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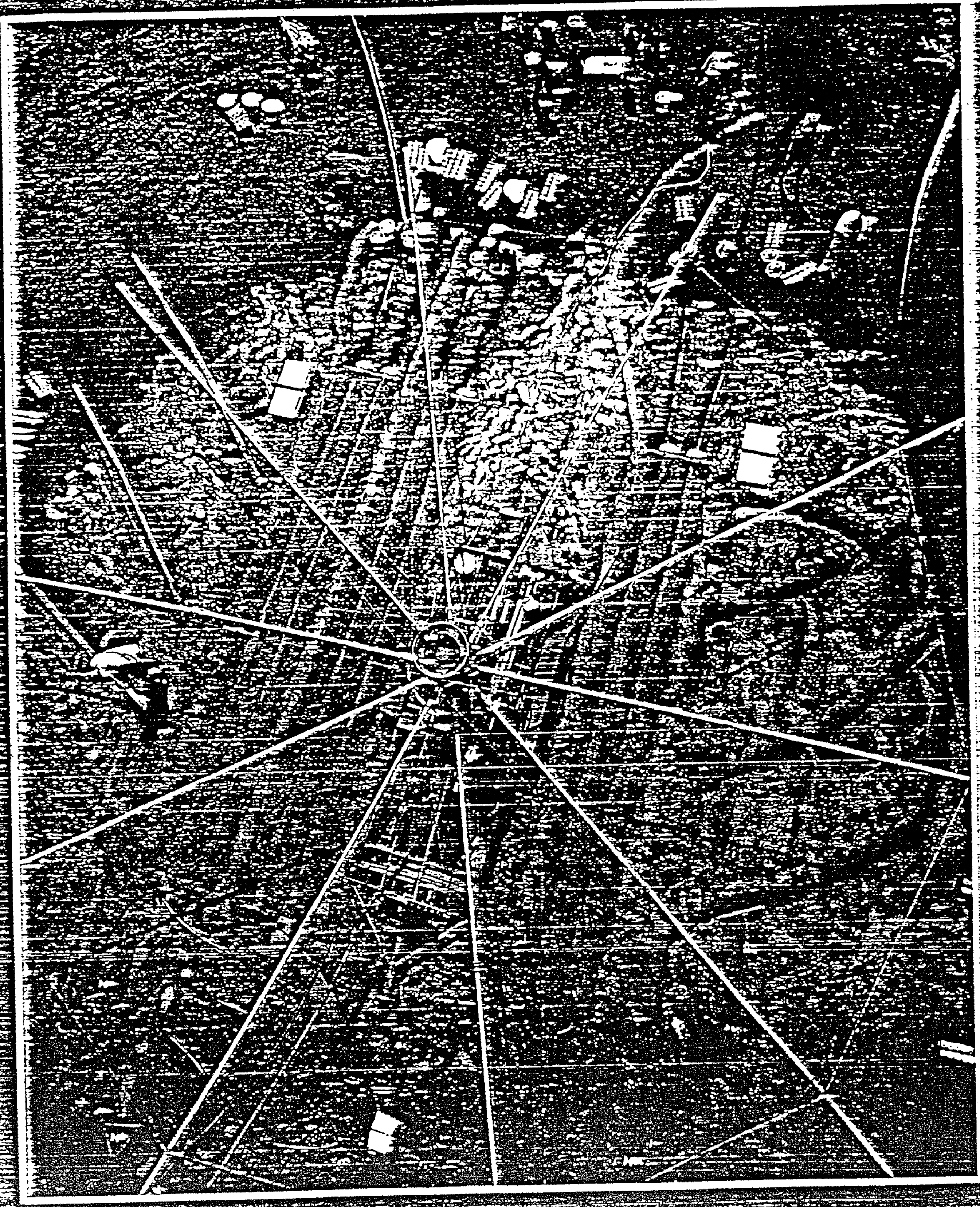
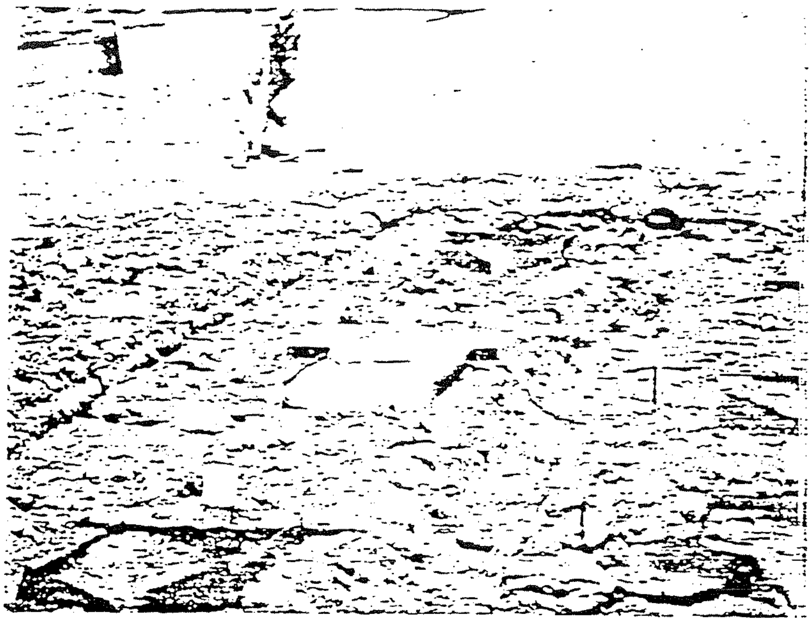


WEPP
Soil erodibility experiments for rangeland and cropland soils



By J. M. Laflen, W. J. Elliot, J. R. Simanton, C. S. Holzhey, and K. D. Kohl

THE Water Erosion Prediction Project (WEPP) combines knowledge of soil erosion processes with other important processes in a simulation model to predict soil erosion by water (*6, 9*). WEPP models soil erosion as a process of rill and interrill detachment and transport (*8*). This is much different than the universal soil loss equation (USLE), in which the factors understood to affect soil erosion were quantified in an empirical technology (*19*). Because WEPP deals with soil erosion prediction in a different manner than the USLE, new soil erodibility parameters are required. This was identified early in the project as a critical component for the successful development of the WEPP technology (*7*).

Soil erodibility in WEPP

The susceptibility or resistance of a soil to detachment and transport usually is recognized as a major determinant of soil erosion for a particular site. Generally, soil erosion models, including the USLE, incorporate a soil's susceptibility to erosion as a single parameter, termed soil erodibility, in the portion of the model dealing with soil detachment and transport. Even such models as CREAMS (*17*), which are process-based, use the USLE soil erodibility values to compute needed erodibilities.

Interrill erosion is the detachment and transport of soil particles by raindrops and shallow overland flow. In WEPP, the delivery of sediment to rills from interrill areas is estimated using the following equation:

$$D_i = K_i I_e^2 G_e C_e S_f \qquad [1]$$

where D_i is the delivery of sediment from interrill areas to a nearby rill (kg/m^2/s), K_i is interrill erodibility (kg/m^4/s), I_e is the effective rainfall intensity (m/s), G_e is a ground cover adjustment factor, C_e is a canopy cover adjustment factor, and S_f is a slope adjustment factor given by

$$S_f = 1.05 - 0.85\, e^{-4 \sin a} \qquad [2]$$

where a is the slope of the surface toward a nearby rill. The relationships expressed in equations 1 and 2 are reasonable fits to data reported by Meyer (*10*), Meyer and Harmon (*11, 12*), and Watson and Laflen (*18*). Equation 1 lumps together the processes of detachment, transport, and deposition on interrill areas.

Rill erosion is the detachment and transport of soil particles by concentrated flowing water. In WEPP, the detachment capacity (D_c) of flowing water is expressed as:

$$D_c = K_r \text{ (tau-taucrit)} \qquad [3]$$

where K_r is rill erodibility, tau is the hydraulic shear of the flowing water, and taucrit is a critical hydraulic shear that must be exceeded before rill detachment can occur. Hydraulic shear is the force exerted on the channel bed by flowing water. The detachment capacity is the maximum rill detachment rate that is assumed to occur when there is no sediment in the water. As the flow fills with sediment, rill detachment rate becomes less than the detachment capacity. The detachment rate (D_r) of flowing water is expressed as

$$D_r = D_c\,(1 - G/T_c) \qquad [4]$$

where G is the sediment load and T_c is the sediment transport capacity. In WEPP, sediment transport capacity is estimated using an approximation of Yalin's sediment transport equation (*5, 20*).

Interrill and rill erodibility and critical hydraulic shear must be estimated for the conditions under which WEPP must operate. In WEPP, the approach has been to develop the technology to estimate rill and interrill soil erodibility and critical hydraulic shear for freshly tilled conditions for soils where the model may be applied. For the USLE, a nomograph was developed from extensive studies on midwestern soils. Field studies were conducted on cropland and rangeland soils to obtain data with which to develop relationships between soil properties and the three WEPP soil erodibility parameters.

The three soil parameters are affected by soil properties, and these parameters can vary widely among soils. They also may vary widely during a year, depending on climate, soil, and management. The USLE handled this temporal, management, and tillage variation at least partially in the cropping and management factor. WEPP deals with this variation through a component to directly adjust interrill and rill erodibility

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and critical hydraulic shear for the changing conditions within a year and for different tillage and management systems. This component is based on an extensive literature review and considerable analysis of available data (2).

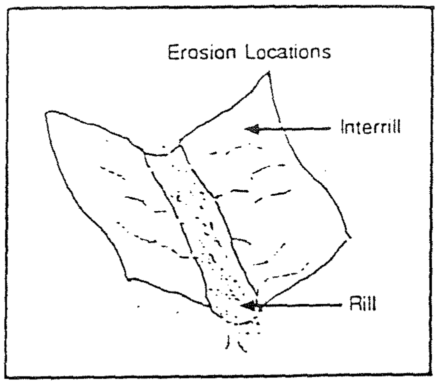


Illustration of the rill-interrill concept.

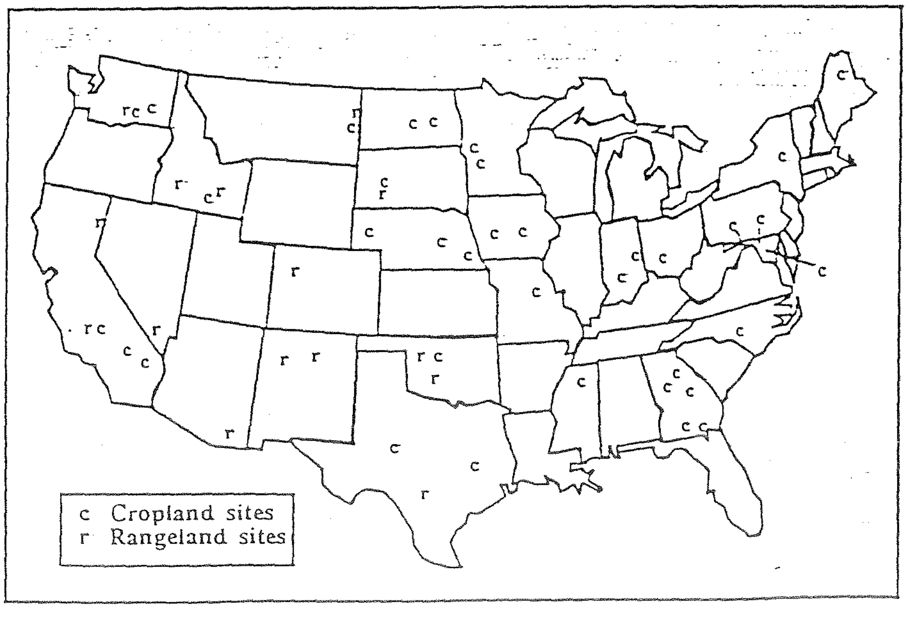
Soil selection and site preparation

Soils from all areas of the United States were considered for the field study. Because the relationships are expected to be used on all U.S. cropland, rangeland, and forestland, and likely in a number of other regions of the world as well, soils with a wide range of soil properties were selected. This broad range of soils is expected to contribute significantly to the applicability of WEPP technology. Where possible, sites were selected where a considerable history of past erosion studies existed. Alberts and associates (*1*) explained in detail most of the judgments related to the selection of the soils. The accompanying table provides a summary of the soil series and their locations. The soils were well distributed geographically.

Sites were selected up to a year prior to the erodibility tests by a joint Agricultural Research Service (ARS) and Soil Conservation Service (SCS) team. The most important criteria were those related to the soil and slope. Slopes that exceeded 4 percent were required; slopes in the 5 percent to 7 percent range were preferred. Accessibility and water supply were also considered. Additionally, for cropland, sites that had been in a row crop, small grain, or fallow the previous year were required. Sites that had been in a crop that might have had a carry-over effect on soil erodibility were avoided in the selection process.

For cropland, residue was removed and the soil tilled about 8 inches (20 cm) deep as soon after site selection as possible. The soil surface was kept weed- and grass-free by secondary tillage and chemical application up to forming of rills just prior to the tests.

Location of cropland and rangeland sites.



For rangeland, there was no tillage before tests; instead, plants were clipped and litter and stone removed shortly before measurements.

Before erodibility testing, a complete soil survey was carried out on each site by SCS personnel. Samples were collected for analysis by SCS's National Soil Survey Laboratory. Samples also have been furnished to numerous scientist-collaborators. Soil samples are stored for future analysis at ARS's National Soil Erosion Research Laboratory. Rangeland sites had additional survey evaluations of vegetation, site, and range conditions.

For cropland soils, measurements were made on six interrill plots to estimate interrill soil erodibility and on four additional interrill plots to estimate infiltration parameters. There were also six rill plots used to estimate rill erodibility and critical hydraulic shear. Measurements on all rill and interrill plots were made simultaneously. Rill plots were about 30 feet (9 m) long and 20 inches (50 cm) wide. Interrill plots were the same width, but only 30 inches (75 cm) long.

For rangeland soils, interrill measurements were made on 2-foot-wide by 4-foot-long (60- × 120-cm) plots, while rill measurements were made on 10-foot-wide by 36-foot-long plots (3 m × 11 m). For each soil, measurements were made on two rill and two interrill plots. Infiltration parameters were determined from two additional interrill plots.

In all experiments, local water supplies were used as the source of water for the rainfall simulation. Water supplies included reservoirs, flowing streams, wells, and, in one case, a treated municipal supply. Five of the water supplies used had electrical conductivities exceeding 1 mmhos/cm, more than half had electrical conductivities less than 0.5 mmhos/cm. Recent studies have indicated that considerable attention should be paid to the quality of water used in rainfall simulation studies for soil erosion and infiltration studies (*14*). Work is in progress and future work planned at the National Soil Erosion Research Laboratory to further explore the ramifications of water quality in rainfall simulation on WEPP soil parameters.

Experimental procedures

The rotating-boom rainfall simulator (*16*) with V-Jet 80100 nozzles was used in both the cropland and rangeland studies. For cropland, a single rainfall intensity of 2.5 inches per hour (6.3 cm/h) was used. For rangeland, intensities were both 2.5 and 5.0 inches per hour (6.3 and 12.5 cm/h) during the test sequence. For both cropland and rangeland sites, flow was added during portions of the test to increase the hydraulic shear of the runoff water. This was required to determine rill erodibility and critical hydraulic shear.

For cropland and rangeland, the test procedure was to rain at 2.5 inches per hour until runoff was virtually constant. During this period, flow rate measurements were made on rill and interrill plots; samples were then collected. These samples were later analyzed for sediment concentration.

For rangeland, the first rain was followed 24 hours later by a 30-minute rain at 2.5 inches per hour. After about 30 minutes, the final rainfall was applied at 2.5 and 5 inches per hour, with flow added at the upper end when rain was applied at 2.5 inches per hour.

For cropland, the first rain was followed about 30 minutes later with a 30-minute rainfall at 2.5 inches per hour, during which flow was added at the upper end of each rill at 1.5, 4.2, 6.3, 8.5, and 10.6 gallons per hour (6, 16, 24, 32 and 40 l/h). Then, after a 30-minute pause, flow was added at the same rates to each rill, but no rainfall simulation occurred.

For cropland, interrill erosion measurements were made during the first rainfall period. For rangeland, interrill measurements were made during all rainfall periods. Data used to compute rill erodibilities for cropland were from the second period—that in which both rainfall and flow addition occurred. Data used to compute rill erodibilities on rangeland were taken from the third period.

Interrill erodibilities on cropland and rangeland soils were determined by measuring erosion rates and dividing these by the square of the measured rainfall intensity and the slope factor computed using equation 2. For cropland, the interrill erosion rate used in the computations was an average of up to four measurements made after erosion rates and runoff rates had stabilized near the end of the first rainfall period. For rangeland, average interrill erosion rates for each period were used. More details are given by Elliot and associates (*3*) and Simanton and associates (*15*).

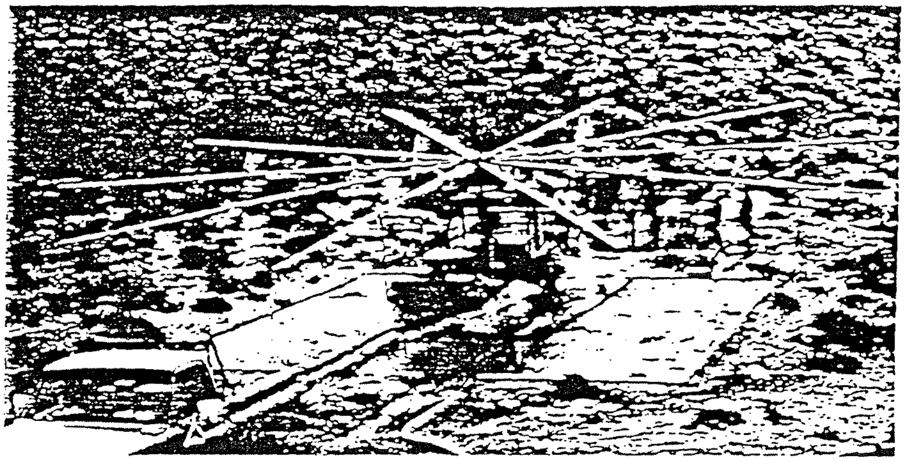
Rill erodibility and critical hydraulic shear were determined experimentally by subjecting the plot surface to varying levels of added inflow, and thus hydraulic shear, and measuring the resulting erosion. For cropland, erosion rates were adjusted for sediment in transport to arrive at the detachment capacity for the given hydraulic shear. For many soils, the adjustment for sediment in transport was small, but where slopes were low or eroded sediment was coarse adjustments were greater. Then, detachment capacity was linearly related to hydraulic shear to determine rill erodibility (K_r) and critical hydraulic shear (taucrit) as shown in equation 3 (*3*). For rangeland, equations 3 and 4 were combined and an iterative optimization scheme used to arrive at values of K_r and taucrit (*13*).

A unique feature of the WEPP erodibil-

Cropland and rangeland rill and interrill soil erodibility, critical hydraulic shear, and USLE soil erodibility

Soil Type and Location	*Surface Texture*	*Critical Hydraulic Shear (Pascals)*	*Soil Erodibility*		
			Rill (sec/m)	*Interrill (kg/sec/m⁴)*	*USLE (t/a/EI)*
Cropland					
Sharpsburg, NE	si c	3.18	0.00529	1,850,000	0.27
Hersch, NE	sa l	1.70	0.01122	3,930,000	0.28
Keith, NE	si l	0.00	0.00118	3,360,000	0.45
Amarillo, TX	l sa	1.66	0.04530	4,120,000	0.20
Woodward, OK	si l	1.31	0.02497	4,000,000	0.50
Heiden, TX	c	2.90	0.00891	1,700,000	0.19
Whitney, CA	sa l	4.66	0.02333	2,740,000	0.24
Academy, CA	l	1.60	0.00570	2,880,000	0.43
Los Banos, CA	c	2.85	0.00117	2,500,000	0.20
Portneuf, ID	si l	3.11	0.01062	1,260,000	0.61
Nansene, WA	si l	3.05	0.03073	3,120,000	0.60
Palouse, WA	si l	0.74	0.00655	4,320,000	0.40
Zahl, MT	l	3.52	0.01226	3,170,000	0.30
Pierre, SD	c	4.80	0.01168	2,180,000	0.22
Williams, ND	l	3.42	0.00448	2,940,000	0.21
Barnes, ND	l	2.52	0.00331	1,710,000	0.16
Sverdrup, MN	sa l	1.37	0.01000	2,110,000	0.09
Barnes, MN	l	3.96	0.00631	1,600,000	0.25
Mexico, MO	si l	0.69	0.00364	2,970,000	0.38
Grenada, MS	si l	4.47	0.00729	2,630,000	0.44
Tifton, GA	l sa	3.47	0.01127	770,000	0.14
Bonifay, GA	sa	1.02	0.01787	870,000	0.06
Cecil(eroded), GA	sa c l	4.48	0.00384	1,860,000	0.20
Hiwassee, GA	sa l	2.33	0.01028	1,880,000	0.17
Gaston, NC	c l	4.37	0.00489	2,040,000	0.16
Opequon, MD	c l	6.28	0.00354	3,200,000	0.20
Frederick, MD	si l	6.64	0.00844	2,480,000	0.41
Manor, MD	l	3.58	0.00540	2,690,000	0.19
Caribou, ME	g l	4.25	0.00451	1,450,000	0.26
Collamer, NY	si l	6.38	0.02413	3,460,000	0.55
Miamian, OH	l	5.45	0.00962	1,650,000	0.28
Lewisburg, IN	c l	3.41	0.00587	2,470,000	0.32
Miami, IN	si l	3.32	0.00949	1,970,000	0.45
Clarion, IA	l	0.40	0.00460	2,060,000	0.24
Monona, IA	si l	2.80	0.00760	1,820,000	0.49
Cecil, GA	sa l	2.20	0.00840	1,210,000	0.25
Rangeland					
Stronghold, AZ	g sa l	0.50	0.00053	439,652	0.18
Forrest, AZ	sa l	1.36	0.00035	647,410	0.28
Durorthid, NV	sa l	0.14	0.00046	240,257	0.50
Undesignated, NV	g sa l	0.29	0.00033	307,585	0.33
Purves, TX	co c	1.99	0.00010	288,262	0.06
Grant, OK	sa l	0.71	0.00011	375,852	0.36
Grant(eroded), OK	l	1.17	0.00015	614,916	0.50
Pratt, OK	sa	5.71	0.00302	10,782	0.10
Quinlan, OK	l	1.88	0.00083	802,256	0.51
Tivoli, OK	l sa	0.46	0.00064	145,085	0.07
Woodward, OK	l	0.05	0.00010	992,850	0.39
Woodward, OK	l	0.00	0.00009	1,197,575	0.48
Vida, MT	l	0.84	0.00032	528,799	0.04
Degater, CO	si c l	4.36	0.00162	1,872,648	0.29
Pierre, SD	c l	0.43	0.00020	1,469,245	0.21
Pierre, SD	si c	3.27	0.00015	1,425,843	0.20
Hackroy, NM	sa l	0.53	0.00021	939,715	0.50
Querencia, NM	sa l	0.58	0.00017	494,055	0.55
Jauriga, CA	g l	0.31	0.00012	119,170	0.15
Apollo, Ca	l	0.03	0.00004	415,282	0.28

ity experiments was the use of close-range photogrammetry for both permanently recording the state of the plots and for measuring critical flow parameters. A pair of aerial photographic cameras were located about 16 feet (5 m) apart and about 50 feet (15 m) above the plot. These were supported by a boom truck. Stereo pairs were taken when hydraulic measurements or a permanent record of the state of the plot area were needed. More conventional methods were used for backup measurements for cross-sectional and flow velocity data. Most hydraulic computations have been based upon the latter measurements. The rainfall simulation setup for rangeland and cropland are shown in the accompanying figures.



Rainfall simulator on rangeland.

Results and discussion

Soil erodibility and critical hydraulic shear values for the rangeland and cropland soils are shown in the accompanying table. For the most part, rill and interrill erodibilities for rangeland are much lower than for cropland soils. A major reason for this is that the erodibilities for rangeland soils were measured on plots that had no disturbance prior to rainfall simulation; in fact, these plots, for the most part, had never been tilled. This is much different than the cropland plots, which usually had been tilled immediately prior to the rainfall simulation and in no case had received rainfall between tillage and the rainfall simulation.

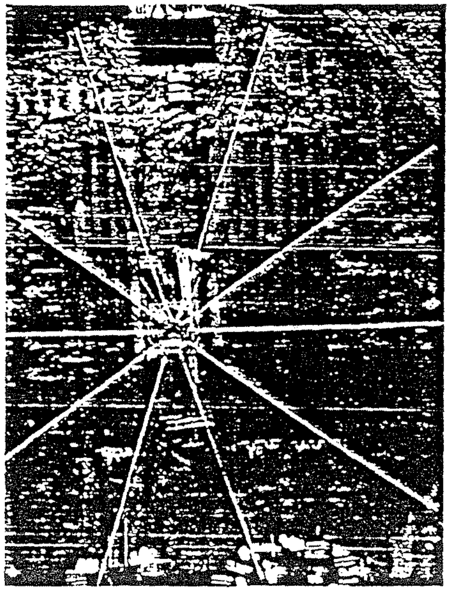
Calculated interrill erosion rates versus rainfall intensity are shown in the figure for the two soil types that were common to both the rangeland and cropland experiments.

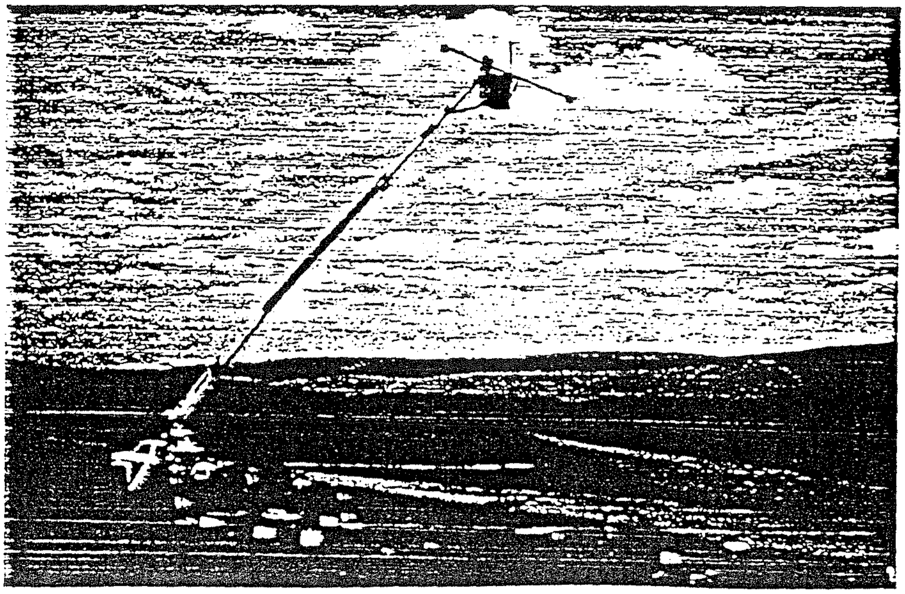
Note that, as given in the table, these two soils had somewhat different textures. For both soils shown in the figure, interrill erosion rates were considerably greater for a cropland soil than for a rangeland soil. This is likely due to the compaction and surface sealing that has occurred over a long period of time on the undisturbed rangeland soil. For cropland soils, the Woodward soil had almost the highest interrill erodibility, while the Pierre soil was of moderate interrill erodibility. For rangeland soils, both the Pierre and Woodward soils were among the most erodible. Of the rangeland soils, the Pierre and Woodward soils were the most likely to have been tilled in the past, but any tillage was likely over a decade ago. The relationships shown in the figure are given by equation 1 with values of 1 for G_e, C_e, and S_f. Units in the figure have been changed from the kilograms per square meter per second in equation 1 to tons per hectare per hour for improved perspective.

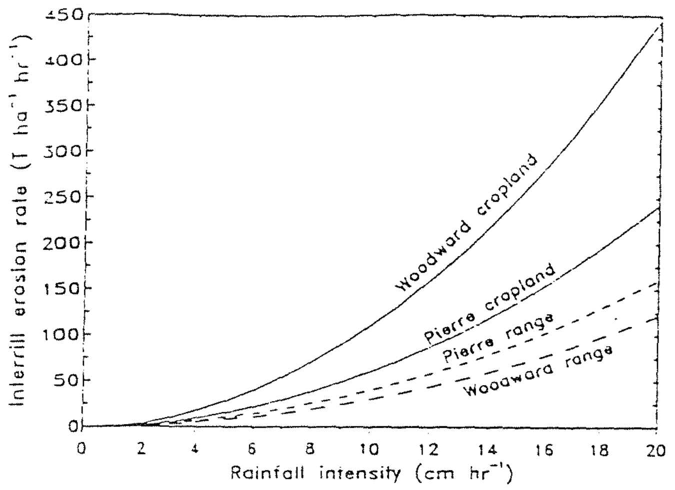
The experimental work related to interrill erosion in WEPP was performed under simulated rainfall conditions at 2.5 inches per hour. In the figure, the curves are extrapolated far beyond this value. Most interrill experiments have shown an exponent in equation 1 that is in the vicinity of 2 (*10*), but Meyer and Harmon (*11*) showed that the exponent is related to soil properties. Hence, it should be recognized that there is some risk associated with extrapolating well beyond the simulated rainfall intensity, particularly if small channels develop on the interrill area. This should not be a serious limitation because much rainfall occurs at intensities less than that used in these experiments. However, some rainfall events have brief periods of rainfall intensity well above 8 inches per hour (20 cm/h), and frequently, these events have very high erosion rates.

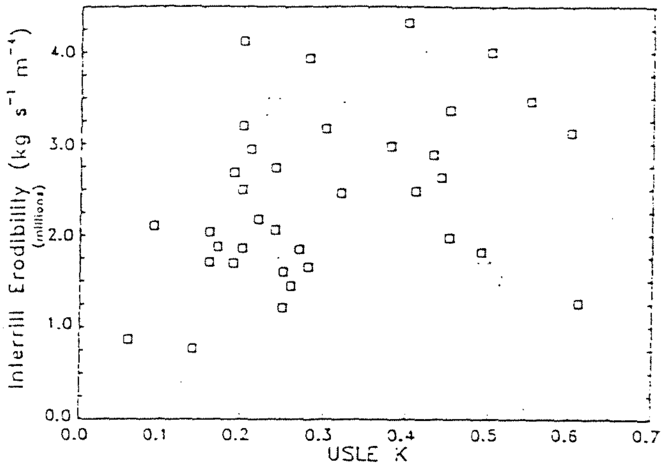
WEPP interrill soil erodibility for the

Rainfall simulator on cropland.





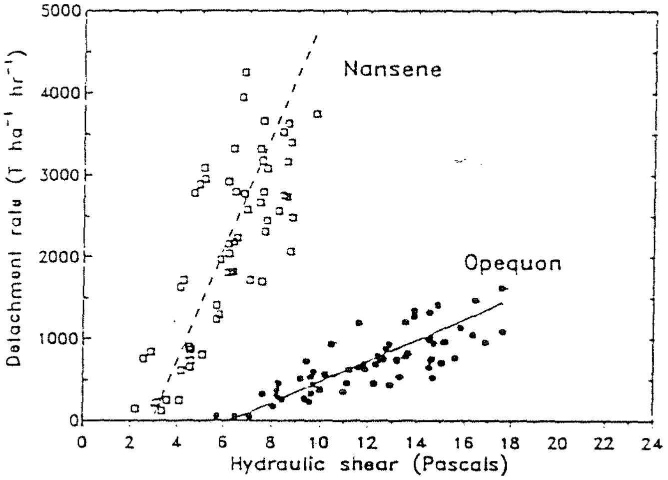




(Above): Interrill erosion rate versus rainfall intensity for soils common to both croplands and rangelands.

(Top, right): Interrill erodibility versus USLE K values for cropland soils.

(Bottom, right): Rill detachment rate versus hydraulic shear for two cropland soils.



cropland soils are plotted versus USLE soil erodibility values in the next figure. It is quite obvious that there is virtually no correlation between the USLE soil erodibility and interrill soil erodibility values. Similar comparisons could be shown for rangeland soils. The USLE lumps together many processes, such as infiltration, detachment, and transport. Separation into the more fundamental processes, as in WEPP, yields greatly different and unrelated soil erodibility values.

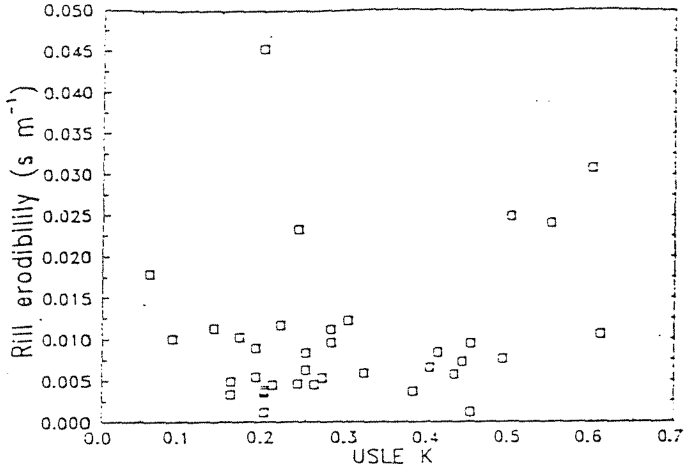
Rill detachment rates (not adjusted for sediment load) versus hydraulic shear are shown for two cropland soils in another figure. The units for detachment are different than those in equation 3 for better understanding of the magnitudes of detachment occurring in rills. Each cropland data set contains information collected simultaneously from all six rills. Data sets similar to those in the figure were collected for each of the cropland soils.

The slope of the best fit line (when the data are adjusted for sediment load), as determined by linear regression techniques, is the rill erodibility, with the critical hydraulic shear being the hydraulic shear when detachment is predicted to be zero. Rill erodibility and critical hydraulic shear were determined for each rill and averaged to determine the values for a soil. The data shown in the figure is quite representative, in terms of scatter, for the data collected in the WEPP cropland experiments. On the average, the coefficient of variation for rill erodibility and critical hydraulic shear for the six rills was about 30 percent.

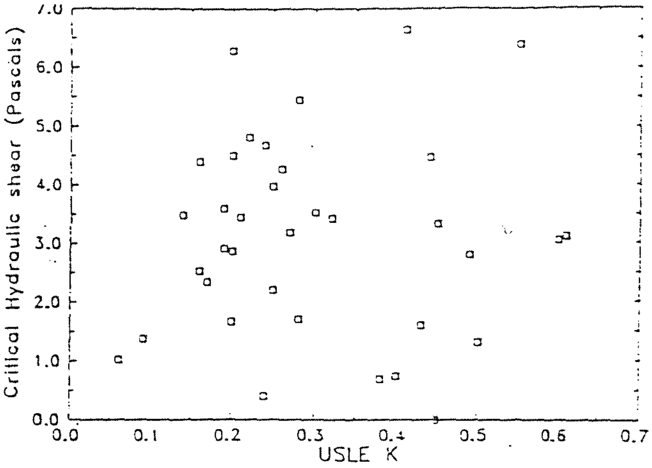
The units for detachment included in the figure would indicate an extremely high detachment rate. A few words of explanation are in order. First, the detachment rate is for detachment in a rill, and rills characteristically cover a small portion of a field. For example, rills may cover less than 10 percent of a field when it is row-cropped. Additionally, hydraulic shears in rills, particularly at the upper end of rills, may be less than critical hydraulic shear and no rill detachment would occur until flow exceeded the critical hydraulic shear. Also, rates are given in the figure in tons per hectare per hour, and most events, in terms of rill detachment, are much shorter. On the other hand, it is obvious that extremely high erosion rates occur in rills in many storms and rill erosion at high rates severely degrades the soil resource. It is not uncommon to find rill erosion rates at the lower end of rill, or in ephemeral gullies in excess of 1,500 tons per hectare in the area where soil was detached. In fact, we measured a rill erosion rate in excess of 7,000 tons per hectare per hour (3,123 tons/acre/hour) from one WEPP cropland soil and rates in excess of 5,000 tons per hectare per hour (2,230 tons/acre/hour) from several soils. In terms of application to field situations, these rates would be from a very small portion of the field; hence, average erosion rates would be much smaller.

Rangeland soil data sets were somewhat different with rills subjected to both increased rainfall rates and different rates of added inflow that generated different rates of hydraulic shear. Because of plot size and the wider number of treatments on rangeland compared to cropland, measurements were made only on duplicate plots. Hence, no measure of statistical confidence can be made.

Rill erodibilities and critical hydraulic shear values were compared with USLE soil erodibility values for cropland soils (see figures). Rill soil erodibility and critical hydraulic shear values, as for interrill erodibility, were poorly correlated with USLE soil erodibility values. Interrill soil erodibility values were poorly correlated, if at all, with rill erodibility values or critical hydraulic shear values for either cropland or rangeland soils. In addition, there was little correlation between rill erodibility and crit-



Rill erodibility versus USLE K values for cropland soils.



Critical hydraulic shear versus USLE K values for cropland soils.

ical hydraulic shear for cropland or rangeland soils. This finding reinforces the fact that interrill and rill processes are greatly different and that different forces and resistances are involved in the detachment processes. Also, the rate of detachment due to the forces involved in rill detachment is not related to the resistant force that must be overcome to initiate the rill detachment process.

Analyses of the data collected have not yet been completed. Preliminary equations relating rill and interrill soil erodibilities and critical hydraulic shear to soil properties have been developed and are being used in preliminary testing of WEPP (*1*). These preliminary equations usually contain terms relating to surface texture, mineralogy, and biological and chemical properties. Additional work is continuing to arrive at the best relationships for predictive purposes. Judgments involved include availability of data and reliability of prediction for data ranges not included in the measured data sets.

Summary

The experimental determination of soil erodibility values for WEPP requires the use of different plot areas, procedures, and measurements than those for determining USLE soil erodibility. A study on rangeland and cropland soils has been conducted over much of the United States to produce the data base needed to estimate soil erodibility for application of WEPP to the nation's soils. Analyses indicate that the soil erodibility values bear little quantitative resemblance to USLE soil erodibility values, but variables important in determining USLE soil erodibility values, such as particle size distribution and organic matter content, may also be important in determining WEPP soil erodibility values.

Extremely high erosion rates may occur in rills, particularly if flow rates are high and slopes are fairly steep. Some of these rates are so high that they should be cause for immediate concern. These rates are realistic on freshly tilled soils, and were observed in the WEPP field studies. They also are supported by field observations of soil removal in rills and ephemeral gullies. This is an illustration of the power for analyzing natural resource problems, particularly those related to soil erosion, and for developing solutions to these problems that will be gained through the use of WEPP. In addition, as surface water quality becomes a greater concern, the use of the WEPP erosion technology to evaluate the chemicals transported in surface runoff will become more important.

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