

Empirical and physical modelling of soil erosion in agricultural hillslopes

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Abstract: Soil erosion is a complex and highly heterogeneous process with a wide range of environmental and economic impacts. Its estimation is particularly challenging and modelling is typically used for erosion estimation over large areas. The aim of this study was to compare the two leading empirical and physical erosion estimation models, i.e. the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP). The models were calibrated and validated using data collected from field experiments conducted in agricultural lands of Mexico. The simulated rainfall experiments involved measuring erosion from field plots subjected to four tillage systems (No crop, Conventional tillage, Conventional tillage + residues, and Handspike) under two antecedent soil moisture conditions (dry and wet). Different calibration approaches based on the factors K and C for RUSLE, and interrill erodibility and hydraulic conductivity in WEPP were tested. The best-performing methods in RUSLE involved measuring the K factor and adopting the recommended C factor by the National Forestry Commission of Mexico. In WEPP, the best results were obtained when interrill erodibility was estimated from experimental measurements. Overall, RUSLE outperformed WEPP in most of the treatments except for CT under WAMC.

Keywords: RUSLE; WEPP; Tillage systems; Rainfall simulation.

INTRODUCTION

Soil erosion by water occurs when raindrops cause detachment of soil particles, which are then transported by runoff and eventually deposited elsewhere in the landscape. While soil erosion is a natural process, it can be exacerbated by human activities such as agriculture, construction, and mining. The impacts of soil erosion can be both negative and positive. Areas with long-term soil accumulation are typically the most fertile lands while the eroded zones have lower fertility and capacity for supporting life. Globally, water erosion leads to an estimated annual soil loss of 20–30 Gt. Erosion rates vary depending on factors such as land use and climate, ranging from 10–20 t ha⁻¹ yr⁻¹ in hilly croplands under conventional agriculture and temperate climate to 50–100 t ha⁻¹ yr⁻¹ in tropical and subtropical regions (FAO and ITPS, 2015). Soil erosion also has significant economic consequences, with an estimated cost of \$44 billion per year in the United States (Pimentel et al., 1995), and a 0.43% annual loss of crop productivity in severely eroded agricultural lands in the European Union, amounting to EUR 1.25 billion (Panagos et al., 2018). Erosion is significant in agricultural lands located in semi-arid regions, where intense rainstorms and low soil organic matter exacerbate the erosive effects.

Given the economic importance of soil erosion, accurate prediction over large areas based on precipitation data is essential. Selecting the right model for a given soil erosion process is critical as uncertainties are typically large in erosion modelling. For instance, the Universal Soil Loss Equation (USLE) and its variants are the most used erosion models but have limitations (Roose, 1996). USLE is based on experimental relations that can hide the effects of key variables which limit their replicability, also has temporal limitations because it is designed for long-term erosion and may not be effective in predicting short-term erosion. USLE-type models provide broad estimations that are often sufficient for determining the best

practices in land use management. Many models have been developed since 1940 and can be classified as empirical, physical and conceptual. The Revised Universal Soil Loss Equation (RUSLE) is the most applied soil erosion model worldwide due to its flexibility and accessibility. It calculates long-term average annual soil erosion by considering factors such as rainfall-runoff erosivity, soil erodibility, slope length, slope steepness, land cover and management, and soil conservation practices (Alewell et al., 2019; Renard et al., 1991; Wischmeier and Smith, 1978). Empirical USLE-type models rely on statistical relationships derived from field observations.

Alternative to empirical models are the conceptual and physical models. Physical models aim to describe the underlying processes and interactions, while conceptual models take an intermediate approach, combining empirical and physical elements (Patil, 2018; Zingg, 1940). Since 1940, numerous physical and conceptual models have been developed, based on the continuity equation for both runoff and erosion prediction. Although sharing the same root, they present variations in approaches and methods showing similarities and differences.

Examples of physical models include the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1980), the Cellular Automaton Evolutionary Slope and River Model (CAESAR) (Coulthard et al., 2002), and CASC2D. Conceptual models encompass SWAT (Arnold et al., 1998) and WATEM/SEDEM (Notebaert et al., 2006), the latter being a combination of the Water and Tillage Erosion Model (WATEM), which estimates erosion using the Revised Universal Soil Loss Equation (RUSLE), and the Sediment Delivery model (SEDEM). Additionally, empirical models like EGEM (Woodward, 1999) and EPIC, which employs the Universal Soil Loss Equation (USLE) and Modified Universal Soil Loss Equation (MUSLE) to predict soil erosion (Williams, 1990), offer alternative approaches to erosion modelling.

Worldwide, the most employed soil erosion and sediment yield models in descending order of importance are RUSLE, USLE, WEPP, SWAT, and WATEM/SEDEM, they are all based on USLE-type equations with the exception of WEPP (Borrelli et al., 2021). WEPP was developed as a replacement of empirical models. It takes a physical-based approach and offers a more detailed understanding of erosion processes (Flanagan et al., 2007). WEPP considers various processes at both hillslope and watershed scale, offering a comprehensive perspective on erosion dynamics (Flanagan et al., 1995).

For calibrating USLE-types models, experiments are often conducted, mainly focused on changes of Factor C (soil surface condition) and Factor K (soil erodibility). For instance, Prado-Hernández et al. (2017) calibrated MUSLE based on Factor K, replacing the default method and suggestions from FAO (Food and Agriculture Organization) with their own estimations obtained from regressions with the least squares method. In the case of calibrating WEPP in single storm mode, it is recommended for soil losses prediction, doing adjustments in erodibility parameters, including interrill erodibility, rill erodibility and critical shear stress (Flanagan and Frankenberger, 2012). In a study by Wang et al. (2023), the WEPP was calibrated modifying the range of values for hydraulic conductivity according to Risse et al. (1994) and subsequently adjusting shear stress, rill erodibility and interrill erodibility, like the ranges of Nearing et al. (1990). Searching for the perfect method for calibrating environmental models is impractical due to uncertainties in inputs, outputs and the model structure itself. Nevertheless, to obtain reliable results, a robust calibration setup proves valuable, especially in cases where certain parameters are challenging to measure. Therefore, a carefully design in calibration process is essential (Mai, 2023).

The objective of this paper is to compare the performance of RUSLE and WEPP, two widely used empirical and physical models, studying different calibration approaches in simulating erosion at a small scale. The experiment was conducted in Mexico, a country where 76% of the total area is affected by soil erosion by water.

MATERIAL AND METHODS

Experimental setup

The experiment was conducted in the locality of Santo Domingo, Durango, México, at the coordinates 25° 49' 41.94" N and 104° 26' 18.97" W, with an altitude of 1750 m.a.s.l. The climate is arid with an average annual temperature ranging from 14 to 22 °C. The annual rainfall typically falls between 200 and

400 mm. The soil in this area is classified as Leptosol, with sandy clay loam texture and soil organic matter of 2.31%.

Rainfall simulation and sediment sampling

To perform the simulated rainfall, we developed a rainfall simulator based on the apparatus of Miller (1987). The setup consisted of a water supply tank, a pump, a Programmable Logic Controller, three 360° nozzles, solenoid valves, manometers and hoses. To power the simulator, we used a portable generator of 5500 watts (Figure 1).

The rainfall simulations were conducted from November 11 and 16, 2015. The soil moisture levels during these simulations ranged from 16 to 19% for DAMC and 23 to 25% for WAMC (Table 5). Each simulation lasted 45 minutes. We measured the rainfall intensity every minute using a standard pluviometer placed randomly at each plot. Every 5 minutes, we collected a 1-liter sample from 19-liter containers after mixing the runoff collected. These samples were later filtered, oven-dried at 105 °C, and weighed for further analysis.

Treatments

We set experiments under different treatments: 1. No crop (NC), without movement of soil and vegetation; 2. Conventional tillage (CT), with moldboard plough following by harrowing, furrowing and corn sowing; 3. Conventional tillage + residues (CTR) that was the same as CT but with crop residues on soil surface; and 4. Handspike (HS), without movement of soil and the corn sowing was using a wooden stick (Figure 2). The density of plants in CT and CTR was 68000 per hectare. Each treatment was replicated four times, and the experiments were conducted under both dry and wet antecedent soil moisture conditions (DAMC and WAMC). The erosion plots were delimited with smooth galvanized sheets measuring 1 x 3 m. To facilitate the collection of surface runoff, a structure was installed at the lower part of each plot. The slope of the plots was 2.8%. In total, there were 16 plots under DAMC and 14 plots under WAMC because of missing data.

RUSLE parameterization

The main equation of RUSLE is the next:

$$A = R * K * LS * C * P \quad (1)$$

where A is the annual average soil erosion ($\text{Mg ha}^{-1} \text{ year}^{-1}$); R is the rainfall-runoff erosivity factor ($\text{mm h}^{-1} \text{ ha}^{-1} \text{ year}^{-1}$); K is

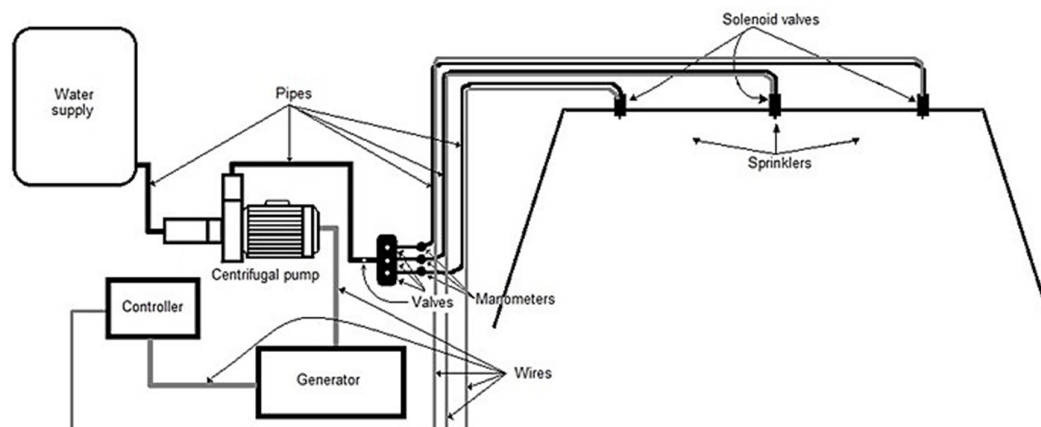


Fig. 1. Rainfall simulator.

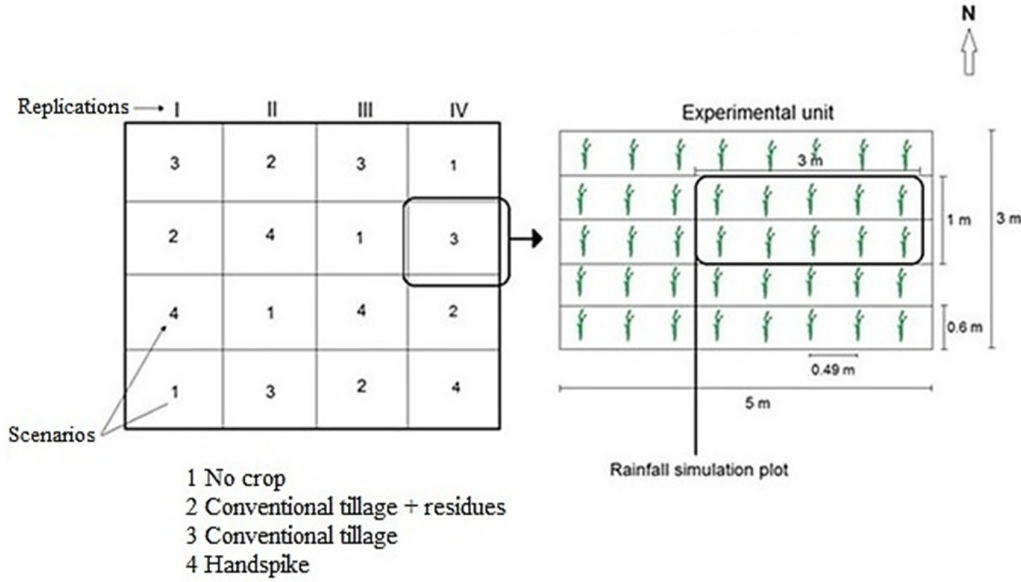


Fig. 2. Distribution of scenarios on the experiment and dimensions of the rainfall simulation plot.

the soil erodibility factor ($\text{Mg h}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$); L is the slope length factor (dimensionless); S is the slope steepness factor (dimensionless); C is the land cover and management factor (dimensionless), and P is the soil conservation or prevention practices factor (dimensionless). All the factors were considered in this study, with exception of P factor, which value was equal to 1.

Calculation of R-factor

Renard et al. (1997) recommended calculating the R factor with Equation (2).

$$R = \frac{\sum_{i=1}^j (EI_{30})_i}{N} \quad (2)$$

where R is the rainfall erosivity ($\text{M.J. mm}^{-1} \text{ ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$); N is the number of years of observations; E is the kinetic energy (M.J. ha^{-1}), and I_{30} is the maximum intensity in 30 minutes for storm i ; j is the number of storms in N years. The suggested value of kinetic energy by Renard et al., (1997) is $0.283 \text{ MJ ha}^{-1} \text{ mm}^{-1}$ for rainfall intensities greater than 76 mm h^{-1} , the mean measured rainfall intensity was 152 mm h^{-1} . The maximum measured rainfall intensity was assumed as the I_{30} , which was 352 mm h^{-1} . In this research, the resulted R factor was $99.61 \text{ MJ mm}^{-1} \text{ ha}^{-1} \text{ h}^{-1}$.

Calculation of K-factor

We calculated K factor based on a nonlinear relationship (Eq. 3) developed by Wang et al. (2016).

$$K = 0.0667 - 0.0013 \left[\ln \left(\frac{SOM}{Dg} \right) - 5.6706 \right]^2 - 0.015 \exp \left[-28.9589 (\log Dg + 1.827)^2 \right] \quad (3)$$

$$Dg = \exp(0.01 \cdot \sum_{i=1}^n f_i \ln m_i) \quad (4)$$

where Dg is the geometric mean diameter (mm); f_i is the weight of the particle size fraction, m_i is the arithmetic mean of the particle size (mm), and n is the number of particle size fractions; SOM is the soil organic matter in %. The calculated K factor in

the current study was $0.059 \text{ t ha}^{-1} \text{ h}^{-1} \text{ ha MJ}^{-1} \text{ mm}^{-1}$ for all the scenarios because the equation considered SOM and Dg that were the same throughout the experiment.

Calculation of LS-factor

We used the Equations (5) to (9) for calculating the LS factor.

$$L = \left(\frac{\lambda}{22.1} \right)^m \quad (5)$$

where 22.1 is the RUSLE unit plot length (m); m is a variable slope-length exponent, λ is the horizontal projection of the plot length, which was 3 meters in this case.

The values of "m" exponent were 0.172 for conventional tillage and 0.454 for no till scenarios. These were obtained from the Table 2 of a research of McCool et al. (1989).

To calculate the slope steepness factor (S) we used the Equations (6) and (7), for conventional tillage and no tillage scenarios, respectively (McCool et al., 1997).

$$S = 10.8 \sin \theta + 0.03 \quad s < 9\% \quad (6)$$

$$S = 16.8 \sin \theta - 0.50 \quad s \geq 9\% \quad (7)$$

Calculation of C-factor

The C factor was obtained using the Eq. (8), we considered the conditions did not change rapidly, so EI was not in the calculation. The most subfactors of C are listed in Table 1.

$$SLR = PLU \cdot CC \cdot SC \cdot SR \cdot SM \quad (8)$$

PLU is the prior land use, CC is the canopy cover, SC is the surface cover, SR is the surface roughness, and SM is the soil moisture.

The PLU includes the subsurface residual and tillage practices effects from the previous crop.

$$PLU = C_f \cdot C_b \cdot \exp \left[(-c_{ur} \cdot B_{ur}) + \left(\frac{c_{us} \cdot B_{us}}{C_{uf}} \right) \right] \quad (9)$$

where PLU ranges from 0 to 1, C_f is a soil consolidation factor (dimensionless), C_b is the effectiveness of subsurface residue in consolidation, B_{ur} is the mass density of roots ($\text{kg ha}^{-1} \text{cm}^{-1}$), B_{us} is the mass density of incorporated residues ($\text{kg ha}^{-1} \text{cm}^{-1}$), c_{ur} is the impact of soil consolidation, C_{ur} (acres per in lb^{-1}) and C_{us} (acres per in lb^{-1}) are calibration coefficients. The prior land use (PLU) and the b value of surface cover subfactor (SC) were the same for all treatments, 0.45 and 0.030, respectively. The C_f was 0.45 because is the default value for undisturbed soil, the B_u , B_{ur} , B_{us} , C_b , c_{ur} , c_{us} , c_{uf} were not considered in the equation.

The canopy cover effect is represented by Equation (10):

$$CC = 1 - F_c \cdot \exp(-0.1 \cdot H) \quad (10)$$

where F_c is the fraction of area covered by the canopy, and H is the distance that drops have to travel on the plant to reach the soil.

The % of canopy cover was estimated based on Equation (10) but with modifications proposed by Roloff and Bertol (1998). The relationship is presented in Equation (11):

$$F_{cd} = (1 - e^{-\varepsilon Bmd})\delta \quad (11)$$

where F_{cd} is the soil fraction covered by canopy, Bmd is the above-ground biomass in kg ha^{-1} , δ and ε are parameters according to a specific crop, in corn, δ is 0.67 and ε is 1.5×10^{-3} .

The surface cover subfactor SC accounts for everything on soil, such as crop residue, rocks, etc. The effect of SC is given by Eq. (12) (Yoder et al., 1997).

$$SC = \exp \left[-b \cdot S_p \cdot \left(\frac{0.24}{R_u} \right)^{0.08} \right] \quad (12)$$

where b is a coefficient of the effectiveness of surface cover. This varies from 0.030 to 0.070 in row crops; S_p is the percentage of covered area, R_u is the surface roughness.

The higher the b , the more significant the rill erosion. Large b corresponds to steep and/or long slopes. In contrast, the b value decreases if interrill erosion is more significant than rill erosion, common in flat and/or short slopes. b is also influenced by soil texture and soil cover.

The area covered by residue was obtained with Eq. (13).

$$S_p = [1 - \exp(-\alpha \cdot B_s)] \cdot 100 \quad (13)$$

where α is the ratio of covered area and the mass of the residue, B_s is the dry weight of residue.

The surface roughness was calculated using the Eq. (14) (Yoder et al., 1997).

$$SR = \exp[-0.66(R_u - 0.24)] \quad (14)$$

where R_u is the roughness before the tillage operation.

The soil moisture subfactor (SM) was obtained applying Equation (15), considering the soil moisture, field capacity, and wilting point calculated with Eq. (16) and Eq. (17).

The soil moisture is near to 1.0 if the water content is close to field capacity. In contrast, a value of 0 indicates that soil moisture is near to the wilting point. Lianes Revilla (2008) proposed the following equation for SM:

$$SM = \frac{M - WP}{FC - WP} \quad (15)$$

where M is the soil moisture (dimensionless); WP is the moisture in/of wilting point (%), and FC is the field capacity (%).

There are several approximations to obtain field capacity and wilting point considering the particle sizes of soil, as the equations proposed by Smith (1917) for field capacity (Eq. 16) and Silva et al. (1988) for wilting point (Eq. 17). Both were used in the present research.

$$FC = 0.1(\% \text{ sands}) + 0.15(\% \text{ silt}) + 0.61(\% \text{ clay}) \quad (16)$$

$$WP = FC \times 0.74 - 5 \quad (17)$$

WEPP parameterization

There are three modules of parameters in WEPP: weather, management and soil. The next paragraphs describe how we parameterized them.

Table 1. Subfactors used to calculate C factor in RUSLE for all the scenarios.

Scenario	R ^a	Rb ^b	Ce ^c (%)	AFH ^d (m)	Ru ^e (cm)	RC ^f (%)	VRC ^g (%)	SM dry ^h	SM wet ⁱ
No crop	1				1.68	1.66	0.00	0.20	0.92
	2				nd ^j			0.25	0.81
	3				nd			0.30	0.90
	4				1.93			0.45	0.90
Conventional tillage + residues	1	48.88	3.32	0.26	1.27		23.33	0.31	0.98
	2	44.61	3.04	0.20	1.50		29.17	0.20	0.89
	3	111.14	7.31	0.48	1.45	1.66	35.00	0.40	0.89
	4	15.35	1.06	0.18	1.50		29.17	0.39	0.90
Conventional tillage	1	97.09	6.43	0.34	1.12	3.33		0.20	0.92
	2	55.93	3.79	0.32	1.70			0.28	0.90
	3	19.75	1.36	0.18	1.91			0.44	0.90
	4	33.68	2.31	0.29	1.09			0.44	0.90
Handspike	1	64.42	4.34	0.23	1.78			0.20	0.86
	2	38.67	2.64	0.25	1.85			0.28	0.94
	3	9.23	0.64	0.20	2.36			0.20	0.90
	4	28.54	1.96	0.26	1.42			0.47	0.90

^a Replication. ^b Root biomass. ^c Canopy cover. ^d Average fall height. ^e Roughness; ^f Rock cover; ^g Vegetative residue cover. ^h Soil moisture subfactor under DAMC. ⁱ Soil moisture subfactor under WAMC. ^j No data.

In the single storm mode, the data for the weather module were 114.28 mm of storm amount, 0.75 of duration, 182.14 mm h⁻¹ of maximum intensity, which was the maximum value registered of the mean, and 51 of duration to peak intensity.

Regarding the management parameterization, some parameters were measured, and others calculated from equations found in literature, some were not applicable, and they were left blank or with zero. WEPP has two groups of parameters in the management section, these are initial conditions and plant databases. The initial conditions are listed in Table 2, the canopy cover was estimated with the Equation (11). The rill and interrill cover, ridge height and roughness were measured with a pin meter. The plant database is organized in plant growth and harvest, temperature and radiation, canopy, LAI (Leaf Area Index) and root, senescence, residue, and other. The biomass energy ratio and the parameter value for canopy height equation was obtained from the WEPP manual, as well as the base daily air temperature, optimal temperature for plant growth, radiation extinction coefficient which were 10, 25 and 0.65°C, respectively (Arnold et al., 1995; Flanagan and Livingston, 1995). The maximum canopy height was measured at field. The parameter of flat residue cover was based on investigations of Gregory (1982), he studied different types of residues, for corn he obtained 0.0004 ha kg⁻¹. This applied just for the treatment CTR. To obtain the growing degree days to emergence on October 1, 2015, we used the recorded temperature from a weather station located in the site of study applying the Equation (18) (Abendroth et al., 2011):

$$GDU = \left(\frac{T_{max} + T_{min}}{2} \right) - 10 \quad (18)$$

where GDU is the growing degree units, T_{max} is the maximum temperature, in this case was 29.2 °C, T_{min} is the minimum temperature, it was 8.6 °C. The number 10 is the base temperature of corn. To estimate the growing degree days for the growing season, the same equation was applied but adding all the days of the crop cycle.

The percent of growing season when LAI starts to decline was 50%, the period over which senescence occurs was fixed to 105 days, just through observing LAI and phenology of a four-month corn crop (Boedthram et al., 2001; Sacks and Kucharik, 2011).

In the soil module, the values for Cation Exchange Capacity (CEC), albedo, effective hydraulic conductivity, organic matter, sand and clay were 18, 0.23, 0.84 mm h⁻¹, 2.31%, 47%, 27%, respectively. The equation to determine the soil albedo (Eq. 19) was proposed by Baumer (1990).

$$SALB = \frac{0.6}{e^{0.4 \cdot OM}} \quad (19)$$

where OM is the percentage of soil organic matter.

To estimate the effective hydraulic conductivity, the default method was applied (Eq. 20) for all the scenarios (Alberts et al., 1995). It was 9.84 mm h⁻¹.

$$K_{hc} = -0.265 + 0.0086(sand)^{1.8} + 11.46CEC^{-0.75} \quad (20)$$

Other parameters like rock cover, and initial saturation level varied for each scenario. The coverage of soil by rocks was measured with a pin meter, and the initial saturation level with the oven drying method (Reynolds, 1970).

Table 2. Parameters of initial conditions and plant database in management module of WEPP.

Scenario	NC ^a				CTR ^b				CT ^c				HS ^d			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Bulk density (g cm ⁻³)									1.5							
Canopy cover (%)					3	3.3	7.3	1.1	6.4	3.8	2.3	1.4	4.3	2.6	0.6	2
Rill cover (%)					48	15	11	21								
Interrill cover (%)					36	15	33	38								
Ridge height (cm)					4	4.3	4.3	5.7	3.7	4.7	6	4				
Roughness (cm)	1.7	1.2	1.7	2	1.3	1.5	1.5	1.5	1.1	1.7	1.9	1.1	1.8	1.9	2.4	1.5
Rill spacing (cm)									49							
Rill width (cm)									60							
Depth of primary tillage (cm)									15							
Depth of secondary tillage (cm)									10							
Biomass energy ratio (kg MJ ⁻¹)									28							
Growing degree days to emergence (°C)									8.9							
Growing degree days for growing season (°C)									266							
In-row plant spacing (cm)									49							
Stem diameter at maturity (cm)									2.7							
Parameter value for canopy height equation									3							
Maximum canopy height (cm)					20	27	49	19	34	33	29	19	24	25	21	26
Maximum root depth (cm)									15							
Root to shoot ratio									0.2							
Percent of growing season when leaf area index starts to decline									50							
Period over which senescence occurs									10							
Percent canopy remaining after senescence							30									
Percent of biomass remaining after senescence							20									
Parameter for flat residue cover equation (m ² kg ⁻¹)							4									
Ridge height value after tillage (cm)					4	4.3	4.3	5.7	3.7	4.7	6	4				
Ridge interval (cm)									49							
Random roughness value after tillage (cm)	1.7	1.2	1.7	2	1.3	1.5	1.5	1.5	1.1	1.7	1.9	1.1	1.8	1.9	2.4	1.5
Mean tillage depth (cm)									10							
Optimum yield under no stress conditions (kg m ⁻²)									0.8							

^a No crop. ^b Conventional tillage + residues. ^c Conventional tillage. ^d Handspike.

The flow and erosion parameters are enclosed in the soil module also, we assumed as negligible the rill erodibility and critical shear due to the dimensions of the plots, thus we set the rill erodibility to 0.002 s m^{-1} and the critical shear stress to $1 \times 10^{-7} \text{ Pa}$. The interrill erodibility was set automatically to $5300000 \text{ kg s}^{-1} \text{ m}^4$, which was then adjusted by WEPP according to canopy effects, ground cover and slope.

Evaluation of model performance

To evaluate the performance of RUSLE and WEPP, we selected the Nash-Sutcliffe efficiency index (NSE), the coefficient of determination (r^2) and percent bias (PBIAS). The equations are next:

$$r^2 = \left(\frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (P_i - \bar{P})^2}} \right)^2 \quad (21)$$

where r^2 is the coefficient of determination, O_i is each of i observations, P_i is each of i predicted data, $\bar{O}$ is the mean of observed data, $\bar{P}$ is the mean of predicted data and n is the number of total observations.

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (22)$$

where NSE is the Nash-Sutcliffe efficiency index, O_i is each of i observations, P_i is each of i predicted data, $\bar{O}$ is the mean of observed data, and n is the number of observations.

$$PBIAS = \left(\frac{\sum_{i=1}^n (Y_{iobs} - Y_{isim}) \cdot (100)}{\sum_{i=1}^n (Y_{iobs})} \right) \quad (23)$$

where $PBIAS$ is the deviation of evaluated data (%), Y_{iobs} is the observed data, Y_{isim} is the simulated data, and n is the total of observations.

According to Moriasi et al. (2007) the performance of hydrological models is satisfactory when NSE is 0.50 or greater and $PBIAS$ is 55% or lower for sediments.

Calibration and validation

We implemented new methods dividing the observed erosion in two groups, one for calibration and another for validation. The calibrated parameters were then considered in the validation phase.

RUSLE calibration

We focused just on changing the methods for calculating factors K and C during the calibration of RUSLE, keeping the methods of the other factors in the model unchanged. The new methods applied included the “measurement method” for estimating factor K and “expert suggestions” for factor C . These additional methods were combined with the ones originally used, resulting in four sets to calibrate RUSLE. Table 3 presents such sets, being the first, the methods also used in uncalibrated RUSLE. The estimated K and C factors are listed in Table 4.

The measurement method was based on the Equations (24) and (25).

$$a_u = \frac{a_f}{L_f S_f C_f P_f} \quad (24)$$

$$K = \frac{\sum_{j=1}^n (a_u)}{\sum_{j=1}^n (EI)_j} \quad (25)$$

where a_u is the estimated soil loss for a specific EI; a_f is the measured soil loss; L_f , S_f , C_f , and P_f are the other factors of USLE for a given plot (Foster et al., 1981).

In estimation of C factor, we considered expert suggestions from CONAFOR (2010), who proposed the following empirical values: 0.80 in CT, 0.15 in HS and 0.20 in CTR; they did not include no cropping, thus we used the mean of DAMC and WAMC obtained with the Eq. (8).

WEPP calibration

For calibrating WEPP, we changed the methods only for estimating the parameters interrill erodibility and effective hydraulic conductivity. We combined these new methods resulting in three sets for calibrating WEPP (Table 3).

Table 3. Methods used to estimate the parameters in calibration and validation of RUSLE and WEPP.

Set	RUSLE		WEPP	
	K Factor	C Factor	Interrill erodibility	Effective hydraulic conductivity
1	Eq. (3) of Wang et al. (2016). $K = 0.0667 - 0.0013 \left[\ln \left(\frac{SOM}{Dg} \right) - 5.6706 \right]^2 - 0.015 \exp \left[-28.9589 (\log Dg + 1.827)^2 \right]$	Default. Eq. (8) $SLR = PLU \cdot CC \cdot SC \cdot SR \cdot SM$	Eq. (26) of Liebenow et al. (1990) $K_t = \frac{D_i}{I^2 (1.05 - 0.85 \exp^{-4 \sin \theta})}$	Default. Eq. (28) of Alberts et al. (1995) for fallow conditions $K_{ef} = 1.17 + 7.2(sand)$
2	Measurement method. Eq. (25) $K = \frac{\sum_{j=1}^n (a_u)}{\sum_{j=1}^n (EI)_j}$	Same as Set 1	Same as Set 1	Eq. (27) of Ferrer Julià et al. (2004) $K_s = -4.994 + 0.56728 \cdot sand - 0.131 \cdot clay - 0.0127 \cdot org.mat$
3	Same as Set 1	Expert suggestions	Same as Set 1	Default. Eq. (20) of Alberts et al. (1995) just for all conditions $K_{hc} = -0.265 + 0.0086(sand)^{1.8} + 11.46CEC^{-0.75}$
4	Same as Set 2	Expert suggestions	Same as Set 1	

Table 4. Factors used in calibration and validation of the RUSLE. R and P factors are equal in all treatments and replications. R = 99.6; P = 1.

Set	Treat.	Rep.	LS	C		K	
				Dry AMC	Wet AMC	Dry AMC	Wet AMC
1	NC ^a	1 – 4	0.31	0.10	0.42	0.06	
	CTR ^b	1 – 4	0.24	0.04	0.16		
	CT ^c	1 – 4	0.24	0.10	0.28		
	HS ^d	1 – 4	0.31	0.07	0.29		
2	NC	1 ^e	0.31	0.06	nd ^h	2.17	nd
		2 ^e		0.13	0.42	0.24	0.15
		3 ^f		0.10	0.42	1.20	0.15
		4 ^f		0.10	0.42	1.20	0.15
	CTR	1 ^e	0.24	0.03	0.14	1.55	0.65
		2 ^e		0.06	0.18	0.99	0.28
		3 ^f		0.04	0.16	1.27	0.47
		4 ^f		0.04	0.16	1.27	0.47
	CT	1	0.24	0.09	0.28	nd	nd
		2 ^e				0.23	0.07
		3 ^f				0.23	0.07
		4 ^f				0.23	0.07
	HS	1 ^e	0.31	0.06	nd	1.15	nd
		2 ^e		0.09	0.29	0.41	0.32
		3 ^f		0.07	0.29	0.78	0.32
		4 ^f		0.07	0.29	0.78	0.32
3	NC	1	0.31	0.18 ^g	nd	0.06	
		2		0.27 ^g			
		3		0.23 ^g			
		4		0.23 ^g			
	CTR	1 – 4	0.24	0.20			
	CT	1 – 4	0.24	0.80			
	HS	1 – 4	0.31	0.15			
4	NC	1	0.31	0.18 ^g	nd	0.76	nd
		2		0.27 ^g		0.11	0.22
		3		0.23 ^g		0.44	0.22
		4		0.23 ^g		0.44	0.22
	CTR	1	0.24	0.20		0.25	0.47
		2				0.28	0.25
		3				0.26	0.36
		4				0.26	0.36
	CT	1	0.24	0.80		nd	nd
		2				0.03	0.03
		3				0.03	0.03
		4				0.03	0.03
	HS	1	0.31	0.15		0.47	nd
		2				0.24	0.62
		3				0.35	0.62
		4				0.35	0.62

^aNo crop. ^bConventional tillage + residues. ^cConventional tillage. ^dHandspike. ^eReplications used in calibration. ^fReplications used in validation. ^gNo experts suggestions available, the default method was applied. ^hNo data.

We calculated the interrill erodibility (Table 5) with the Eq. (26) of Liebenow et al. (1990) and the effective hydraulic conductivity with the Eq. (27) (Ferrer Julià et al., 2004) for all the scenarios and Eq. (28) just for the CTR and CT (Alberts et al., 1995).

$$K_i = \frac{D_i}{I^2(1.05 - 0.85\exp^{-4\sin\theta})} \quad (26)$$

where K_i is the interrill erodibility in $\text{kg s}^{-1} \text{m}^4$, D_i is the interrill erosion rate in $\text{kg m}^2 \text{s}^{-1}$, I is the rainfall intensity in m s^{-1} , and θ is the slope angle in radians.

$$K_s = -4.994 + 0.56728 \cdot \text{sand} - 0.131 \cdot \text{clay} - 0.0127 \cdot \text{org.mat} \quad (27)$$

where K_s is the hydraulic conductivity in mm h^{-1} , *sand*, *clay* and *org.mat* are in percentage.

$$K_{ef} = 1.17 + 7.2(sand) \quad (28)$$

where K_{ef} is the hydraulic conductivity for fallow conditions in mm h^{-1} .

The resulted hydraulic conductivity was 18.10 mm h^{-1} applying the Equation (27), and 7.19 mm h^{-1} with the Equation (28).

Table 5. Interrill erodibility and initial saturation level used in calibration and validation of WEPP for both Dry and Wet Antecedent Soil Moisture conditions (DAMC and WAMC).

Treatment & replication		Interrill erodibility (kg m ⁻⁴ s ⁻¹)	Int. sat. (%)	
DAMC	NC ^a	1 ^e	232597.91	16.19
		2 ^e	51803.65	16.85
		3 ^f	142200.78	17.4
		4 ^f	142200.78	19.08
	CTR ^b	1 ^e	63875.37	16.19
		2 ^e	72618.16	17.56
		3 ^f	68246.76	18.52
		4 ^f	68246.76	18.48
	CT ^c	2 ^e	27088.93	17.21
		3 ^e	57633.29	18.99
		4 ^f	42361.11	18.98
	HS ^d	1 ^e	117446.29	16.19
		2 ^e	60327.99	17.21
		3 ^f	88887.1083	16.28
		4 ^f	88887.1083	19.38
	WAMC	NC	2	102210.90
3			102210.90	24.39
4			102210.90	24.36
CTR		1	121300.76	24.28
		2	64445.72	25.33
		3	92873.24	24.24
		4	92873.24	24.32
CT		2	26609.36	24.32
		3	84752.14	24.37
		4	55680.75	24.36
HS		2	154591.55	24.80
		3	154591.55	24.33
	4	154591.55	24.35	

^a No crop. ^b Conventional tillage + residues. ^c Conventional tillage.

^d Handspike. ^e Replications used in Calibration. ^f Replications used in validation.

RESULTS AND DISCUSSION

Performance of RUSLE

The uncalibrated RUSLE exhibited good performance in treatments of CT and HS under DAMC and NC, CT, and HS under WAMC, where the r^2 was high (more than 0.70). During calibration, RUSLE performance improved in CT under WAMC using method 1, and in all treatments using methods 2 and 4, as these methods incorporated observed erosion data into their calculations. Later, during validation, RUSLE exhibited good performance (with PBIAS from -43.98% to 49.19%) in all treatments using different methods. Methods 2 and 4 generally yielded the best performances, except for CT under the two AMC's, where method 3 outperformed the others (see Table 6).

The good performance of uncalibrated RUSLE may be questionable due to the calculation of r^2 using 4 replications, a small number of data points. In this context, it is prudent to consider the other two statistics available, NSE and PBIAS. Both NSE and PBIAS indicated poor model performance, with negative values for NSE and PBIAS exceeding 55% in all treatments.

The calibration of RUSLE aimed to enhance model performance by changing parameter values for further validation. Table 4 lists the calibrated and validated parameters, which varied depending on the method used and treatments.

For the validated K factor, it was evident that methods 2 and 4 consistently produced K values with the best performance across all treatments, except for method 3. Method 3 exhibited good performance specifically in CT under both AMC's. Notably, method 4 generally produced lower K values compared to method 2, except in the case of NC under DAMC.

Regarding the influence of AMC on K values, we observed they were generally lower under WAMC compared to DAMC. This suggests a higher resistance to erosion when the soil is moist, leading to lower soil erodibility. In terms of tillage treatments, there was no clear trend observed in K values. The influence of tillage treatment on K factor varied across different scenarios, indicating that the impact of tillage practices on soil erodibility may be complex and context-dependent.

For the validated C factor, Method 4 generally yielded larger values of the C factor across all treatments, except for in CT under both AMC's, where Method 3 produced the highest C value recorded in the study, reaching 0.80. Additionally, in the case of HS under wet AMC, Method 2 also resulted in a higher C value compared to Method 4.

Additionally, the C values were generally higher under WAMC compared to DAMC in most treatments that may indicate a higher susceptibility to erosion when the soil is moist. Notably, Method 2 exhibited sensitivity to AMC, with C values being higher under WAMC compared to DAMC, which was not observed with other methods. Also, the highest value of C factor emerged in CT (with method 3 under both AMC's), while the lowest value occurred in CTR.

In other studies applying the RUSLE, researchers have obtained wide ranges of model performances. Spaeth et al. (2003), similar to the current study, reported negative and low values of NSE for experiments conducted in U.S. with natural vegetation and rainfall simulation. The best performance happened under DAMC. The methods used to calculate K factor included the nomograph and the NRCS, while the estimation of C involved field measurements and values derived from the best fitting of a relation of vegetation with root mass, production potential and soil roughness. These results contrasted with ours as the best performance statistics were observed under WAMC, also the methods involved in calculation of factors were different.

Other study conducted by Biddoccu et al. (2020) in vineyards of Europe showed negative values of NSE as low as -33.69, similar to the present research, but the authors obtained positive values as high as 0.84. These investigators also achieved an r^2 from 0.14 to 0.83, a statistic that we could not calculate in validation here due to few replications. Their best results were obtained under CT, where the K factor ($0.025 \text{ t ha}^{-1} \text{ h}^{-1} / \text{ha MJ}^{-1} \text{ mm}^{-1}$) was calculated using a nomograph constant based on a model proposed by Borselli et al. (2012), and C factor (0.13 to 0.54) applying default equation.

In a watershed study in India, Das et al. (2021) simulated erosion using RUSLE, achieving an NSE of 0.73. The watershed comprised 26.4% agriculture lands and scrubland, with slopes ranging from 0 to 8% and sandy clay loam soil texture in those

Table 6. Statistics of performance for uncalibrated, calibrated and validated RUSLE for both Dry and Wet Antecedent Soil Moisture conditions (DAMC and WAMC).

	Uncalibrated	Calibration				Validation			
		1	2	3	4	1	2	3	4
Dry AMC									
No crop									
NSE	-2.97	-2.23	1	-1.86	1	-5.51	-1.26	-4.44	-0.35
PBIAS	91.33	93.25	0	84.19	0	92.91	-44.39	83.40	-23.26
r ²	0.49	na ^a	na	na	na	na	na	na	na
Conventional tillage + residues									
NSE	-16.86	-219.86	1	-146.8	1	-11.69	-2.59	-6.53	-1.65
PBIAS	93.62	95.06	0	77.61	0	93.32	-43.98	69.75	-35.08
r ²	0.03	na	na	na	1	na	na	na	na
Conventional tillage									
NSE	-2.26	na	na	na	na	-7.46	-4.17	-0.78	-4.17
PBIAS	85.17	74.55	0	-125.66	0	92.08	68.85	29.70	68.85
r ²	0.93	na	na	na	na	na	na	na	na
Handspike									
NSE	-2.56	-8.24	1	-6.73	1	-2.92	-0.33	-2.60	-0.46
PBIAS	92.11	91.73	0	83.32	0	94.87	31.74	89.59	37.59
r ²	0.74	na	na	na	1	na	na	na	na
Wet AMC									
No crop									
NSE	-1.25	na	na	na	na	-1.32	-0.50	-1.65	-0.69
PBIAS	77.35	59.82	0	73.62	0	79.58	49.19	88.84	57.71
r ²	0.99	na	na	na	na	na	na	na	na
Conventional tillage + residues									
NSE	-16.73	-8.13	1	-7.45	1	-161.76	-0.30	-150.81	-1.23
PBIAS	88.76	86.82	0	83.54	0	87.83	3.78	84.80	7.65
r ²	0.23	na	na	na	1	na	na	na	na
Conventional tillage									
NSE	-2.07	na	na	na	na	-41.77	-36.46	-9.28	-36.46
PBIAS	68.57	18.41	0	-129.73	0	77.45	72.37	36.52	72.37
r ²	0.79	na	na	na	na	na	na	na	na
Handspike									
NSE	-3.52	na	na	na	na	-3.24	-0.31	-3.75	-0.31
PBIAS	85.44	81.49	0	90.41	0	86.45	26.78	92.98	26.78
r ²	0.79	na	na	na	na	na	na	na	na

^a Not applicable.

areas. The mean K factor was $0.18 \text{ t ha}^{-1} \text{ h}^{-1}/\text{ha MJ}^{-1} \text{ mm}^{-1}$, derived from a modification of the nomograph method. The C factor ranged between 0.50 and 1, calculating it with the NDVI as suggested by van der Knijff et al. (2000). Comparing our results, the closest K factor value to theirs was 0.15, occurring in NC under WAMC, calculated with the measurement method (PBIAS = 49.19%). Similarly, our closest C factor values to theirs were 0.42 and 0.80, observed in NC under WAMC (PBIAS = 49.19%, obtained with the default method), and in CT under both DAMC and WAMC, respectively. The latter was determined using methods 3 (PBIAS = 29.70% under DAMC and PBIAS = 36.52% under WAMC) and 4 (PBIAS = 68.85% under DAMC and PBIAS = 72.37% under WAMC).

In a one-year study conducted by Vieira et al. (2018) with natural rainfall on post-fire soils in Portugal, researchers calculated K factor ($0.017 \text{ t ha}^{-1} \text{ h}^{-1}/\text{ha MJ}^{-1} \text{ mm}^{-1}$) using the nomograph method and the C factor (0.13) using an equation proposed by Borrelli et al. (2016), which provided specific values for disturbed lands. The RUSLE predicted soil loss with a NSE of 0.70, r^2 of 0.89 and PBIAS of -20.1, indicating good model performance. We also evaluated model performance using these three statistics in the current research, but our experiment achieved good performance based solely on PBIAS.

Performance of WEPP

Without calibration, WEPP exhibited poor performance, which improved after calibration in most treatments. Particularly, the best performance was observed in CT treatment under both DAMC and WAMC when all three calibration methods were applied. Among these methods, Method 1 stood out, incorporating interrill erodibility based on observed erosion and effective hydraulic conductivity calculated with Equation (28) tailored for fallow conditions, yielding the most favorable performance statistics.

During validation, Method 1 demonstrated superior performance in CT under WAMC, with a PBIAS of 25.97%. Conversely, Method 3 exhibited the lowest level of acceptable performance in CT under DAMC, with a PBIAS of 50.37%, as shown in Table 7.

These results are in line with those of Onsamrarn et al. (2020), who conducted a study under natural rainfall conditions with corn, soil texture of sandy loam to clay loam, and slope gradients from 6 to 12%. Their validation results showed an NSE of -1.89 and an r^2 of 0.26 with no PBIAS calculated. They proposed calibrated interrill erodibility ($250000 \text{ kg s}^{-1} \text{ m}^{-4}$) and hydraulic conductivity (80 mm h^{-1}) parameters for both maize

monocropping with conventional tillage and intercropping high-value chili with *Leucaena* hedgerow with minimum tillage. Our closest calibrated and validated interrill erodibility value to theirs was 154591.55 kg m⁻⁴ s⁻¹, with hydraulic conductivity values of 18.10 and 9.8 mm h⁻¹ in HS treatment under WAMC, where WEPP performed poorly.

In our treatment with the best WEPP performance, CT under WAMC, the interrill erodibility was 55680.75 kg s⁻¹ m⁻⁴ and hydraulic conductivity 18.10, 9.8 and 7.19 mm h⁻¹. Interestingly, the interrill erodibility in Onsamrarn et al.'s investigation was almost three times higher than ours, despite similar soil conditions in their monocrop practice and our CT treatment. Onsamrarn et al. (2020) did not vary this parameter between treatments, consistent with the recommendation in WEPP manual to define a baseline interrill erodibility modified by the model based on vegetation and soil crusting characteristics.

However, we used an equation for calculating interrill erodibility that already included effects from rainfall intensity, sediments rate and slope, potentially resulting in an inaccurate baseline interrill erodibility as required by the WEPP software. Despite this potential discrepancy, our validated interrill erodibility contributed to good WEPP performance (PBIAS of 25.97 and 29.74%). It is worth noting that the uncalibrated

WEPP in CT under WAMC showed poor performance, possibly due to WEPP-calculated interrill erodibility.

The baseline interrill erodibility value (for croplands) used by WEPP, assuming 20% of the sand fraction as very fine sand (Panagos et al., 2014), would be 4533740 kg s⁻¹ m⁻⁴. The WEPP manual recommends a range of interrill erodibility baseline of 500000 to 12000000 kg s⁻¹ m⁻⁴, indicating that both Onsamrarn et al. (2020) and our study had relatively low interrill erodibility inputs. Hypothetically, a better value of interrill erodibility would fall between the range of 140000 and 250000 kg s⁻¹ m⁻⁴, disregarding the lowest value suggested in the WEPP manual. In another study, Mirzaee and Ghorbani-Dashtaki (2021) conducted experiments with artificial rainfall on bare fallow conditions and calcareous soils with slopes mostly greater of 25%. Initially, they observed poor performance from the WEPP model ($r^2 = 0.09$) when using baseline erodibility parameters calculated following WEPP manual recommendations. However, they achieved significant improvement in results ($r^2 = 0.68$) by adopting a new method for calculating erodibility parameters, as proposed by Mirzaee et al. (2017), which involved stepwise multiple-linear regression and artificial neural networks.

Table 7. Statistics of performance for uncalibrated, calibrated and validated WEPP for both Dry and Wet Antecedent Soil Moisture conditions (DAMC and WAMC).

	Uncalibrated	Calibration			Validation		
		1	2	3	1	2	3
Dry AMC							
No crop							
NSE	−1192.19		−0.24	0.02		−1.35	−0.80
PBIAS	−1827.68		57.49	35.92		51.31	42.81
r ²	0.09		na ^a	na		na	na
Conventional tillage + residues							
NSE	−18953.49	−52.38	−68.53	−49.77	−0.94	−2.26	−1.34
PBIAS	−3097.38	45.02	51.89	49.68	28.00	42.02	32.91
r ²	0.13	na	na	na	na	na	na
Conventional tillage							
NSE	−9179.04	0.99	0.70	0.98	na	na	na
PBIAS	−4964.64	−1.75	18.10	3.89	47.78	57.83	50.37
r ²	0.83	na	na	na	na	na	na
Handspike							
NSE	−1555.20		−2.48	−1.70		−1.80	−1.58
PBIAS	−2024.44		49.42	40.46		80.30	76.70
r ²	0.00		na	na		na	na
Wet AMC							
No crop							
NSE	−463.33		na	na		−1.09	−0.98
PBIAS	−1564.35		45.10	35.92		72.13	72.35
r ²	0.29		na	na		na	
Conventional tillage + residues							
NSE	−7566.72	−2.58	−3.64	−2.84	−82.54	−150.30	−60.08
PBIAS	−1863.23	47.68	57.50	50.26	61.89	84.69	53.62
r ²	0.96	na	na	na	na	na	na
Conventional tillage							
NSE	−10758.72	0.99	0.84	0.99	na	na	na
PBIAS	−4545.98	−1.41	17.82	3.52	25.97	40.74	29.74
r ²	0.44	na	na	na	na	na	na
Handspike							
NSE	−929.09		na	na		−2.18	−1.87
PBIAS	−1230.56		23.40	9.55		76.82	72.71
r ²	0.05		na	na		na	na

^a Not applicable.

Mirzaee and Ghorbani-Dashtaki (2021) reported a mean of interrill erodibility of $2000000 \text{ kg s}^{-1} \text{ m}^{-4}$, contrasting with the calculated mean of $3300000 \text{ kg s}^{-1} \text{ m}^{-4}$ using the WEPP manual suggestions. Once again, the study demonstrated that lower values of interrill erodibility than the recommended led to better prediction outcomes.

In another study with rainfall simulation in forest environments, Xia et al. (2019) reported NSE values of -0.901 and 0.81 for uncalibrated and calibrated WEPP, respectively. Initially, the researchers followed WEPP recommendations for calculating the erodibility parameter, resulting in a value of $1041200 \text{ kg s}^{-1} \text{ m}^{-4}$. However, after artificially calibrating it to fit the observed data, they improved model performance, with the interrill erodibility adjusted to $4974960 \text{ kg s}^{-1} \text{ m}^{-4}$. The authors concluded that lower values of soil erodibility and hydraulic conductivity led to enhanced WEPP performance.

Comparison of RUSLE and WEPP

Before calibration, WEPP exhibited poor performance, unlike RUSLE, which showed good performance in all treatments except in CTR, based on r^2 values. WEPP underpredicted soil erosion by over 1000%, while RUSLE overpredicted it by more than 68%.

Following calibration, RUSLE's performance improved to perfection in all treatments, whereas WEPP showed good performance, particularly in the CT treatment (refer to Tables 6 and 7). In validation, RUSLE performed well in all the treatments except in CT under both DAMC and WAMC, while WEPP performed well only in CT under WAMC.

Both RUSLE and WEPP performances were influenced not only by their respective parameters but also by the methods employed in their calculation. Notably, default methods impacted better in RUSLE performance than in WEPP. It is worth mentioning that, in RUSLE, the equation referred to as the default method for calculating the K factor the equation was not the one recommended by RUSLE developers, but rather an enhanced version of it. The methods that worked better in calibration of both models included observed data. PBIAS ranged from 53.62 % to 28% in WEPP and from 49.19% to 3.78% in RUSLE. In NC under DAMC, RUSLE demonstrated superior performance, whereas WEPP excelled in simulating soil erosion in CTR under the same conditions. Furthermore, RUSLE outperformed WEPP in CT under DAMC and HS under DAMC scenarios. Similarly, RUSLE exhibited better simulation results in NC and CTR under DAMC conditions. Conversely, WEPP showed better performance in CT under WAMC conditions, while RUSLE was more effective in predicting erosion in HS under WAMC conditions.

CONCLUSION

The empirical approach of RUSLE simulated better the soil erosion than the physical approach of WEPP in the specific conditions of the current study: short term erosion in corn cropping under conventional tillage plus residues or zero tillage, high rainfall intensities, sandy clay loam soil and slopes near to 2.8%.

The input data to parameterize the two models played a crucial role on their performance. The wider use of RUSLE made easier to find a C factor suggested by other researchers for crop management, as well as alternative equations of K factor. The developers of WEPP suggested to calibrate based on soil parameters (Flanagan and Frankenberger, 2012), but in the current research conditions, like the absence of measured

hydraulic conductivity and flow velocity, it may be useful to calibrate based on crop management too.

The RUSLE simulated successfully the erosion in all the studied treatments except in CT under both DAMC and WAMC, while WEPP performed well just in CT under WAMC.

These findings underscore the importance of considering specific agricultural management practices and environmental conditions when selecting erosion prediction models for accurate soil erosion.

REFERENCES

- Abendroth, L.J., Elmore, R.W., Boyer, M.J., Marlay, S., 2011. Corn growth and development. Iowa State University, University Extension.
- Alberts, E.E., Nearing, M.A., Wertz, M.A., Risse, L.M., Pierson, F.B., Zhang, X.C., Laflen, J.M., Simanton, J.R., 1995. SOIL COMPONENT. In: USDA-Water Erosion Prediction Project (WEPP). National Soil Erosion Research Laboratory. NSERL Report No. 10, West Lafayette, IN, pp. 1–47.
- Alewell, C., Borrelli, P., Meusburger, K., Panagos, P., 2019. Using the USLE: Chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research*, 7, 203–225.
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment. Part I: Model development. *Journal of American Water Resources Association*, 34, 73–89.
- Arnold, J.G., Wertz, M.A., Alberts, E.E., Flanagan, D.C., 1995. Plant growth component. In: USDA-Water Erosion Prediction Project (WEPP). National Soil Erosion Research Laboratory. NSERL Report No. 10, West Lafayette, IN, pp. 1–41.
- Baumer, O., 1990. Predictions of soil hydraulic parameters. In: WEPP Data Files for Indiana SCS National Soil Survey Lab., Lincoln, Nebraska, United States.
- Beasley, D.B., Huggins, L.F., Monke, E.J., 1980. ANSWERS: a model for watershed planning. *Transactions, American Society of Agricultural Engineers*, 23, 938–944.
- Biddoccu, M., Guzmán, G., Capello, G., Thielke, T., Strauss, P., Winter, S., Zaller, J.G., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C., Hoble, A., Cavallo, E., Gómez, J.A., 2020. Evaluation of soil erosion risk and identification of soil cover and management factor (C) for RUSLE in European vineyards with different soil management. *International Soil and Water Conservation Research*, 8, 337–353.
- Boedhrum, N., Arkebauer, T.J., Batchelor, W.D., 2001. Season-long characterization of vertical distribution of leaf area in corn. *Agronomy Journal*, 93, 1235–1242.
- Borrelli, P., Alewell, C., Alvarez, P., Anache, J.A.A., Baartman, J., Ballabio, C., Bezak, N., Biddoccu, M., Cerdà, A., Chalise, D., Chen, S., Chen, W., De Girolamo, A.M., Gessesse, G.D., Deumlich, D., Diodato, N., Efthimiou, N., Erpul, G., Fiener, P., Freppaz, M., Gentile, F., Gericke, A., Haregeweyn, N., Hu, B., Jeanneau, A., Kaffas, K., Kiani-Harchegani, M., Villuendas, I.L., Li, C., Lombardo, L., López-Vicente, M., Lucas-Borja, M.E., Märker, M., Matthews, F., Miao, C., Mikoš, M., Modugno, S., Möller, M., Naipal, V., Nearing, M., Owusu, S., Panday, D., Patault, E., Patriche, C.V., Poggio, L., Portes, R., Quijano, L., Rahdari, M.R., Renima, M., Ricci, G.F., Rodrigo-Comino, J., Saia, S., Samani, A.N., Schillaci, C., Syrris, V., Kim, H.S., Spinola, D.N., Oliveira, P.T., Teng, H., Thapa, R., Vantas, K., Vieira, D., Yang, J.E., Yin, S., Zema, D.A., Zhao, G., Panagos, P., 2021. Soil erosion modelling: A global review and statistical analysis. *Science of the Total Environment*, 780, 146494.

- Borrelli, P., Panagos, P., Langhammer, J., Apostol, B., Schütt, B., 2016. Assessment of the cover changes and the soil loss potential in European forestland: First approach to derive indicators to capture the ecological impacts on soil-related forest ecosystems. *Ecological Indicators*, 60, 1208–1220.
- Borselli, L., Torri, D., Poesen, J., Jaquinta, P., 2012. A robust algorithm for estimating soil erodibility in different climates. *Catena*, 97, 85–94.
- CONAFOR, 2010. Coordinación general de producción y productividad. Estudios técnicos especializados para la recuperación de áreas degradadas por disturbios y/o perturbaciones antropogénicas.
- Coulthard, T.J., Macklin, M.G., Kirkby, M.J., 2002. A cellular model of Holocene upland river basin and alluvial fan evolution. *Earth Surface Processes and Landforms*, 27, 269–288.
- Das, S., Deb, P., Bora, P.K., Katre, P., 2021. Comparison of rusle and mmf soil loss models and evaluation of catchment scale best management practices for a mountainous watershed in india. *Sustainability (Switzerland)*, 13, 1–22.
- FAO, ITPS, 2015. Status of the World's Soil Resources (SWSR) - Main Report. Rome, Italy.
- Ferrer Julià, M., Estrela Monreal, T., Sánchez Del Corral Jiménez, A., García Meléndez, E., 2004. Constructing a saturated hydraulic conductivity map of Spain using pedotransfer functions and spatial prediction. *Geoderma*, 123, 257–277.
- Flanagan, D.C., Frankenberger, J.R., 2012. Wepp: model use, calibration, and validation. *Transactions of the American Society of Agricultural and Biological Engineers*, 55, 1463–1477.
- Flanagan, D.C., Gilley, J.E., Franti, T.G., 2007. Water Erosion Prediction Project (WEPP). *Transactions of the ASABE*, 50, 1603–1612.
- Flanagan, D.C., Ii, J.C.A., Nicks, A.D., Nearing, M.A., Laflen, J.M., 1995. Overview of the wepp erosion prediction model. In: *USDA-Water Erosion Prediction Project*. U.S. Department of Agriculture, West Lafayette, IN, pp. 1–12.
- Flanagan, D.C., Livingston, S.J., 1995. WEPP user summary. *USDA-ARS-MWA*, West Lafayette, IN, 141 p.
- Foster, G.R., McCool, D.K., Renard, K.G., Moldenhauer, W.C., 1981. Conversion of the universal soil loss equation to SI metric units. *Journal of Soil and Water Conservation*, 36, 355–359.
- Gregory, J.M., 1982. Soil cover prediction with various amounts and types of crop residue. *Transactions of the ASAE*, 25, 1333–1337.
- Lianes Revilla, E., 2008. Estudio del factor vegetación “C” de la ecuación universal de pérdidas de suelo revisada “RUSLE” en la cuenca del río Berris (Costa Rica). *Universidad Politécnica de Madrid*.
- Liebenow, A.M., Elliot, W.J., Laflen, J.M., Kohl, K.D., 1990. Interrill erodibility. Collection and analysis of data from cropland soils. *American Society of Agricultural Engineers*, 33, 1882–1888.
- Mai, J., 2023. Ten strategies towards successful calibration of environmental models. *Journal of Hydrology*, 620, 129414.
- McCool, D.K., Foster, G.R., Mutchler, C.K., Meyer, L.D., 1989. Revised slope length factor for the Universal Soil Loss Equation. *Transactions of the American Society of Agricultural Engineers*, 32, 1571–1576.
- McCool, D.K., Foster, G.R., Weesies, G.A., 1997. Slope length and steepness factors (LS). In: *Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C. (Eds.): Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE)*. Agriculture Handbook No. 703. US Department of Agriculture, Washington, DC, pp. 19–38.
- Reynolds, S.G., 1970. The gravimetric method of soil moisture determination Part I: A study of equipment, and methodological problems. *Journal of Hydrology*, 11, 258–273.
- Agriculture Handbook No. 703. US Department of Agriculture, Washington, DC, pp. 101–118.
- Miller, W.P., 1987. A solenoid-operated, variable intensity rainfall simulator 1. *Soil Science Society of America Journal*, 51, 832–834.
- Mirzaee, S., Ghorbani-Dashtaki, S., 2021. Calibrating the WEPP model to predict soil loss for some calcareous soils. *Arabian Journal of Geosciences*, 14, 1–10.
- Mirzaee, S., Ghorbani-Dashtaki, S., Mohammadi, J., Asadzadeh, F., Kerry, R., 2017. Modeling WEPP erodibility parameters in calcareous soils in northwest Iran. *Ecological Indicators*, 74, 302–310.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers*, 50, 885–900.
- Nearing, M.A., Deer-Ascough, L., Laflen, J.M., 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. *Transactions of the ASAE*, 33, 839–849.
- Notebaert, B., Vaes, B., Govers, G., 2006. WaTEM / SEDEM version 2006 Manual. *Physical and Regional Geography Research Group*.
- Onsamrarn, W., Chittamart, N., Tawornpruek, S., 2020. Performances of the WEPP and WaNuLCAS models on soil erosion simulation in a tropical hillslope, Thailand. *PLoS ONE*, 15, 1–20.
- Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., Alewell, C., 2014. Soil erodibility in Europe: A high-resolution dataset based on LUCAS. *Science of the Total Environment*, 479–480, 189–200.
- Panagos, P., Standardi, G., Borrelli, P., Emanuele, L., Montanarella, L., Bosello, F., 2018. Cost of agricultural productivity loss due to soil erosion in the European Union : From direct cost evaluation approaches to the use of macroeconomic models. *Land Degradation & Development*, 29, 471–484.
- Patil, R.J., 2018. *Spatial Techniques for Soil Erosion Estimation: Remote Sensing and GIS Approach*. Springer, Cham.
- Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., Mcnair, M., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., Mcnair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science*, 267, 1117–1123.
- Prado-Hernández, J.V., Rivera-Ruiz, P., DeLeón-Mojarro, B., Carrillo-García, M., Martínez-Ruiz, A., 2017. Calibration of the USLE and MUSLE soil loss models in a Mexican forest watershed: El Malacate case study. *Agrociencia*, 51, 265–284.
- Renard, K.G., Foster, G.R., Weesies, G.A., Porter, J.P., 1991. RUSLE: revised universal soil loss equation. *Journal of Soil & Water Conservation*, 46, 30–33.
- Renard, K.G., McCool, D.K., Cooley, K.R., Foster, G.R., Istok, J.D., Mutchler, C.K., 1997. Rainfall-runoff erosivity factor (R). In: *Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C. (Eds.): Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE)*. Agriculture Handbook No. 703. US Department of Agriculture, Washington, D.C., pp. 19–38.
- Reynolds, S.G., 1970. The gravimetric method of soil moisture determination Part I: A study of equipment, and methodological problems. *Journal of Hydrology*, 11, 258–273.

- Risse, M., Nearing, M.A., Savabi, M.R., 1994. Determining the Green-Ampt effective hydraulic conductivity from rainfall-runoff data for the WEPP model. *Transactions of the ASAE*, 37, 411–418.
- Roloff, G., Bertol, O.J., 1998. Method to estimate canopy cover and height of several summer crops. *R. Bras. Ci. Solo.*, 22, 319–327.
- Roose, E., 1996. Land husbandry: components and strategy. *Soil Resources Management and Conservation Service Land and Water Development Division*, FAO. Rome.
- Sacks, W.J., Kucharik, C.J., 2011. Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance. *Agricultural and Forest Meteorology*, 151, 882–894.
- Silva, A., Ponce de León, J., García, F., Durán, A., 1988. Aspectos metodológicos en la determinación de la capacidad de retener agua de los suelos de Uruguay. *Boletín de investigación*, 10.
- Smith, A., 1917. Relation of the mechanical analysis to the moisture equivalent of soils. *Soil Science*, 471–476.
- Spaeth, K.E., Pierson, F.B., Weltz, M.A., Blackburn, W.H., 2003. Evaluation of USLE and RUSLE estimated soil loss on rangeland. *Journal of Range Management*, 56, 234–246.
- van der Knijff, J.M., Jones, R.J.A., Montanarella, L., 2000. Soil erosion risk assessment in Europe. *Office for Official Publications of the European Communities*, Luxembourg.
- Vieira, D.C.S., Serpa, D., Nunes, J.P.C., Prats, S.A., Neves, R., Keizer, J.J., 2018. Predicting the effectiveness of different mulching techniques in reducing post-fire runoff and erosion at plot scale with the RUSLE, MMF and PESERA models. *Environmental Research*, 165, 365–378.
- Wang, B., Zheng, F., Guan, Y., 2016. Improved USLE- K factor prediction : A case study on water erosion areas in China. *International Soil and Water Conservation Research*, 4, 168–176.
- Wang, S., McGehee, R.P., Guo, T., Flanagan, D.C., Engel, B.A., 2023. Calibration, validation, and evaluation of the Water Erosion Prediction Project (WEPP) model for hillslopes with natural runoff plot data. *International Soil and Water Conservation Research*, 11, 4, 669–687.
- Williams, J.R., 1990. The erosion-productivity impact calculator (EPIC) model: a case history. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 329, 421–428.
- Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses - a guide to conservation planning. *Department of Agriculture*, Washington, DC.
- Woodward, D.E., 1999. Method to predict cropland ephemeral gully erosion. *Catena*, 37, 393–399.
- Xia, L., Song, X., Fu, N., Cui, S., Li, L., Li, H., Li, Y., 2019. Effects of forest litter cover on hydrological response of hillslopes in the Loess Plateau of China. *Catena*, 181, 104076.
- Yoder, D.C., Porter, J.P., Laflen, J.M., Simanton, J.R., Renard, K.G., McCool, D.K., Foster, G.R., 1997. Cover-Management Factor (C). In: Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C. (Eds.): *Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE)*. U.S. Department of Agriculture, Washington, DC, pp. 143–167.
- Zingg, A.W., 1940. Degree and length of land slope as it affects soil loss in run-off. *Agric. Engng.*, 21, 59–64.

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