc:

$$\mathrm{RSLRc} = e^{-0.04\, Rc} \qquad (3)$$

RSLRc is soil loss for a soil with a given Rc relative to soil loss for a non-stony soil. This relationship applies because only 13 to 20% of all surface rock fragments at the studied hillslopes are well embedded into the soil surface. In other words, 80 to 87% of all surface rock fragments rest on the soil surface and it has been shown elsewhere that these rock fragments contribute significantly to the lowering of interrill erosion rates (Poesen et al., 1994).

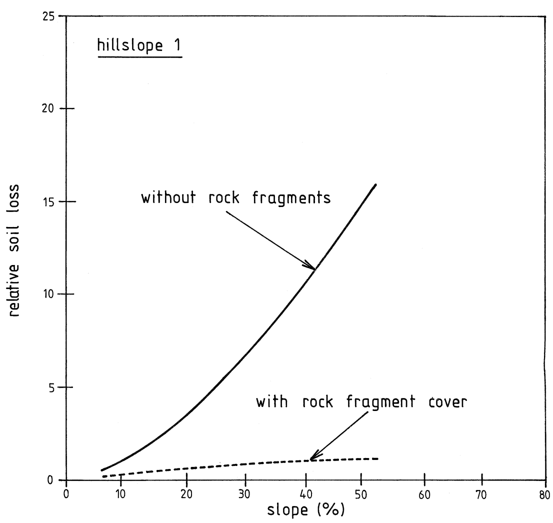

Fig. 12. Relative soil loss due to interrill and rill erosion (dimensionless) calculated for hillslope 1 without and with the observed rock fragment cover pattern. The slope–relative soil loss relation for this hillslope without a rock fragment cover was calculated using the slope factor of the USLE (Eq. (1); note that relative soil loss equals unity for a hillslope gradient of 9%). The slope–relative soil loss relation for this hillslope with rock fragment cover was calculated by combining Eqs. (1)–(3).

Applying Eqs. (1)–(3) to hillslope 1 yields a relation between hillslope gradient and relative soil loss due to interrill and rill erosion that takes into account the spatial distribution of rock fragment cover percent along the hillslope (Fig. 12). This relation deviates strongly from the hillslope gradient–soil loss relation expected for soils without rock fragments, and indicates the protective effect of rock fragments. The plot of our relation between hillslope gradient and relative soil loss has only a slightly convex shape in which the relative soil loss tapers off for high rock fragment covers. Abrahams and Parsons (1991), however, demonstrated for hillslopes in Arizona that the slope–sediment yield relation for stony soils could even have a strong convex upward trend. The importance of employing a spatially varied rock fragment cover percent along hillslopes for soil loss predictions is further stressed by Lane et al. (1995) who demonstrated that observed erosion and deposition rates, and thus sediment yield, deviated strongly from modelled sediment yield when the model assumed a uniform distribution of surface ground cover. They argued that the concept of spatially varied surface ground cover must be incorporated into erosion models in order to describe hillslope erosion and sediment yield processes more accurately.

The data reported in this study form an essential basis for modelling sediment yield along hillslopes in semiarid regions of the Mediterranean. Many studies on soil degradation in semiarid environments are based on experimental erosion plots of limited size, and results from individual plots are quite variable. Data presented in this study integrate over the plot scale and make it possible to assess the variability of individual plot results at a hillslope scale.

Mediterranean landscapes could experience a desertification trend due to global warming. Under this scenario it is expected that vegetation cover will decrease which would lead to intensified soil degradation. The effects of this soil degradation (i.e., surface sealing, crusting, compaction, interrill and rill erosion) are expected to be the least intense on the steepest hillslope sections of abandoned hillslopes with concave profiles because of: (1) their high rock fragment cover, (2) the large clast size, and (3) the fact that surface rock fragments act as natural soil surface stabilisers; (Poesen et al., 1994; van Wesemael et al., 1995). Intensively cultivated gentle-sloped convex hillslope tops with high rock fragment covers are also less likely to experience a substantial increase in soil loss due to water erosion. Under such landuse, soil losses by water erosion can be expected to be highest on the central hillslope sections where the effects of steep hillslope gradients on soil loss are less well mitigated by a high, protective, rock fragment cover.

6. Conclusions

Along semiarid hillslopes and transects of the Mediterranean, rock fragment cover and size are not randomly distributed but follow typical spatial patterns. The results of this study show that overall, Rc and Rs are largely controlled by hillslope gradient. On many hillslopes, total rock fragment cover (Rc > 5 mm) increases in a convex upward curve with hillslope gradient whereas the D_{50} of the surface rock fragments > 5 mm increases linearly with hillslope gradient. This spatial variation of rock fragment cover could reflect spatial variation in past erosion and deposition rates. Hillslope segments characterised by high rock fragment cover are slope sections which underwent intense interrill and rill erosion (steep hillslope sections and sections oriented towards the south in rangelands; hillslope sections which have been abandoned a long time ago) or intense tillage erosion (convex hillslope sections in intensively cultivated areas). Information on the linkages between rock fragment cover and size on the one hand and hillslope gradient, aspect, lithology and landuse on the other is crucial for understanding and modelling the spatial variation of the hydrological processes and erosion response of semiarid hillslopes under environmental change.

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References

Abrahams, A.D., Parsons, A.J., 1991. Relation between sediment yield and gradient on debris-covered hillslope, Walnut Gulch, Arizona. Geol. Soc. Am. Bull. 103, 1109–1113.

Abrahams, A.D., Parsons, A.J., 1994. Hydraulics of interrill flow on stone-covered desert surfaces. Catena 23, 111–140.

Abrahams, A.D., Parsons, A.J., Hirsch, P.J., 1985. Hillslope gradient–particle size relations: evidence for the formation of debris slopes by hydraulic processes in the Mojave Desert. J. Geol. 93, 347–357.

Brakensiek, D.L., Rawls, W.J., 1994. Soil containing rock fragments: effects on infiltration. Catena 23, 99–110.

Brandt, J., Thornes, J., 1996. Mediterranean Desertification and Land Use. Wiley, Chichester, England, 554 pp.

Brubaker, S.C., Jones, A.J., Lewis, D.T., Frank, K., 1993. Soil properties associated with landscape position. Soil Sci. Soc. Am. J. 57, 235–239.

Brubaker, S.C., Jones, A.J., Frank, K., Lewis, D.T., 1994. Regression models for estimating soil properties by landscape position. Soil Sci. Soc. Am. J. 58, 1763–1767.

Carson, M.A., Kirkby, M.J., 1972. Hillslope Form and Process. Cambridge Univ. Press, Cambridge.

Cooke, R.U., Warren, A., Goudie, A.S., 1993. Desert Geomorphology. UCL Press, London.

Danalatos, N.G., 1993. Quantified analysis of selected land use systems in the Larissa Region, Greece. Doctoral thesis, Agricultural University, Wageningen, 370 pp.

Delgado Castilla, L., 1974. Caracteristicas sedimentarias del Mioceno al Sur de la Siera de Gador (Provincia de Almeria). Arch. Inst. Aclimatacion 19, 131–153.

FAO, 1994. Soil Map of the World; Revised Legend. ISRIC, Wageningen.

Harvey, A.M., 1987. Patterns of quaternary aggradational and dissectional landform development in the Almeria region, southeast Spain: a dry region, tectonically active landscape. Die Erde 118, 193–215.

ICONA, 1993. Proyecto LUCDEME; Mapa de Suelos Escala 1:100,000, Hoja 952 (Velez Blanco). Instituto Nacional para la Conservacion de la Naturaleza, Madrid, Spain.

IGME, 1985. Mapa geológico de España 1:200.000. Almeria. Servicio de Publicaciones. Ministerio de Industria y Energia, Madrid.

INM, 1986. Estaciones meteorológicas de la Provincia de Almería: datos mensuales y anuales de temperatura y pluviosidad. Período 1952-1985. Instituto Nacional de Meteorologia, Madrid.

Kirkby, A., Kirkby, M.J., 1974. Surface wash at the semi-arid break in slope. Z. Geomorphol. Suppl. Band 21, 151–176.

Kosmas, C.S., Danalatos, N.G., Moustakas, N., Tsatiris, B., Kallianou, Ch., Yassoglou, N., 1993. The impacts of parent material and landscape position on drought and biomass production of wheat under semiarid conditions. Soil Technol. 6, 337–349.

Lane, L.J., Nichols, M.H., Simanton, J.R., 1995. Spatial variability of cover affecting erosion and sediment yield in overland flow. Int. Assoc. Hydrol. Sci. Publ. 226, 147–152.

Lee, M.D., 1988. The development of a distributed computer simulation model of a reconstructed ancient water-harvesting system, Avdat, Israel. In: Whitehead, E.E., Hutchinson, C.F., Timmermann, N., Varady, G. (Eds.), Arid Lands Today and Tomorrow. Proceedings of an International Research and Development Conference, Tucson, October 1985. Westview Press, Boulder, CO, pp. 919–934.

Le Roux, J.S., Vrahimis, S., 1987. The relationship between gradient and the size of rock fragments on debris slopes on dolerite-capped inselbergs in the southern Orange Free State. S. Afr. Geogr. J. 69, 157–164.

Marques, M.A., Mora, E., 1992. The influence of aspect on runoff and soil loss in a mediterranean burnt forest (Spain). Catena 19, 333–344.

Martinez, M., Lane, L.J., Fogel, M.M., 1979. Experimental investigation of soil detachment by raindrop impacts. Proceedings of the Rainfall Simulator Workshop. Tucson, AZ, USDA ARM-W-10, pp. 153–155.

Miller, M.P., Singer, M., Nielsen, D.R., 1988. Spatial variability of wheat yield and soil properties on complex hills. Soil Sci. Soc. Am. J. 52, 1133–1141.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A., 1993. Soil attribute prediction using terrain analysis. Soil Sci. Soc. Am. J. 57, 443–452.

Parsons, A.J., Abrahams, A.D., 1987. Gradient-particle size relations on quartz monzonite debris slopes in the Mojave Desert. J. Geol. 95, 423–432.

Pierson, F.B., Mulla, D.J., 1990. Aggregate stability in the Palouse Region of Washington: effect of landscape position. Soil Sci. Soc. Am. J. 54, 1407–1412.

Poesen, J., 1987. Transport of rock fragments by rill flow—a field study. In: Bryan, R.B. (Ed.), Rill Erosion. Catena Suppl. 8, 35–54.

Poesen, J., Bunte, K., 1996. Effects of rock fragments on desertification processes in mediterranean environments. In: Brandt, J., Thornes, J. (Eds.), Mediterranean Desertification and Land Use. Wiley, Chichester, England, pp. 247–269.

Poesen, J., Lavee, H., 1994. Rock fragments in top soils: significance and processes. Catena 23, 1–28.

Poesen, J., Torri, D., Bunte, K., 1994. Effects of rock fragments on soil erosion by water at different spatial scales: a review. Catena 23, 141–166.

Poesen, J., van Wesemael, B., Govers, G., Martinez-Fernandez, J., Desmet, P., Vandaele, K., Quine, T., Degraer, G., 1997. Patterns of rock fragment cover generated by tillage erosion. Geomorphology 18 (3–4), 183–197.

Simanton, J.R., Toy, T.J., 1994. The relation between surface rock fragment cover and semiarid hillslope profile morphology. Catena 23, 213–225.

Simanton, J.R., Renard, K.G., Christiaensen, C.M., Lane, L.J., 1994. Spatial distribution of surface rock fragments along catenas in semi-arid Arizona and Nevada, USA. Catena 23, 29–42.

Thornes, J.B., Shao, J.X., Diaz, E., Roldan, A., McMahon, M., Hawkes, J.C., 1996. Testing the MEDALUS hillslope model. Catena 26, 137–160.

Tomer, M.D., Anderson, J.L., 1995. Variation of soil water storage across a sand plain hillslope. Soil Sci. Soc. Am. J. 59, 1091–1100.

Valentin, C., 1994. Surface sealing as affected by various rock fragment covers in West Africa. Catena 23, 87–97.

van Wesemael, B., Poesen, J., de Figueiredo, T., 1995. Effects of rock fragments on physical degradation of cultivated soils by rainfall. Soil Till. Res. 33, 229–250.

van Wesemael, B., Poesen, J., Kosmas, C.S., Danalatos, N.G., Nachtergaele, J., 1996. Evaporation from cultivated soils containing rock fragments. J. Hydrol. 182, 65–82.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses—a guide to conservation planning. USDA Agricultural Handbook, Vol. 537, 58 pp.

Yair, A., Klein, M., 1973. The influence of surface properties on flow and erosion processes on debris covered slopes in an arid area. Catena 1, 1–18.