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Effects of rain characteristics and terracing on runoff and erosion under the Mediterranean

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Abstract

Soil aggregate stability along with the erosive effect of rainfall is two main crucial factors, which contribute to soil erosion and runoff. A 2-year experiment was conducted to study the effects of rainfall characteristics and terracing conservation practice on erosion and runoff. The results of the experiment showed that erosion processes were mostly transport-limited, only 6.5% of the rain events were detachment-limited due to their erratic nature. Rainfall events of >60 mm and with 30-min intensity (I_{30}) of $\geq$12 mm h^{-1} shifted the erosion process from the transport-limited to the detachment-limited phase. Under conditions of high saturation, runoff and erosion is probable with rainfall events of I_{30} $\geq$4 mm h^{-1}. Organic carbon, Ca, Mg, EC and K showed significant differences between terraced treatment and non-terraced one. The kinetic energy revealed a strong and significant correlation with interrill erosion, splash erosion and runoff when applied to both terraced and non-terraced systems, although the correlation was highest in the case of splash erosion ($r = 0.93$). Stepwise multiple regression equations between runoff, interrill and splash erosion with rainfall kinetic energy, storm duration, EI_{30} and I_{30} ($r = 0.87, 0.87, 0.93$ for runoff, interrill and splash erosion, respectively) were found to be significant, where the effect of kinetic energy was more pronounced and stronger than other parameters ($r = 0.93$). Interrill erosion can best be estimated using a highly significant multiple regression equation ($r = 0.96$) between interril with runoff and splash erosion.

Keywords: Interrill erosion; Splash; Surface runoff; Aggregate stability; Mediterranean climate

1. Introduction

Population growth, along with anthropogenic activities, have led to the intensification of soil erosion and land degradation, particularly in the arid and semi-arid regions of the Mediterranean (Cerda, 1998a; Pimentel, 2000). The newly formed Palestinian autonomous areas, which are located in the eastern Mediterranean region, are characterized by a mountainous and fragile semi-arid system with many environmental problems, such as loss of vegetative cover; low organic matter content; erratic rainfall events during periods with no canopy cover; increased

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soil susceptibility to interrill erosion and overland flow (Soil and Water Conservation Society, 1994).

Soil erodibility is a measure of its susceptibility to detachment and transport by water, which is, in turn, determined by different soil properties as well as the rainfall characteristics (Cerda, 1998c). Aggregate stability, organic matter, clay mineralogy, and other chemical and physical soil properties are important factors, which affect soil erodibility as well as rainfall erosivity (Cerda, 1998c; Frasera et al., 1999; Herrick et al., 2001). Aggregate stability qualifies as an important parameter for the evaluation of soil erodibility because it indirectly measures the interactive effects of the soil with the surrounding fauna, flora, parent material, climate, soil management and soil properties (Cerda, 2000). Hence, strong relevance of aggregate stability can be established with soil erosion and runoff under natural rainfall conditions (Chappell et al., 1999). The relation between aggregate stability with erosion and runoff, however, is questionable when runoff and erosion data are measured under simulated rainfall, since these conditions lack the correlation to natural phenomena (Le Bissonnais and Arrouays, 1997; Barthes and Roose, 2002).

The kinetic energy of raindrops comprises the major erosive factor of rainfall. This energy causes splash erosion through the detachment of the soil particles with the consequent aggregate disintegration and slacking. The detached soil particles are then transported by the initiated overland flow, which is also a function of the intensity, amount and duration of rainfall (Morgan, 1986). Previous studies have indicated that only 0.06% of rainfall energy contributes to splash erosion by soil detachment (Morgan, 1978).

The relationship between soil erodibilty, rainfall erosivity, and the interaction between interrill and splash erosion under the Mediterranean conditions, has not been intensively investigated. The study of such relationships might contribute to a better understanding and management of this fragile ecosystem. This study has the main objective of assessing the effect of rainfall characteristics and rain erosivity on runoff, splash and interrill erosion. A second objective is to investigate the effect of stonewalled terraces and non-terraced systems on some soil properties and aggregate stability.

2. Materials and methods

2.1. Experimental site and climatic conditions

Two adjacent locations were selected to conduct the experiment: the first was situated in an area with a soil-conserving stonewalled terrace, more than 50 years old; the second in an area with no conservation measure employed. The experiment was conducted during the winter seasons of 2000 and 2001. The experimental location has an altitude of 900 m above sea level. The area has two distinctive seasons, summer and winter. The mean annual precipitation is 580 mm, of which 90% occurs from October to April during the winter (Ministry of Transport, 1998). Summer is completely dry with no rainfall. The mean annual temperature is 17.1 °C, with the hottest months being July, August and September (Ministry of Transport, 1998). Large soil moisture deficits prevail during the summertime, with high mean annual potential evapotranspiration being 861 mm (Land Research Center, 1999). Soil temperature and moisture regimes are Thermic and Xeric, respectively (Dan et al., 1976; Soil Survey Staff, 1998).

The area features limestone, marl and dolomite bedrock dated to the Turonian age (Abed, 1999). The topsoil (0–15 cm) is silt loam and the subsoil is silt clay loam. The USDA soil classification is Lithic Xerorthent loamy, mixed, thermic, whereas the FAO classification is Calcaric Leptosol (Land Research Center, 1999). The soil itself is shallow with depths not exceeding 40 cm in the hilly and the non-terraced areas, whereas in the lower slopes and in the terraced areas, the soil depth is moderate with a maximum of 100 cm.

2.2. Experimental design, rainfall, runoff and erosion measurements

The experiment features two treatments, which are replicated three times in randomized complete block design. The treatments are stonewalled terraced (Tr) and non-terraced (NTr) plots. The experimental area has a well-known history of cultivation of wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*). Erosion and runoff plots were 15 m × 2 m with a main slope of 2–3% along the length of the plot. Each plot was bound on all sides by earth levees except for the downstream end. A drain was dug around each experimental location to prevent run-on from adjacent areas. A plate was installed at the downstream end of each plot to block the runoff and direct it to a 0.2 m^3 tank through a conveyor pipe. After each rainstorm event, the amount of runoff was measured after allowing the sediments to settle down. The runoff in each tank was then mixed thoroughly and four sub-samples were taken to determine the weight of soil loss after oven drying at 105 °C. The average of the four sub-samples was used to conduct the necessary statistical analysis. All plots were kept free of weeds by hand hoeing during the winter season. Rainfall amounts were measured at 30-min intervals, using a tipping bucket pluviometer with 0.2 mm per tip and recorded on a data logger.

Measurements of splash erosion were made only during 2001 using splash funnels (Gorchichko, 1977). The funnels had a diameter of 20.5 cm and protruded 2 mm above the ground level to eliminate the entry of overland flow (Morgan, 1986). Each splash funnel was directing the collected splash material to 2 l underground plastic bottles. Two splash funnels were used in each plot, and at the end of each rain event, the contents of each plastic bottle were mixed thoroughly and dried at 105 °C. The average of the two bottles was used to conduct statistical analysis and comparisons.

2.3. Soil analysis

Water-stable aggregates (WSA) were determined for the 2–6 mm and 0.6–2 mm diameter air-dried, macro-aggregate and micro-aggregate, respectively. Two replicates were made for each plot to determine the WSA of the upper 0–10 cm layer. The WSA determination is based on the procedures described by Young (Amezketa, 1999), which prescribes subjecting 20 g of the soil aggregates placed on a 0.5 mm sieve to rainfall from drip-free nozzles at 1.5 bar. The water-stable aggregate percentage is then calculated by applying the following formula (Amezketa, 1999):

$$\%\,\mathrm{WSA} = \left[\frac{\mathrm{SA} - \mathrm{SM}}{\text{Original mass of the soil} - \mathrm{SM}}\right] \times 100$$

where SA is the mass of stable aggregate and SM is the mass of sand particles greater than 0.06 mm.

Soil pH and EC were measured using a 1:2.5 soil to water mixture (Skoog and West, 1976; FAO, 1980). Soil organic matter content was analyzed using the Walkley–Black method (Nelson and Sommers, 1982). The exchangeable bases were determined using ammonium acetate extract at pH 8.2 and measured by atomic spectrometry (Schollenbergen and Simon, 1945). Soil particle size distribution was determined using the pipette method (Bouwer, 1986), while soil bulk density was determined by the core method (Bouwer, 1986). Two replicates for each plot were used to determine soil chemical and physical properties.

2.4. Data analysis and calculations

Erosion and runoff data for each rainfall event were analyzed by the linear correlation and regression procedures utilizing Minitab version 13. The level of significance, if not otherwise indicated, reflects a statistical significant correlation ($P < 0.05$). Correlation matrices between soil erosion, runoff and event-rainfall variables were performed using the linear correlation procedure.

Rainfall kinetic energy and erosivity were calculated using the Wischmeier and Smith equation (Wischmeier and Smith, 1978). Splash erosion during the 2001 winter season was calculated as kg ha^{-1} in order to judge whether the erosion process was detachment-limited or transport-limited.

Maximum 30-min intensity (I_{30}) and 60-min intensity (I_{60}) were calculated on rain-event basis, taking the highest 30-min rainfall intensity for the former parameter, whereas for the latter, the sum of the two highest consecutive 30-min intensities was taken. In the statistical program used, variables are automatically removed from the stepwise regression model if their P-values are >0.15, whereas variables are entered into the stepwise regression model if their P-values are <0.15.

3. Results and discussion

3.1. Soil aggregate stability and topsoil layer features

Soil erodibilty is a function of soil aggregate stability, which is affected by different soil properties (Duiker et al., 2001; Descroix et al., 2001; Idowu, 2003). Table 1 shows some soil properties for both

Table 1
Water-stable aggregates (WSA), soil chemical properties, and topsoil layer particle size distributions in terraced and non-terraced systems

Topsoil layer features	Terraced	Non-terraced	
Water-stable macro-aggregate (%)	74.7 ± 2.1[a]	54.7 ± 10.4	s[b]
Water-stable micro-aggregate (%)	72.9 ± 4.1	46.2 ± 9.2	s
Organic carbon (%)	1.8 ± 0.2	1.3 ± 0.1	s
Ca (cmol kg^{-1})	54.3 ± 2.6	48.4 ± 0.6	s
Mg (cmol kg^{-1})	6.7 ± 0.5	6.0 ± 0.4	s
K (cmol kg^{-1})	1.25 ± 0.15	0.85 ± 0.13	s
Na (cmol kg^{-1})	0.18 ± 0.02	0.27 ± 0.03	ns
pH	8.0 ± 0.2	7.9 ± 0.1	ns
EC (μS cm^{-1})	332.3 ± 60.3	431.4 ± 53.0	s
SAR	0.034 ± 0.007	0.045 ± 0.004	ns
Bulk density (mg m^{-3})	1.10 ± 0.05	1.12 ± 0.06	ns
Clay (g kg^{-1})	237 ± 12	225 ± 6	ns
Silt (g kg^{-1})	581 ± 15	560 ± 28	ns
Sand (g kg^{-1})	182 ± 25	215 ± 26	ns

[a] Means of six replicates ± standard deviation.
[b] Significant at $P = 0.05$ according to Tukey's test; ns: not significant.

terraced and non-terraced treatments. Water-stable aggregates, organic carbon, Ca, Mg, K and EC show significant differences between terraces and non-terraced treatments ($P < 0.05$) (Table 1). The differences in the aforementioned properties may be attributed to differences in soil erosion between both treatments, where runoff and erosion rates are higher in the non-terraced than the terraced treatment. In addition, the shallow soil depth with restricted root growth coupled with the weak canopy cover in the non-terraced plots (as witnessed in past years) may also be important factors contributing to the differences between both systems. Other soil properties show no significant differences.

Due to the limited number of treatments and samples that were used in the analysis, it is important to note that this relationship should be viewed with some degree of discrimination. To draw out more specific and reliable relationships, more samples with more than two treatments and/or different soil types should be included in such analysis.

3.2. Rainfall characteristics, runoff and erosion

Table 2 shows different categories of rainfall events and their characteristics in addition to the average runoff, interrill and splash erosion of those events. The erosion processes was mostly transport-limited rather than detachment-limited. Most of the rainfall events produced higher amounts of detached soil particles,

Table 2
Runoff, interrill and splash erosion for categorized rainstorm events with their associated characteristics in terraced and non-terraced systems

Rainfall variables	Rainfall events category (mm)						
	0–10	10–20	20–30	30–40	40–50	50–60	60–70
Number of events	13	6	3	2	2	2	3
Rainfall (mm)	4.9	16.4	23.4	34.4	47.1	51.0	62.3
Kinetic energy (K.E.) (J m^{-2})	76.3	273.1	424.0	529.4	750.3	911.7	1128.8
Rainfall erosivity (EI_{30}) (J mm m^{-2} h^{-1})	405	1964	4141	2725	6398	11527	20235
Storm duration (h)	2.7	6.8	6.0	18.5	23.2	15.5	18.5
30-min intensity (I_{30}) (mm h^{-1})	4.2	6.8	10.0	5.1	8.4	12.7	17.1
60-min intensity (I_{60}) (mm h^{-1})	2.4	5.3	8.4	4.2	7.4	11.2	10.8
Terraced system							
Runoff (mm)	0.05	2.01	0.82	3.38	4.30	10.10	14.17
Interrill erosion (kg ha^{-1})	0.9	40.4	38.4	99.0	137.5	202.4	309.2
Splash erosion (kg ha^{-1})	68.7	182.3	247.6	285.7	261.2	437.9	444.9
Non-terraced system							
Runoff (mm)	0.33	2.85	3.19	12.23	10.99	16.60	15.72
Interrill erosion (kg ha^{-1})	5.6	139.1	192.9	341.8	267.5	369.5	1017.7
Splash erosion (kg ha^{-1})	74.9	197.4	283.8	312.2	281.6	506.5	489.8

All values represent the mean of different rain events under each category.

which indicates that the amount of detached particles is higher than the transport capacity of the runoff water. Only the 30–40 mm and 60–70 mm rainfall categories in the non-terraced plots represent the detachment-limited phase. In both cases, the capacity of overland flow was high enough to load and transport all the detached soil particles. Additionally, the overland flow was capable of eroding further soil particles through its movement action. The high velocity, large amount of runoff, and high kinetic energy of the overland flow enabled it to erode more particles than those available through splash erosion, which is in line with previous studies (Renschler et al., 1999; Mamedov and Levy, 2001; Salles et al., 2002). A detailed analysis of the rainfall characteristics, which were detachment-limited (data are not shown), indicates three main possible reasons for this phenomenon: (i) a high antecedent soil moisture content, indicating that aggregates in the topsoil layer were already disintegrated and slaked, with a low resistance to erosion by overland flow (Barthes and Roose, 2002), (ii) a high rainfall amount within short period of time, exceeding the infiltration capacity of the soil, and (iii) high rainfall erosivity during one or more rain event(s), resulting in a high erosive and transport capacity of the initiated overland flow.

Fig. 1 presents the polynomial regression curves between interrill erosion and splash erosion with the kinetic energy. The point of intersection between the curves represents the alteration between the detachment-limited phase and the transport-limited phase of erosion. The area preceding this point represents the transport-limited phase of erosion, where splash erosion is higher than interrill erosion, with more detached soil particles than the transport capacity of runoff water. The area following the point of intersection represents the detachment-limited phase of erosion. In this area, the amount of detached particles is less than the transport capacity of the runoff water, though the runoff water has an excess kinetic energy. This excessive energy can be utilized by eroding more soil particles through overland flow. The application of suitable management practices (i.e., terraces, canopy cover, etc.) is essential to reduce the effects of this excessive kinetic energy and though reduce the erosion by overland flow.

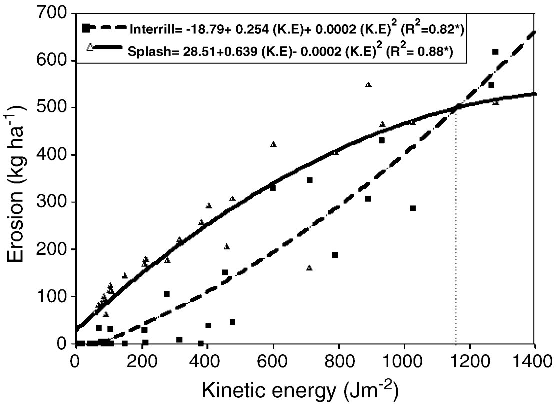

Fig. 1. Polynomial regression curves between interrill and splash erosion with storms' kinetic energy during the 2001 winter season. *Regressions are significant at $P < 0.01$.

About 1100 J m^{-2} is needed at the equilibrium phase (the intersection point) to cope with erosion by both overland flow and splash erosion. This amount of kinetic energy is produced by one rainfall event of 60 mm rainfall with I_{30} of 12 mm h^{-1} (Table 2). It is significant to emphasize that in the Mediterranean, very few rainfall events are responsible for the majority of the erosion occurring.

During the detachment-limited phase, the amount of energy required to erode a certain amount of soil particles is higher than that required during the transport-limited phase (Fig. 1), which may be due to a wider availability of easily detached soil particles in the later phase than the former one. In the detachment-limited phase, the most easily detached particles were eroded by previous rainfall events, and the detachment is confined to larger particles that required higher amount of kinetic energy.

Table 3 reveals positive and highly significant correlations between rainfall variables, runoff, interrill and splash erosion. Under both treatments, splash erosion can be strongly correlated with both the kinetic energy and the amount of rainfall ($r = 0.93$ and 0.92) suggesting two main facts: (i) the deleterious effect of kinetic energy on soil erosion, particularly during the initial phases of soil erosion (detachment, disintegration and slacking of soil aggregates) and (ii) the kinetic energy response is similar to that of natural rainfall, making it an appropriate parameter for reflecting the response and the erratic effect of rainfall on runoff and erosion. Other rainfall variables are less correlated with the natural rainfall effect, which has also been confirmed

Table 3
Linear correlation coefficients between runoff, interrill erosion and splash erosion with different rainfall variables in stonewall terraced and non-terraced systems

Treatments	Erosion parameters	Kinetic energy (K.E.) (J m^{-2})	Rainfall erosivity index (EI_{30}) (J mm m^{-2} h^{-1})	Storm duration (h)	Maximum 30-min intensity (I_{30}) (mm h^{-1})	Maximum 60-min intensity (I_{60}) (mm h^{-1})	Amount of rainfall (mm)
		Rainfall variables					
Terraced	Runoff	0.75	0.75	0.55	0.63	0.64	0.66
	Interrill erosion	0.70	0.63	0.56	0.54	0.60	0.62
	Splash erosion	0.93	0.73	0.7	0.74	0.86	0.92
Non-terraced	Runoff	0.80	0.68	0.78	0.59	0.62	0.82
	Interrill erosion	0.64	0.50	0.52	0.48	0.61	0.63
	Splash erosion	0.93	0.74	0.70	0.75	0.87	0.92

All correlations are significant at $P = 0.01$ according to Pearson correlation test.

by other researchers (Torri et al., 1999; Cerda, 2000; Salles et al., 2002).

Fig. 2 shows scatter-plot graphs for the relationship between different rainfall variables. A systematic and ascending trend between the amount of rainfall and kinetic energy is obvious (Fig. 2a), emphasizing that kinetic energy is the most appropriate variable for outlining the behavior of natural rainfall. Such systematic relationship is absent in other rainfall variables; they present only random sporadic patterns (Fig. 2b and c).

The cumulative sediment deposition graph for the 2001 winter season with the I_{30} is shown in Fig. 3 for both treatments (as an average of three replicates). The graph shows that terraced treatment is more effective than non-terraced in controlling interrill erosion. The graph also reveals that soil loss in both treatments is most likely to occur for rainfall intensities >4 mm h^{-1}.

Runoff and erosion depend on the equilibrium and interactions between different rainfall variables rather than on any single variable (Cerda, 1998b; Salles et al., 2002). Table 4 shows the results of stepwise multiple regression for three response factors (runoff, interrill and splash erosion). The data shows a highly significant regression relationship between runoff, EI_{30}, storm duration and I_{30}. The regression equation for interrill erosion has similar parameters with the exception of I_{30}, where it has been replaced by kinetic energy (K.E.). The inclusion of I_{30} in the runoff equation emphasizes the importance of rainfall intensity in runoff occurrence, which is due to its close relationship to the infiltration capacity of the soil. Conversely, the kinetic energy is included in the interrill regression equation, emphasizing the importance and close relationship between kinetic energy and splash erosion. The storm duration is included in both regression equations due to its significance to two soil surface features. The first is its evidence to the soil moisture condition (increased duration is directly proportional to soil moisture content); the second is its indirect link to the status of the topsoil aggregates (i.e., strength, disintegration and slacking). In the case of splash erosion, the regression equation emphasizes the importance of the K.E. as a major cause of splash erosion ($R^2 = 0.86$). The addition of further rain variables (regression equations are not shown) to splash regression equation increases R^2 only slightly (0.91). Consequently, kinetic energy can provide a good approximation for the initial phase of soil erosion (detachment and splash).

3.3. Relationship between runoff, interrill and splash erosion

Linear and exponential regression equations between interrill erosion, splash erosion and runoff (as shown in Fig. 4) indicate a highly significant relationship between runoff, interrill and splash erosion. The strongest relationship is between runoff and interrill erosion. This relation is largely controlled by the amount of overland flow, which is affected directly by soil surface conditions (moisture content and infiltration capacity), as well as rainfall intensity and amount (Ekwue, 1991; Descroix et al., 2001). An increase in overland flow indicates more runoff with a

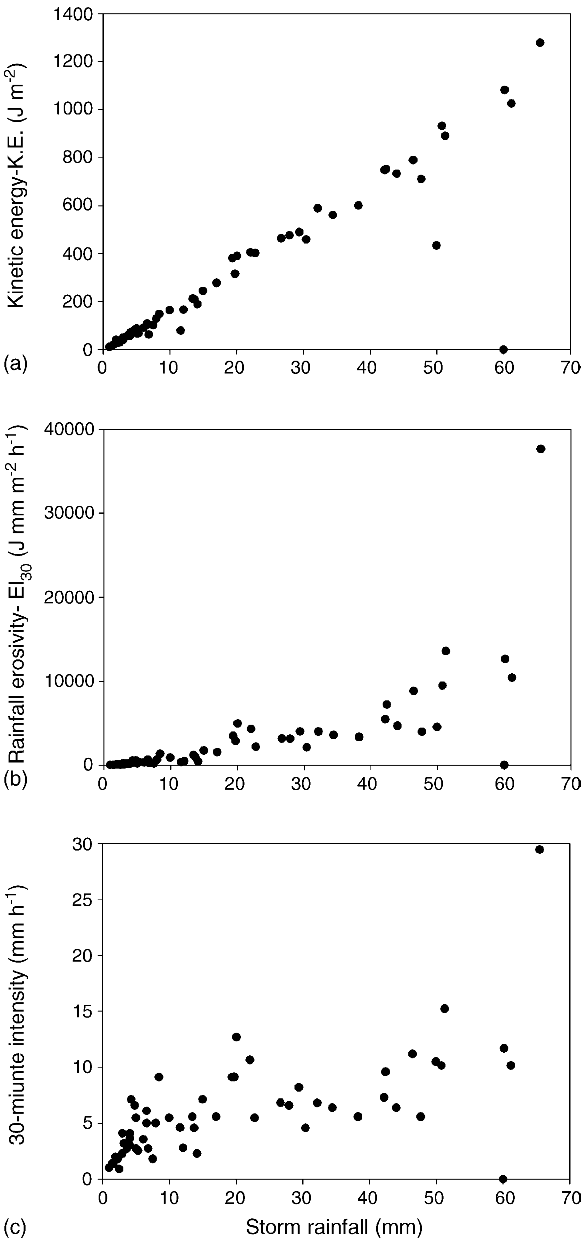

Fig. 2. A scatter-plot graph for the relation between storm rainfall with kinetic energy (a), rainfall erosivity (b) and with 30-min intensity (c).

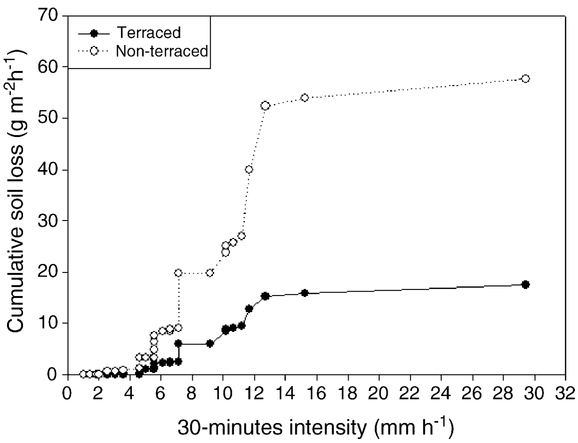

Fig. 3. Sediment graphs showing the relation between cumulative soil loss and 30-min rainfall intensity in both terraced and non-terraced treatments during the 2001 winter season.

Table 4
Stepwise multiple regression analysis of runoff, interrill and splash erosion with different rainfall variables

Parameters	Multiple regression equation	R^2	MSE[b]
Runoff[a]	5.96 + 0.0069 (EI_{30}) + 2.03 (storm duration) − 3.4 (I_{30})	0.76	20.2
Interrill erosion[a]	−17.17 + 0.0124 (EI_{30}) + 7.9 (storm duration) − 0.107 (K.E.)	0.75	47.7
Splash erosion[a]	56.46 + 0.395 (K.E)	0.86	56.9

Level of significance is 0.01 for all equations.
[a] Runoff and interril regression equations were obtained using 96 measurements; splash regression was done using 62 measurements.
[b] Mean square error.

higher kinetic energy of the flow and results in greater interrill erosion (Fig. 4b and c) (Schultz et al., 1985). This relationship is also influenced by rainfall amount and/or rainfall intensity, particularly when large amount or high intensity coincides with weak aggregates (Parsons et al., 1994), causing large amount of interrill and splash erosion. This is apparent in the measured differences in interrill and splash erosion as occurred in terraced and non-terraced plots (Table 2), which may be due to differences in aggregate stability among treatments (Table 1).

A multiple regression equation between interrill erosion, runoff and splash erosion revealed a highly significant relation ($P < 0.01$) between these variables (Eq. (1)):

$$\text{Interrill erosion} = -2.7 + 2.25 \times \text{Runoff} + 0.038 \times \text{Splash erosion}, \quad R^2 = 0.93 \qquad (1)$$

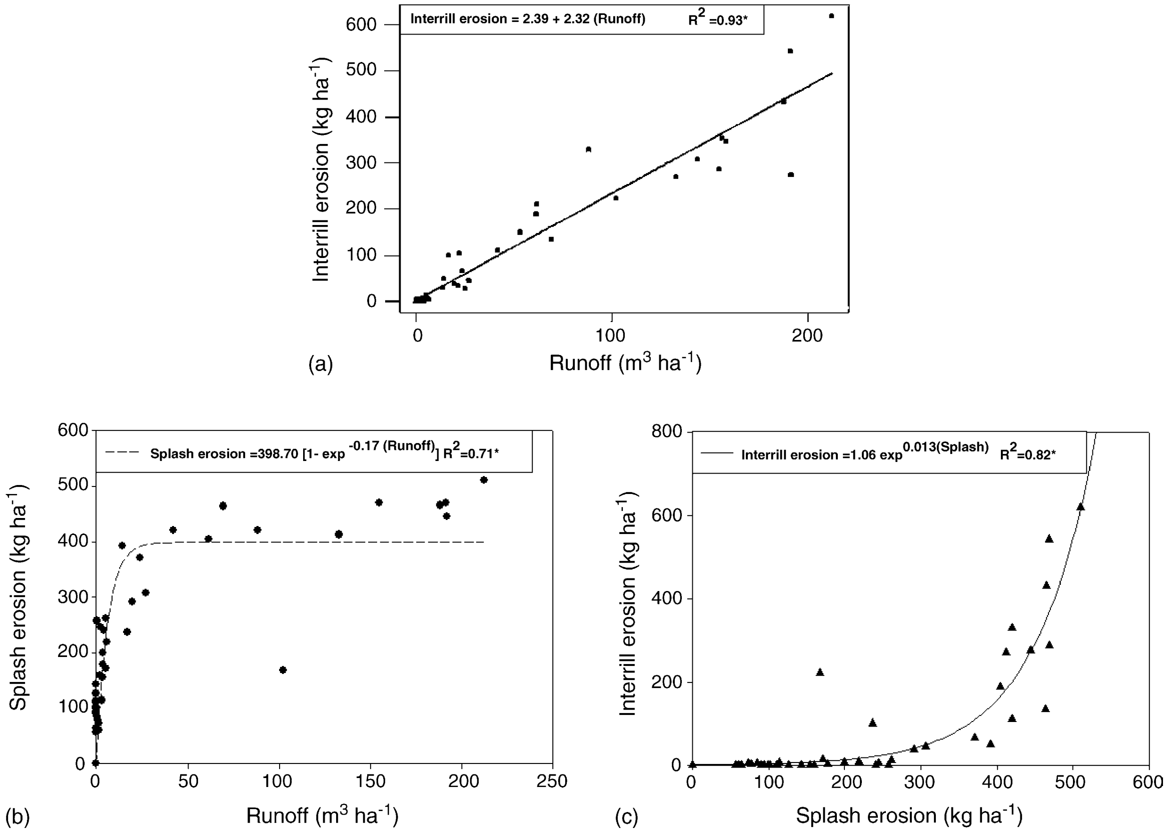

Fig. 4. Linear regression between interrill erosion with runoff (a), exponential regression between splash erosion with runoff (b), and with interril erosion (c) for terraced treatment. *Regressions are significant at $P < 0.01$.

The equation puts more of an emphasis on runoff as a major cause of interrill erosion. A similar trend is observed in the non-terraced treatment.

4. Conclusions

The data presented supports the following conclusions:

(1) Most of the erosion processes in the semi-arid condition of the Mediterranean region were transport-limited, only few erratic rainfall events caused a detachment-limited erosion. This conclusion necessitates the application of surface management (residue and/or plant cover) at the beginning of the winter season to control splash erosion.
(2) The kinetic energy of rain was strongly correlated with runoff and erosion, and its effect was similar to that of natural rainfall. Hence, erosion and runoff can be predicted by rain intensity, while simple regression equations may be used to calculate kinetic energy.
(3) The terraced conservation system reduced the negative effect of intense rainfall, resulting in a lower amount of runoff and erosion than in the non-terraced system.
(4) Organic carbon, Mg, Ca and K showed significant differences between terraced and non-terraced treatments, which could be attributed to the differences in erosion between both treatments.
(5) A positive and significant linear correlation was observed between runoff and erosion. The relationship is stronger when interrill ersoion was linked to both runoff and splash erosion (R^2=0.93).

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