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Empirical modeling of soil erosion using unit plot data at Sparacia experimental area (southern Italy)

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Abstract

Purpose Soil loss estimation by the Universal Soil Loss Equation (USLE) – based approach is widely used to perform soil conservation interventions. The recently proposed USLE-MB model explicitly accounts for plot runoff coefficient in the erosivity factor. Both the USLE and the USLE-MB can be deduced using a reference condition given by the unit plot, which is characterized by fixed length, steepness and bare soil tilled along the steepest slope. There is little evidence about the existence of the unit plot among those used to develop the USLE model, and few investigations experimentally considered this condition later.

Methods In the present investigation, the USLE and USLE-MB models were parameterized using measurements performed in the Sparacia unit plots, in Sicily.

Results The USLE soil erodibility factor differed significantly from the nomograph value and also from the estimates previously obtained by two methods applied to measurements collected in plots having different length and steepness compared to the unit plot. The experimentally determined soil erodibility factor of the USLE-MB also differed from those determined with these two methods. The slope steepness factor determined according to its definition was not consistent with that estimated with known literature relationships. The slope length factor was nearly constant for the USLE and assumed to be constant for the USLE-MB, in contrast with the increasing relationship with the plot length suggested by the USLE.

Conclusion This investigation elucidated the discrepancy between the single factors of the models obtained using measurements from the unit plot and those otherwise estimated.

Keywords Soil erosion · Plot measurements · Soil loss estimation · Rainfall-runoff erosivity · USLE · USLE-MB

1 Introduction

According to the European Commission's thematic strategy on soil (European Commission 2006), the soil is a finite resource. A few centimeters of topsoil can be formed in the soil over the course of hundreds to thousands of years under regular agricultural land use (Bazzoffi 2009). In contrast, the rate of soil degradation or destruction caused by water soil erosion processes is quick and can be sped up by human activity (Raclot et al. 2018). In many regions of the European Union, the rate of soil erosion exceeds that of soil formation, and the annual cost of repairing the damages caused by water erosion phenomena is approximately $20 billion (Panagos et al. 2015).

In this context, soil erosion measurement and modelling are useful to implement conservation strategies and evaluate their effectiveness, that can be evaluated by the difference

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between the measured or estimated soil loss and a tolerable value named "soil loss tolerance" (Johnson 2005; Bagarello and Ferro 2006; Li et al. 2009; Di Stefano and Ferro 2016; Carollo et al. 2023; Di Stefano et al. 2023). Currently, different types of models, including the empirical ones, allow for soil loss estimation from plot to basin scale and from the event to the mean annual scale (Bagarello et al. 2018a, b).

According to Boardman (2006), the reliability of the process-oriented models is comparable to that of the empirical Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) or its revised versions (RUSLE and RUSLE2) (Renard et al. 1997; Foster 2005). Moreover, the latter are attractive for practical applications (Morgan 2005; Bagarello et al. 2008, 2015b; Cao et al. 2015; Gessesse et al. 2015) and currently used (e.g. Galdino et al. 2015; Ligonja and Shrestha 2015) as they guarantee a fair balance between the effort needed to gather input data and the accuracy of the predictions (Risse et al. 1993). Therefore, attempts to improve empirical soil loss prediction technologies are still pursued (Renard et al. 1997; Kinnell and Risse 1998; Bagarello et al. 2011; Porto et al. 2022).

The USLE originated from the statistical analysis of more than 10,000 plot-years of runoff and soil loss measurements (Gilley and Flanagan 2007) and to estimate plot soil loss at the mean annual scale even if its applicability for predicting event soil loss was also tested or assumed (Hann and Morgan 2006; Di Stefano et al. 2017; Bagarello et al. 2020). In this last case, the event soil loss per unit area A_e (Mg ha^{-1}) is estimated by the following expression of the USLE:

$$A_e = R_e\, K\, L\, S\, C\, P \tag{1}$$

where R_e (MJ mm ha^{-1} h^{-1}) $= EI_{30}$ (Wischmeier and Smith 1978) is the event rainfall erosivity factor in which E (MJ ha^{-1}) is the rainfall kinetic energy and I_{30} (mm h^{-1}) is the maximum rainfall intensity in 30 min, K (Mg ha^{-1} MJ^{-1} ha mm^{-1} h) is the soil erodibility factor, and the remaining dimensionless factors, L, S, C, and P, stand for slope length and steepness factor, cover and management factor, and support practice factor, respectively.

Previous studies (Kinnell 2005; Gao et al. 2012) highlighted that systematic soil loss estimation errors of the USLE can be overtaken using an erosivity term including runoff. Following the approach by Ferro (2010), Bagarello et al. (2018a) developed the USLE-MB, based on the rainfall-runoff erosivity factor $EI_{30}\, Q_R^{\,b1}$, in which EI_{30} is coupled with the power of the runoff coefficient Q_R and b_1 is higher than one. This rainfall-runoff erosivity factor can be experimentally and theoretically justified as the linear relationship of EI_{30} vs. A_e derives from the USLE development while, following the WEPP scheme (Nearing et al. 1989), the term $Q_R^{\,b1}$ accounts for flow transport capacity (Bagarello et al. 2018a). The USLE-MB is expressed as:

$$A_e = R_e\left(Q_R\right)^{b_1} K_{MB}\, L_{MB}\, S_{MB}\, C_{MB}\, P_{MB} \tag{2}$$

in which K_{MB} (Mg ha^{-1} MJ^{-1} ha mm^{-1} h) is the erodibility factor of the soil, and L_{MB}, S_{MB}, C_{MB} and P_{MB} are the analogous dimensionless factors of L, S, C, and P for the USLE-MB. When $b_1 = 0$ the USLE-MB model reduces to USLE.

The USLE mathematical structure was developed using a reference condition, named *unit plot*. The unit plot is 22.1 m long, 9% sloped, tilled along the maximum slope direction, and permanently in fallow condition. The empirical nature of the USLE has often drawn criticism (Alewell et al. 2019). However, Ferro (2010) and Bagarello et al. (2018a) pointed out that the multiplicative form of both the USLE and USLE-MB can be theoretically deduced by using the dimensional analysis and self-similarity theory (Barenblatt 1979, 1987), the representative variables of soil erosion, and the unit plot. The dimensionless factors of Eqs. (1) and (2) allow operating the passage from the reference condition, for which they are equal to 1, to that of any plot characterized by different topographic conditions, cover and management and support practices.

According to the USLE scheme, the soil erodibility factor is directly measured on the unit plots (Renard et al. 1997) and each dimensionless factor, which accounts for a specific variable, is defined as the ratio of soil loss from a given plot to that from a plot where the variable meets the unit plot characteristic, when all other conditions are the same. A single measurement of K for mean annual soil loss estimation requires collection of several plot measurements over a long time period while a simpler estimation can be obtained using the nomograph proposed by Wischmeier et al. (1971). However, the nomograph is not expected to be appropriate for clay soils (Römkens et al. 1997), and its applicability should be tested, consequently. Moreover, different equations are available in the literature for expressing the slope length and steepness factors. For example, according to Renard et al. (1997), L is expressed with the following equations:

$$L = \left(\frac{\lambda}{22.13}\right)^m \tag{3}$$

$$m = \frac{aF}{1 + aF} \tag{4}$$

$$F = \frac{\sin\beta/0.0896}{3\sin^{0.8}\beta + 0.56} \tag{5}$$

in which λ (m) is the plot length, β (°) is the slope angle, F is the ratio between rill and interrill erosion, and $a = 0.5$ when interrill erosion prevails over the rill one while $a = 2$

for highly susceptible soil to rill erosion. The early equation by Wischmeier and Smith (1965) for the S estimate is:

$$S = \frac{0.043\, s^2 + 0.30\, s + 0.43}{6.613} \tag{6}$$

which was obtained dividing the following relationship of the average annual soil loss A_{av} vs. plot steepness s by the value (6.613) calculated with the same equation for $s = 9\%$

$$A_{av} = 0.043\, s^2 + 0.30\, s + 0.43 \tag{7}$$

in which s is expressed in per cent and A in t acre^{-1}. Equation (7) was obtained for slope steepness values ranging from 3 to 18% and without specific measurements in the unit plot. In other words, to derive Eq. (6), soil loss from the unit plot was estimated and not measured. For slope steepness values less than 15%, Eq. (6) is practically coincident with the expression by Nearing (1997):

$$S = -1.5 + \frac{17}{1 + \exp(2.3 - 6.1 \sin\beta)} \tag{8}$$

Notwithstanding the importance of the unit plot for the development of the USLE, Laflen and Flanagan (2013) have been doubtful of the existence of the unit plot. In the book focusing on the USLE story, Laflen and Moldenhauer (2003) stated that "*while the unit plot concept was widely used, there has never been a unit plot, or if one ever existed, data from it has not been found.*" The direct K measurement on the unit plots was recently performed for Iranian soils (Vaezi et al. 2008; Ostovari et al. 2016) while, to the best of our knowledge, most of the field investigations were carried out using plots with different characteristics. Therefore, there is a knowledge gap regarding potential differences between the soil erodibility and topographic factors determined using the unit plot concept and those, commonly applied worldwide, deriving from indirect estimations of the soil erodibility and literature relationships for describing topographic effects.

The general aim of the present study was to parameterize the USLE and USLE-MB models starting from measurements performed in the unit plots of the Sparacia station, southern Italy. The specific aims were to (i) measure the soil erodibility factors for the USLE and USLE-MB, (ii) determine the relationships expressive of the slope length factor and slope steepness factor for the two models, and (iii) compare the estimation performances of the two models.

2 Materials and methods

2.1 Experimental site

The Sparacia station for soil erosion measurement of the Palermo University (Agricultural, Food and Forest Sciences Department) is situated in western Sicily, Southern Italy. The soil is characterized by 62% clay, 33% silt, and 5% sand. The experimental installation consists of 22

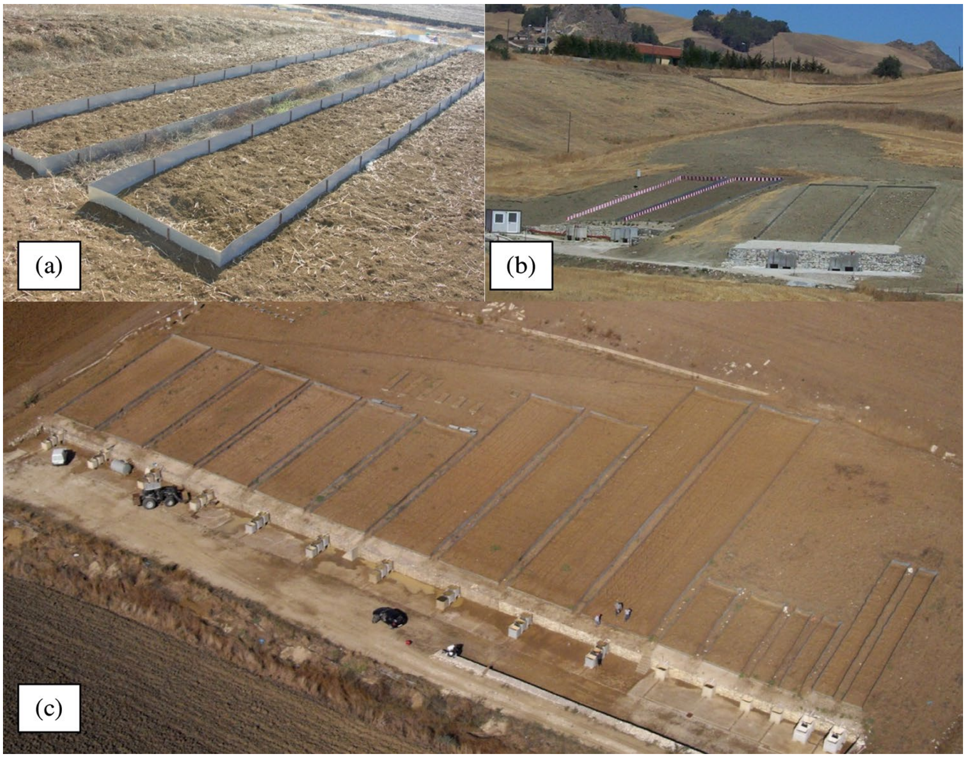

Fig. 1 View of the **a** unit plots, **b** 22% and 26% sloping plots, and **c** 14.9% sloping plots of the Sparacia experimental area

plots having the following sizes: two unit plots ($\lambda = 22$ m, width $w = 2$ m, $s = 9\%$) (Fig. 1a), two plots with $\lambda = 22$ m, $w = 6$ m and $s = 22\%$, two plots with $\lambda = 22$ m, $w = 6$ m, and $s = 26\%$ (Fig. 1b), and 16 plots with λ ranging from 11 to 44 m, w ranging from 2 to 8 m and $s = 14.9\%$ (Fig. 1c). The 9%–14.9% sloping plots and the 22%–26% sloping plots are respectively equipped with a rain-gauge which records rainfall intensity at 1-min temporal scale. All plots are tilled along the maximum slope direction and are permanently in fallow condition, hence $C = C_{MB} = 1$ and $P = P_{MB} = 1$. Plots are maintained in cultivated fallow, with up and downhill tillage, by a power cultivator. Tillage is conducted 3–4 times per year when the soil is relatively dry.

For each plot, sediments and runoff are conveyed towards a downstream storage system where some tanks are arranged in series. The measurements of plot soil loss, A_e (Mg ha^{-1}), and runoff per unit area, V_e (mm), are carried out after each rainfall event producing erosion or, in some cases, after aggregated rainfall events separated by no-rain periods not long enough to perform the measurements. The weight of the collected sediment is obtained multiplying the suspension volume by its mean concentration. The former is measured by reading the suspension level within the tanks having known geometric characteristics. The mean concentration is measured by sampling five columns of the suspension for each tank with a sampler (Carollo et al. 2016). This measurement statistically coincides with the actual concentration and is characterized by a decreasing margin of error for increasing values of the actual concentration (Carollo et al. 2016). The total rainfall depth of the event, P_e (mm), was measured and the runoff coefficient $Q_R = V_e/P_e$ was also determined. The recorded rainfall intensities were processed to calculate the erosivity index R_e (Wischmeier and Smith 1978). For a given event and plot type, i.e., plot with fixed length and steepness, individual measurements were averaged to obtain the mean soil loss $A_{e,m}$. Measurements from plots with different widths were put together for the averaging calculation as the USLE establishes that the width of the plot does not affect A_e.

2.2 Datasets

The measurements were simultaneously collected from unit plots, 14.9%, 22% and 26% sloping plots from February 2014 to November 2018, which is the functioning period of the unit plots. Nine erosive events occurred in the unit plots, featured by R_e varying from 51.2 to 517.4 MJ mm h^{-1} ha^{-1} (Table 1), individual A_e ranging from 0.01 to 11.81 Mg ha^{-1} and Q_R ranging from 0.004 to 0.273.

The number of the events monitored in the other plots range from eight to nine, depending on the plot type (Table 1). The datasets for the calibration of the USLE and USLE-MB consist of 139 soil loss, A_e, measurements and 121 contemporaneous measurements of soil loss, A_e, and runoff, V_e, respectively. The difference between the two datasets is due to the unavailability of runoff measurement in some cases. The mean soil loss over the monitoring period, μ (A_e), is equal to 5.48 Mg ha^{-1} for the parameterization dataset of the USLE and 5.88 Mg ha^{-1} for that of the USLE-MB.

All the data refer to events with only interrill erosion, except for the September 2017 event characterized by both interrill and rill erosion components for all plots.

2.3 Parameterization of USLE and USLE-MB

For the reference condition, the soil erodibility factor, K_x, was experimentally obtained as follows (Foster et al. 1981):

$$K_x = \frac{\sum_{j=1}^{N} A_{e,m,j}}{\sum_{j=1}^{N} R_{e,j} \left(Q_{R,j}\right)^{b_1}} \tag{9}$$

where N is the number of measurements, $K_x = K$ for $b_1 = 0$, $K_x = K_{MB}$ for $b_1 \neq 0$, and R_e $(Q_R)^{b1}$ is equal to the mean value for the two-unit plots. According to a previous study (Bagarello et al. 2018a) not including unit plot measurements, for the USLE-MB model b_1 is equal to 1.45. A recent investigation performed in the Sparacia experimental area (Pampalone et al. 2023) highlighted that the value of b_1 depends on the nature of the erosion process and is close to 1 when both the interrill and rill components occur while is nearly 1.4 when the interrill component is the only one. Considering that almost all the present data refer to the latter case, here b_1 was set equal to 1.45.

Following the USLE assumptions, the parameterization was performed setting $L = L_{MB} = 1$ for the plot length of 22 m and $S = S_{MB} = 1$ for the plot steepness of 9%.

Considering the steepness factor definition, the value for each investigated plot slope, different from 9%, was determined by adding the $A_{e,m}$ values from the 22 m long plots and normalizing the result with the cumulative $A_{e,m}$ value from the unit plot, under the hypothesis that minor differences in R_e between the two recording rain gauges (Table 1) can be neglected. Therefore, the experimental slope steepness factor does not depend on the model ($S = S_{MB}$) and is indicated as S_x hereinafter.

For the 14.9% slope, the slope length factor for $\lambda = 11$, 33, 44 m was calculated by the following relationship:

$$L_x = \frac{\sum_{j=1}^{N} A_{e,m,j}}{K_x S_x \sum_{j=1}^{N} R_{e,j} \left(Q_{R,j}\right)^{b_1}} \tag{10}$$

where $L_x = L$ and $K_x = K$ for $b_1 = 0$, $L_x = L_{MB}$ and $K_x = K_{MB}$ for $b_1 = 1.45$, R_e $(Q_R)^{b1}$ is equal to the mean value for the

Table 1 Characteristic data (rainfall amount *Pe*, rainfall erosivity index *Re*, plot length λ and steepness *s*, mean event soil loss $A_{e,m}$, mean event runoff $V_{e,m}$) of the present investigation

Event	Date	P_e mm	R_e MJ mm ha^{-1} h^{-1}	λ m	s -	$A_{e,m}$ Mg ha^{-1}	$V_{e,m}$ mm
1	1–2 February 2014	57.0	128.5	22	0.09	0.16	
				11	0.149	0.02	
				22	0.149	0.56	
				33	0.149	0.04	
				44	0.149	0.02	
				22	0.22	0.35	
				22	0.26	0.32	
2	18–22 January 2015	43.0	79.9	22	0.09	0.08	1.43
				11	0.149	0.06	2.23
				22	0.149	0.18	1.52
				33	0.149	0.04	0.54
				44	0.149	0.02	0.41
				22	0.22	2.97	6.62
				22	0.26	3.67	6.87
3	28–29 + 30–31 January 2015	51.2	51.2	22	0.09	0.04	2.34
				11	0.149	0.02	2.38
				22	0.149	0.64	5.52
				33	0.149	0.02	0.70
				44	0.149	0.01	0.55
3	28–29 + 30–31 January + 3 February 2015	58.8	60.6	22	0.22	2.09	11.81
				22	0.26	3.69	12.05
4	17–26 February 2015	145.8	273.1	22	0.09	0.09	3.16
				11	0.149	0.10	9.69
				22	0.149	3.86	10.62
				33	0.149	2.09	5.50
				44	0.149	0.30	5.51
				22	0.22	8.84	9.57
				22	0.26	13.31	9.53
5	16–17 March 2015	47.0	111.3	22	0.09	0.01	1.48
				11	0.149	0.04	3.95
				22	0.149	0.82	8.24
				33	0.149	0.29	5.26
				44	0.149	0.11	4.96
				22	0.22	6.66	11.69
				22	0.26	9.22	11.96
6	24 September 2017	33.0	517.4	22	0.09	6.48	5.96
				11	0.149	39.75	12.35
				22	0.149	35.86	8.90
				33	0.149	30.70	7.76
				44	0.149	47.81	5.85
				22	0.22	90.66	8.91
				22	0.26	76.58	8.86
7	18–25 February 2018	94.6	163.3	22	0.09	0.07	1.65
				11	0.149	2.10	7.15
				22	0.149	1.94	5.46
				33	0.149	1.41	5.05
				44	0.149	1.14	4.24
7	18–25 February 2018	87.0	142.3	22	0.22	7.35	10.82
				22	0.26	8.46	11.13
8	2–3 May 2018	37.4	413.2	22	0.09	1.24	0.94

Table 1 (continued)

Event	Date	P_e mm	R_e MJ mm ha^{-1} h^{-1}	λ m	s -	$A_{e,m}$ Mg ha^{-1}	$V_{e,m}$ mm
				11	0.149	13.51	4.06
				22	0.149	5.99	2.47
				33	0.149	0.32	0.65
				44	0.149	1.22	0.75
8	2–3 May 2018	41.2	472.9	22	0.22	55.19	9.45
				22	0.26	76.94	
9	31 October 2018–20 November 2018	106.4	469.8	22	0.09	0.18	2.51
				11	0.149	1.19	4.06
				22	0.149	6.72	7.90

replicated plots, and S_x is the slope steepness factor experimentally determined for $s = 14.9\%$.

2.4 Assessing USLE and USLE-MB performance

The reliability of the USLE and USLE-MB was tested by comparing soil loss measurements and predictions, and also using the root mean square error, *RMSE*:

$$RMSE = \sqrt{\frac{\sum_{j=1}^{N}\left(A_{e,calculated,j} - A_{e,j}\right)^2}{N}} \tag{11}$$

that describes the mean deviation of the prediction, $A_{e,calculated}$, from the measurement of the variable, A_e, expressed in its measurement unit. The prediction error decreases as the *RMSE* decreases. To account for the different values of μ (A_e) of the two calibration datasets, *RMSE* was normalized with μ (A_e).

The performance of the USLE and USLE-MB was initially evaluated on the complete dataset, i.e. independently of the event severity degree. Then, the *RMSE* was separately calculated for small erosion events, i.e. characterized by measured soil losses less than 1 Mg ha^{-1}, intermediate ($1 < A_e \leq 10$ Mg ha^{-1}) and severe ($A_e > 10$ Mg ha^{-1}) erosion events. This classification was adopted in a previous paper (Bagarello et al. 2020) to distinguish between different event severity levels. The mean annual soil loss of 10 Mg ha^{-1} is close to the tolerable soil loss of 11.2 Mg ha^{-1} suggested by Wischmeier and Smith (1978) (Carollo et al. 2023) and, therefore, $A_e > 10$ Mg ha^{-1} represents a severe erosion condition at event scale. This distinction was especially aimed to check the estimation performance of the models concerning the higher soil losses, that can control the total amount over a long time frame (Larson et al. 1997; Pampalone and Ferro 2020).

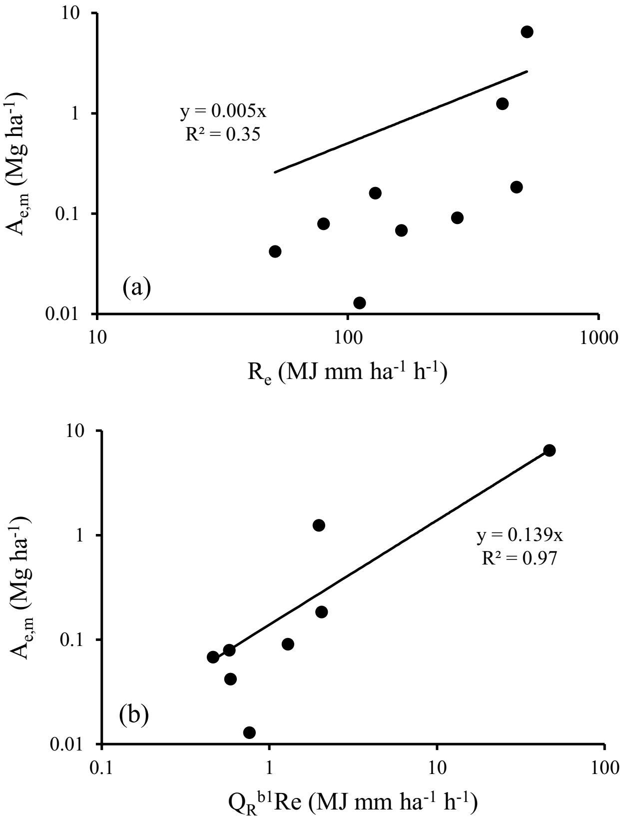

Fig. 2 Relationship between the measured soil loss $A_{e,m}$ and the erosivity factor **a** R_e, and **b** $Q_R^{b1}R_e$

3 Results

3.1 Parameterization analysis

The experimental values of K and K_{MB}, determined by Eq. (9), were equal to 0.0038 Mg ha^{-1} MJ^{-1} ha mm^{-1} h and 0.15 Mg ha^{-1} MJ^{-1} ha mm^{-1} h. Figure 2 shows the relationship between the measured soil loss $A_{e,m}$ and the selected erosivity factor (R_e, $Q_R^{b1}R_e$) (Wischmeier and Mannering 1969). Although the goodness of fit for USLE is poor, for both models (USLE, USLE-MB) the estimated soil erodibility values are close to those obtained by Eq. (9). Figure 2a shows that K varies between events as the data pairs are not aligned along a single straight line, which would be expressive of a time independent K.

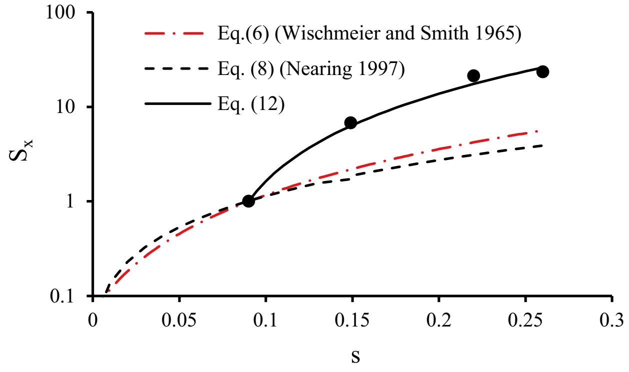

Fig. 3 Experimentally determined slope steepness factor, S_x, against the plot steepness s

Conversely, Fig. 2b highlights that the data pairs are better aligned and this result can be justified considering that Q_R^{b1} explains the event variability of soil loss.

For $s = 0.149$, 0.22, and 0.26 the experimental slope steepness factor was equal to 6.8, 21.3, and 23.5, respectively. The following relationship was applied to account for slope steepness effect (Fig. 3):

$$S_x = 525.1\, s^2 - 36.1s \tag{12}$$

which is applicable for $0.09 \le s \le 0.26$. The experimental S_x values were 3.1 to 5.1 times higher than those predicted by Eq. (6) (Fig. 3).

The L experimental values obtained by Eq. (10) were 1.00, 0.78, and 1.14 for the plot length of 11, 33, and 44 m, respectively. Assuming $L = 1$ for the plot length of 22 m, L can be considered constant and equal to the unit, that is very close to the mean value of 0.98 (Fig. 4a). The experimental L_{MB} values were equal to 0.35, 0.46, and 0.95 for the plot length of 11, 33, and 44 m, respectively. Assuming $L_{MB} = 1$ for the plot length of 22 m, the L_{MB} values were widely fluctuating around the mean of 0.69 (Fig. 4b), which was assumed as representative of the slope length factor given that a relationship between L_{MB} and λ was not perceivable.

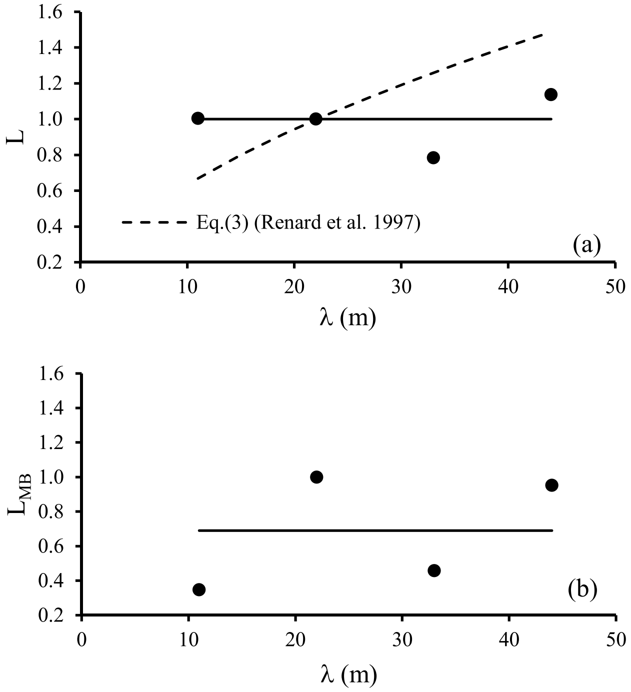

Fig. 4 Experimentally determined slope length factor for the **a** USLE, L, and **b** USLE-MB, L_{MB}, against the plot length λ

3.2 Accuracy of soil loss estimations

For both equations and the complete dataset, the $RMSE/\mu(A_e)$ (Table 2) points out that the USLE performs a little worst than USLE-MB. However, Fig. 5 shows that, for $A_e \le 1$ Mg ha^{-1}, the USLE is inclined to dramatically over predict soil loss while the USLE-MB overestimation is clear but less relevant in terms of error, as suggested by the $RMSE/\mu(A_e)$ values reported in Table 2. For $A_e > 1$ Mg ha^{-1}, the combined analysis of Fig. 5 and Table 2 points out that, overall, the USLE-MB predictions are more accurate than the USLE ones. Indeed, for the intermediate severity level the $RMSE/\mu(A_e)$ value of the former model is lower than that of the latter and the USLE prediction is biased in contrast with the USLE–MB one. For the severe soil loss level, the

Table 2 Values of the root mean square error, *RMSE*, and *RMSE* normalized with the mean of the measured soil loss values, $\mu(A_e)$, from complete datasets and small, intermediate and severe erosion events

Model	Variable	Complete dataset	Small $A_e \le 1$ Mg ha^{-1}	Intermediate $1 < A_e \le 10$ Mg ha^{-1}	Severe $A_e > 10$ Mg ha^{-1}
USLE	*N*	139	81	35	23
	RMSE (Mg ha^{-1})	9.69	4.09	4.00	22.0
	$\mu(A_e)$ (Mg ha^{-1})	5.48	0.16	2.82	28.31
	$RMSE/\mu(A_e)$	1.77	26.29	1.42	0.78
USLE-MB	*N*	121	66	33	22
	RMSE (Mg ha^{-1})	9.96	1.80	3.30	22.8
	$\mu(A_e)$ (Mg ha^{-1})	5.88	0.18	2.88	27.48
	$RMSE/\mu(A_e)$	1.69	9.93	1.15	0.83

Table 3 Values of the soil erodibility of the USLE for the Sparacia soil obtained in the present and previous investigations

Method	Reference	K (Mg ha^{-1}MJ^{-1} ha mm^{-1} h)
Unit plots	Equation (9)	0.0038
M1 - nomograph	Wischmeier et al. (1971)	0.021
M2 -L (Eq. 3), S (Eq. 8), regression	Bagarello et al. (2008)	0.0595
M2 - L (Eq. 3), S (Eq. 8), sum	Bagarello et al. (2008)	0.0405
M2 - $L=1$, S (Eq. 8), sum	Bagarello et al. (2012)	0.0389
M3 -parameterization procedure	Di Stefano et al. (2017)	0.031
M2 - L (Eq. 3), S (Eq. 8), regression	Bagarello et al. (2020)	0.0391

$RMSE/\mu(A_e)$ calculated for the USLE is slightly less than that of the USLE-MB but the USLE systematically underestimates the soil loss whereas this result does not occur for the USLE-MB.

The values of the statistical index reported in Table 2 also highlight that, for both USLE and USLE-MB, the estimation accuracy increases with the magnitude of soil loss.

4 Discussion

4.1 Parameterization analysis

In Tables 3 and 4 the soil erodibility factor (K and K_{MB}) determined on the unit plots is compared with that previously obtained using (M1) the nomograph by Wischmeier et al. (1971) (only for K), (M2) the soil loss measurements collected in different plot types normalized with the topographic factors predicted by literature expressions, and (M3) applying a specific parameterization procedure. Specifically, in the second case, the soil erodibility was the slope of the linear regression line of normalized soil loss against rainfall erosivity index, whose intercept was imposed to be zero (Bagarello et al. 2008, 2020) or was calculated by dividing the sum of normalized soil losses and the sum of the erosivity index values (Bagarello et al. 2008, 2012; Di Stefano et al. 2019). In the third case (parameterization procedure), assuming $L_x=1$ for $\lambda=22$ m, the K_xS_x values were calculated as the ratio between the sum of soil losses from 22 m long plots m and fixed steepness and the sum of the corresponding values of erosivity index. A K_xS_x vs. s relationship was fitted to the data pairs and extrapolated to $s=0.09$. Assuming $S_x=1$ for $s=0.09$, K_x was the calculated value for $s=0.09$ (Di Stefano et al. 2017; Bagarello et al. 2018a).

The K values calculated by methods M2 and M3 were similar to the nomograph value, whereas soil erodibility measured on the reference plots was one order of magnitude lower (Table 3). In other words, even though the limited sample size of the unit plot dataset, this result suggests that the nomograph soil erodibility is not consistent with that determined using the unit plots for the investigated clay soil, while it agrees with the K values obtained by methods M2 and M3. The disagreement between the measured K values by unit plots and the values determined by the nomograph can also be due to the circumstance that the experimental conditions supporting the nomograph were heterogeneous in terms of slope steepness, vegetation cover and support practices (Olson and Wischmeier 1963; McGregor et al. 1969; Mutchler et al. 1976; Lombardi 1979; Carollo et al. 2024).

Based on the partition of possible K values included in a global dataset (Torri et al. 1997), for which soil erodibility is low if K is less than 0.0225 Mg ha^{-1} MJ^{-1} ha mm^{-1} h, and is relatively low if K ranges from 0.0225 to 0.045 Mg ha^{-1} MJ^{-1} ha mm^{-1} h, this clay soil fall within the former class if the K measurement is considered and within the latter class if the estimated K value is considered. The measured K value is markedly low relative to the global dataset but realistic, as demonstrated by the results by Vaezi et al. (2008). Indeed, using measurements performed

Table 4 Values of the soil erodibility of the USLE-MB for the Sparacia soil obtained in the present and previous investigations

Method	Reference	K_{MB} (Mg ha^{-1}MJ^{-1} ha mm^{-1} h)
Unit plots	Equation (9)	0.150
M3 - parameterization procedure	Bagarello et al. (2018a)	0.568
M2 - L_{MB} (Eq. 3), S_{MB} (Eq. 8), sum	Di Stefano et al. (2019)	0.465
M2 - L_{MB} (Eq. 3), S_{MB} (Eq. 8), regression	Bagarello et al. (2020)	0.233

in Iran on unit plots with loam and clay loam soils, they obtained mean values of soil erodibility ranging from 0.0008 to 0.0073 Mg ha^{-1} MJ^{-1} ha mm^{-1} h, with average equal to 0.0043 Mg ha^{-1} MJ^{-1} ha mm^{-1} h, significantly lower than that (0.0359 Mg ha^{-1} MJ^{-1} ha mm^{-1} h) estimated using the USLE nomograph.

The K_{MB} obtained from the unit plots was lower than those calculated by methods M2 and M3 by a factor of 1.6 to 3.8 (Table 4). This discrepancy might depend on the relatively reduced dataset available for the unit plots, the fact that literature relationships cannot apply to accurately describe topographic effects on soil loss with USLE-MB, the limits of the extrapolation procedure. As the K_{MB}/K ratio was equal to 40, soil erodibility was strongly dependent on the prediction model.

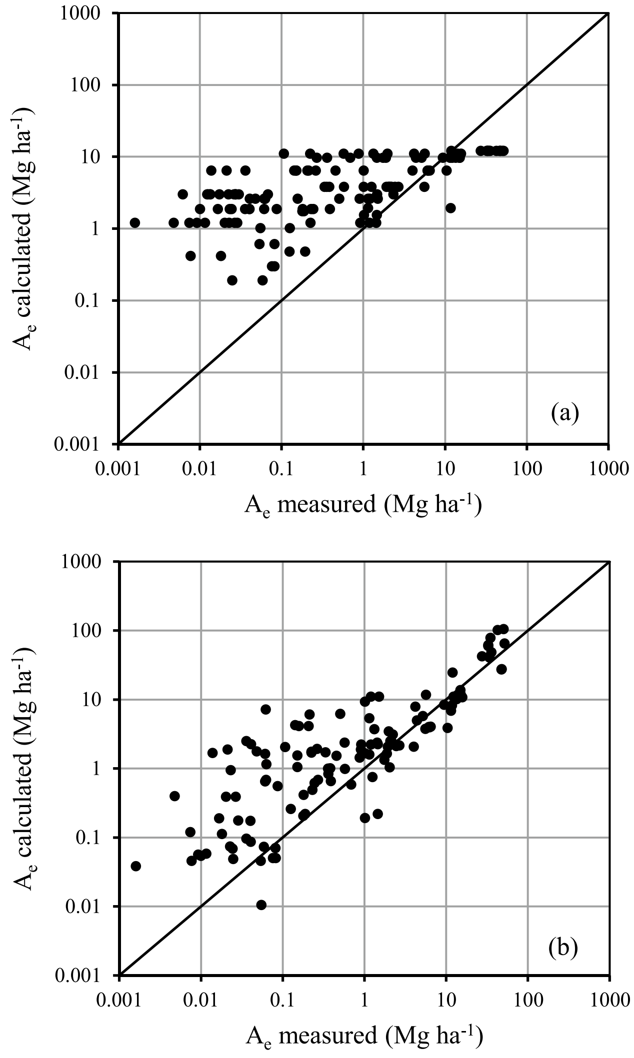

Fig. 5 Comparison between the measured values of event soil loss and those predicted by the **a** USLE and **b** USLE-MB

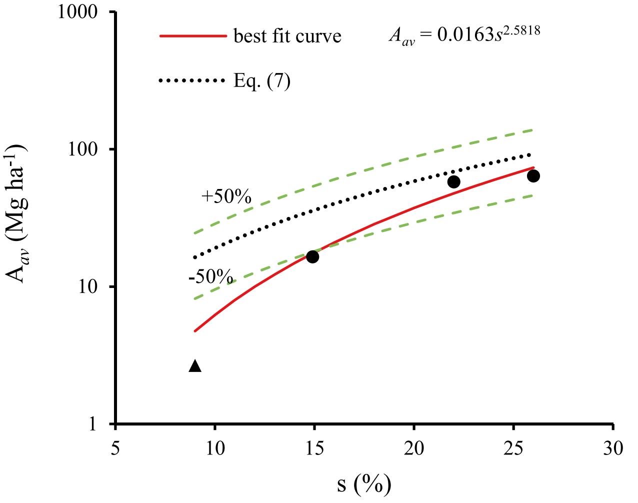

Fig. 6 Plot of the (s, A_{av}) experimental pairs for the 22 m-long plots established at the Sparacia station and comparison between the related power best fit curve and Eq. (7). The triangle point refers to the unit plots, the dashed lines are obtained by multiplicative factors of 0.5 (–50%) and 1.5 (+50%) applied to Eq. (7)

Figure 3 highlights that, for the investigated soil, the expressions (6) and (8) of the slope steepness factor cannot be applied to explain slope effect on soil loss. This finding also elucidates the difference between the experimentally determined soil erodibility values (K and K_{MB}) and those estimated by method M2. The high values of the experimentally determined slope steepness factor account for the much higher erosion detected on plots steeper than the unit plots. Taking into account that plots do not differ for the susceptibility to soil detachment, the raised soil loss can be justified by the increased detachment and transport capacity of the flow with plot steepness. The discrepancy between Eq. (12) and those available in the literature (Eqs. (6) and (8)) can be explained with the following reasoning and the support of Fig. 6. The latter shows the (s, A_{av}) pairs for the 22 m-long plots at Sparacia, A_{av} being the annual soil loss averaged on the 3 years (2015, 2017, 2018) in which, as soil loss and runoff measurements are available for all the four steepness values, both USLE and USLE-MB are applicable. Moreover, this figure reports the related power best-fit curve obtained for $14.9\% \leq s \leq 26\%$, and Eq. (7) with the calculated A_{av} converted into Mg ha^{-1}. While the representativeness of Eq. (7) is corroborated by different data sources from US locations, the underlying heterogeneity in terms of soil, rainfall, vegetation cover, makes the reliability of such a relationship uncertain when applied in a specific site, even more if it is located in another climatic context as the Mediterranean one of the Sparacia station. Instead, the site-specific $A_{av}(s)$ power curve was obtained for complete homogeneity conditions for rainfall, soil, slope length, cover, and tillage, and is fully consistent with the model approach, accordingly. Considering an uncertainty band of ± 50% for Eq. (7), which can be considered reasonable as a discrepancy by a factor of two between the experimental and the predicted soil loss is not substantial from a practical point of view (Bagarello et al. 2012), it is apparent that, for $s \geq 14.9\%$, the site-specific $A_{av}(s)$ power curve fall within the band. In other words, the discrepancy between this curve and Eq. (7) is expected and so is that between Eqs. (6) and (12). Indeed, Eq. (6) derives from Eqs. (7) and (12) is the best-fit curve of the S_x experimental values, each of them determined by adding the measured $A_{e,m}$ values for a given s and dividing the sum by the cumulative $A_{e,m}$ measured value from the unit plot, that is the same as operating with the corresponding A_{av} values.

For the unit plot condition, the power curve gives $A_{av} = 4.74$ Mg ha^{-1} year^{-1} against the measured value of 2.67 Mg ha^{-1} year^{-1}. Therefore, a proportionality factor of 1.77 results for S_x as determined with the measured and the calculated value, respectively. In other words, the slope steepness factor obtained using the average soil loss measured in the unit plot is 1.77 times that obtained when the calculated value is applied in place of the former. This is a measure of the extent of the deviation in the S_x factor for the sampled soil resulting from hypothesizing the unavailability of unit plot measurements.

A constant slope length factor contrasts with the increasing pattern with λ predicted by the RUSLE (Eqs. 3–5 with $a = 1$, Renard et al. 1997) (Fig. 4) but was also found in other studies (Rejman et al. 1999; Laflen and Moldenhauer 2003; Parsons et al. 2006; Moreno-de las Heras et al. 2010). Considering the USLE mathematical structure, the independence of the slope length factor of λ implies that soil loss is independent too. This result is in line with the result obtained by Bagarello et al. (2015a) that event soil loss in the Sparacia area generally does not vary appreciably with λ, which was attributed to more sediment deposition in the interrill areas on longer plots. This circumstance can be justified by the discontinuity of the flow through the plot length due to the short time span of rain showers producing runoff (Bagarello et al. 2015a).

For the investigated plots, Bagarello and Ferro (2017) detected that statistically significant relationships of runoff and soil loss with λ did not generally occur (62% of the analyzed events). Although the relatively high L_{MB} variability, the assumption of a constant slope length factor for the USLE-MB allows the model to be consistent with the most common hydrological-erosive response in the experimental area, i.e. to predict event soil loss independent of plot length for λ–independent runoff coefficient.

Finally, the temporal extent (4 years) of the limited available dataset for the unit plots is, however, comparable with that of early (3 to 11 years depending on the site, see Olson and Wischmeier (1963) and Renard et al. (1997)) and recent (1 year, Vaezi et al. 2008) studies on the determination of the soil erodibility factor using fallow-plot data. This circumstance supports the idea that the determined model factors are comparatively meaningful, although the suggested observation period, rarely satisfied, is of 20–22 years (Renard et al. 1997). Management and economic factors often limit the establishment of long-term plots, while a natural cause, i.e. a landslide in the unit plot area, interrupted temporarily the unit plot monitoring at Sparacia.

The present analysis suggested that different values of the model factors can be obtained if the original unit plot concept is applied or literature relationships for describing topographic effects are used along with soil erodibility as a calibration parameter. On the other hand, other findings from measurements performed in the Sparacia plots (e.g. Bagarello et al. 2020) demonstrated that using literature relationships for estimating the topographic factors and considering soil erodibility as a calibration parameter gave an accuracy level of the soil loss predictions comparable to the present one, as a consequence of the multiplicative structure of the models.

4.2 Accuracy of soil loss estimations

The USLE confirms the well-known result that empirical models overestimate low values of soil loss and underestimate the large ones (Fig. 5a) (Risse et al. 1993; Rapp 1994), which is, however, common to the process-oriented WEPP model (Zhang et al. 1996; Nearing 1998; Tiwari et al. 2000; Kinnell 2010).

The USLE-MB gives more reliable soil loss estimates than USLE as expected due to the increased experimental information, concerning the runoff coefficient, required to apply the model. For both USLE and USLE-MB, large estimation errors are confined to small soil losses while they significantly decrease for severe erosion events (Table 2). This investigation confirms the result by Di Stefano et al. (2019) that USLE-MB predicts the highest soil losses better than the low ones. Considering that the former often produce most of the total soil loss in a long time period (Edwards and Owens 1991; Larson et al. 1997; Bagarello et al. 2010, 2011), models should be specifically capable to estimate these high values of event soil loss. For $A_e > 10$ Mg ha^{-1}, the USLE systematically underestimates event soil loss (Fig. 5a) whereas the USLE-MB prediction are not biased (Fig. 5b), thus highlighting the improved quality of the more interesting predictions for the runoff-driven model. This result supports the application of the USLE-MB for practical purposes.

5 Conclusions

Empirical soil loss prediction models are still attractive for practical applications and are requested to accurately predict higher event soil losses since the latter can control long-term soil erosion in an area of interest. Both the USLE and USLE-MB can be deduced using the dimensional analysis and self-similarity theory, the controlling factors of the phenomenon and the reference condition given by the unit plot concept. For the Sparacia soil, the soil erodibility factor of the two models, determined applying the measurements performed in the unit plots, was different (USLE-MB) or significantly different (USLE) from that calculated by USLE nomograph and previously applied methods. The experimentally determined slope steepness factor differed from that estimated by a commonly applied relationship available in the literature. Moreover, the slope length factor determination, depending on soil erodibility and steepness factor, revealed the unsuitability of the USLE/RUSLE increasing relationship with λ. Therefore, the present analysis pointed out the discrepancy between the single factors of the models obtained from their own definition, using the unit plot concept, and those otherwise estimated. Although the limited available database, this result can be deemed relevant as data from unit plots are rather uncommon in the literature. The predictions of the USLE-MB were more accurate than the predictions of the USLE and improved with increasing soil loss.

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Data availability statement The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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