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A new expression of the slope length factor to apply USLE-MM at Sparacia experimental area (Southern Italy)

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ABSTRACT

Predicting soil loss due to water erosion by empirical models is useful to assess the severity of the phenomenon in an area of interest and to predict the effect of alternative soil erosion control practices. The USLE scheme cannot be used at the Sparacia experimental area (Sicily, South Italy) to predict event soil loss per unit plot area, A_e, because experimental data suggest that, generally, A_e does not increase with plot length, λ. The USLE-MM scheme uses the runoff coefficient, Q_R, as an additional independent variable in order to develop an empirical model allowing prediction of storm soil loss values that do not necessarily increase with λ. According to this model, A_e is expected to increase with λ when the rest of factors do not vary between plots of different length, but an inverse relationship between these two variables can be predicted when Q_R decreases as λ increases, which is a common occurrence at the study area. Plot length was found to be enough to predict the mean Q_R for a set of erosive events. Testing the model with an independent data set supported its applicability for predictive purposes. Collecting additional plot data is necessary to develop simple plot Q_R predictive procedures at the event temporal scale.

1. Introduction

Predicting soil loss due to water erosion allows establishing the severity of the phenomenon in an area of interest and it allows assessing the effect of alternative soil erosion control practices. The use of empirical models, mainly represented by the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) and its revised version (RUSLE; Renard et al., 1997), is still common to solve practical problems (e.g., Hann and Morgan, 2006). Probably, the reason is that these models allow obtaining a reasonably accurate soil loss prediction for many practical purposes (Bagarello et al., 2008; Risse et al., 1993) with an affordable effort by an individual practitioner although, in an European context, the USLE could be inappropriate because of differences in rainfall, dominant hydrological process and landscape diversity, compared to the eastern USA (Boardman, 2006).

Both the USLE and the RUSLE establish that mean annual soil loss per unit area, A (t ha^{-1} year^{-1}), increases linearly with the slope length factor, L:

$$L = \left(\frac{\lambda}{22.1}\right)^m \tag{1}$$

where λ (*m*) is the plot length and *m* is an exponent. In the USLE, *m* is equal to 0.5 if slope steepness, *s*, is greater than or equal to 5%, 0.4 on slopes of 3.5 to 4.5%, 0.3 on slopes of 1 to 3% and 0.2 on uniform gradients of less than 1%. Eq. (1) was derived from data obtained on cropped land, under natural rainfall, on slopes ranging from 3 to 18% in steepness and about 9 to 90 m in length (Wischmeier and Smith, 1978). In the RUSLE, *m* is related to the ratio, β, of rill to interrill erosion:

$$m = \frac{\beta}{1+\beta} \tag{2}$$

$$\beta = \frac{\sin\theta \,/\, 0.0896}{3.0(\sin\theta)^{0.8} + 0.56} \tag{3}$$

where θ (°) is the slope angle.

However, the experimentally determined soil loss *versus* λ relationship shows an appreciable variability. In particular, Laflen and Moldenhauer (2003) reported that the *m* exponent in the USLE varied widely between years; at times even becoming negative (i.e., soil loss per unit area decreases as λ increases), and mean *m* values for locations varied between 0 (soil loss does not vary with λ) and 0.9. Loch (1996) suggested that the rilling phenomenon controls sensitivity of soil erosion to slope length because interrill erosion rates do not vary both across and down slope. In particular, erosion is not expected to be greatly sensitive to slope length in soils i) where thresholds for rill development are low and rill sediment concentrations show little increase with increasing discharge, or ii) with a low susceptibility to rilling. Slope length can be expected to have a considerable effect on erosion when susceptibility to rilling is high and sediment concentrations increase with increasing discharge.

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Rejman et al. (1999) examined the slope length effect on soil loss measured during a four-month period on the bare surface of a silt soil with 12% slope. Within the three considered slope lengths (λ = 5, 10, and 20 m), soil loss decreased with the increase in λ. Rejman et al. (1999) suggested that the scale dependency arises because sediment collected from an erosion plot derives mainly from the part of the plot that is situated close to the outlet and not from the whole plot. Other experimental results suggesting an inverse relationship between plot soil loss and λ, at least for a given range of the sampled plot lengths, were obtained in cropped plots or in plots comprising a mixture of desert pavement and vegetation cover (Lal, 1988; Parsons et al., 2006). Moreno-de las Heras et al. (2010) recently suggested that the effects of scale on runoff and erosion change with the extent of degradation. Unit area sediment yield declines with increasing plot length in undisturbed and moderately disturbed sites, but it actually increases in highly disturbed sites. In an investigation carried out at the Sparacia experimental area (Sicily, Italy), event soil loss per unit plot area was not statistically dependent on λ or it decreased as λ increased (Bagarello and Ferro, 2010). This investigation also suggested that soil loss per unit area is expected to increase with λ when rill erosion is the dominant erosive process. A possible effect of non-continuity of the runoff process along a relatively short slope (60–70 m), due to short duration of individual showers, high roughness and high absorption capacity of the soil, was suggested by Yair et al. (1980) to explain a runoff yield per unit area decreasing with slope length in an arid region of Israel.

Bagarello et al. (2010) used data collected on bare plots of different length (λ = 11, 22, 33 and 44 m) established on a 14.9% slope at the Sparacia area to derive the following predictive equation of event soil loss per unit area, A_e (t ha^{-1}):

$$A_e = 0.031(Q_R EI_{30})^{1.47} LS \quad (4)$$

where Q_R is the event runoff coefficient, EI_{30} (MJ mm ha^{-1} h^{-1}) is the event erosivity index, given by the product of total kinetic energy of the rainstorm, E (MJ ha^{-1}), and maximum 30-min intensity, I_{30} (mm h^{-1}), and S is the slope steepness factor. The L factor was calculated by Eqs. (1)–(3) and the S factor was calculated according to Nearing (1997):

$$S = -1.5 + \frac{17}{1 + exp(2.3 - 6.1\ sin\theta)} \quad (5)$$

Following the USLE scheme, the coefficient 0.031 of Eq. (4) represents the erodibility factor of a frequently tilled, bare soil with a clay texture. This factor can be considered expressive of an intrinsic property of the porous medium since it is independent of both λ and the erosive event. Eq. (4) was named USLE-MM (Bagarello et al., 2008; 2010) since it represents a modified version of the USLE-M by Kinnell and Risse (1998). A possible limitation of USLE-MM is related to the choice of Eqs. (1)–(3) to predict the slope length effect and Eq. (5) to predict the slope steepness effect.

Taking into account that plots of different length (11 ≤ λ ≤ 44 m) were sampled at Sparacia, the objective of this investigation is to carry out an alternative analysis of the data, to derive a new expression of the L topographic factor for use with the USLE-MM. An additional objective is to assess the suitability of the model to predict an event soil loss per unit area that does not necessarily increase with plot length.

2. Materials and methods

2.1. Study area

The experimental station for soil erosion measurement "Sparacia" of the Agricultural Faculty of the Palermo University is located in western Sicily, Southern Italy, approximately 100 km south of Palermo. The area has a typical Mediterranean semi-arid climate with an average annual rainfall of approximately 700 mm. The dry period of the year can extend for seven months (April–October). The soil is a Vertic Haploxerept (Soil Survey Staff, 2006) with a clay texture (62% clay, 33% silt, 5% sand). The soil shows a massive consistency in winter, when it is wet and fully swelled, but it develops a polygonal pattern of surface shrinkage cracks (approximately 2 cm in width) in late spring or early summer as the soil dries. The gravel content is negligible. The depth of the Ap horizon is of approximately 0.30 m.

2.2. Experimental design and data analysis

The experimental station includes two plots of 44 × 8 m^2 (Fig. 1), two plots of 33 × 8 m^2, six plots of 22 × 8 m^2, two plots of 22 × 2 m^2, two plots of 11 × 4 m^2, two plots of 11 × 2 m^2, and several microplots. The oldest plots (four plots of 22 × 8 m^2) were constructed in 1999, whereas the most recent plots (two plots of 22 × 2 m^2 and some microplots) have been constructed in 2007. All listed plots and microplots were installed on a 14.9% slope and they were maintained in cultivated fallow (tillage performed at least twice in a year). This 14.9% slope is equipped by a recording rain-gauge operating at 1-min time intervals. Two additional plots of 22 × 6 m^2 were established on a 22% slope and other two similar plots were established on a 26% slope within the Sparacia experimental area. These four plots are equipped by a rain gauge.

Runoff and associated sediments from each plot are intercepted by a gutter placed at the lower end of the plot, and collected into a storage system consisting of three tanks of known geometric characteristics, each having a capacity of approximately 1 m^3, that are arranged in series at the base of each plot. A single tank is installed at the base of the 11-m-long plots and two tanks are used for the 22 × 2 and 22 × 6 m^2 plots. Total runoff and soil loss are measured after each erosive event (i.e., an event producing measurable runoff) or, occasionally, after a series of events if they are separated by a short time interval. At first, the water level in the tank is measured. Then, the suspension (water + sediments) is thoroughly mixed and samples are collected at 10 depths along a vertical by sampling taps to determine the suspended sediment concentration profile. A mean measured concentration value is calculated by integrating the measured profile and this mean value is then transformed into the actual concentration of sediments stored in the tank using the calibration curve of the storage system (Bagarello et al., 2004; Bagarello and Ferro, 1998). These authors showed that using the calibration curve appreciably reduces the risk of measuring soil loss values lower than the actual ones. Rills were obliterated at the end of each erosive event by simple hand implements (hoe or powered cultivator) operated in the up and down direction, according to the reference plot condition (Wischmeier and Smith, 1978). This form of tillage, although performed with heavier machinery, is common in some periods of the year in the hills of western Sicily planted with wheat.

Simultaneous measurement of runoff and soil loss from individual plots established on the 14.9% slope started on January 2002 and continued until December 2008. A total of 34 erosive storms yielding 316 simultaneous measurements of runoff, V_e (mm), and soil loss, A_e (t ha^{-1}), from individual plots were recorded at the Sparacia station during the study period. In particular, the number of A_e and V_e data pairs varied from a minimum of nine for the 22 × 2 m^2 plots to a maximum of 153 for the oldest 22 × 8 m^2 plots (Table 1). For each event, the total rainfall depth, h_e (mm), and the rainfall erosivity index, EI_{30} (MJ mm h^{-1} ha^{-1}) (Wischmeier and Smith, 1978), were determined. A value of the runoff coefficient $Q_R = V_e/h_e$ was associated to each V_e, A_e data pair (Table 1). For a given storm event, measurements from individual plots were considered separately