Quantifying the Performance of Hillslope Erosion Control Best Management Practices

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Abstract

Interest in reducing erosion from disturbed lands has increased in recent years due to the promulgation of the National Pollutant Discharge Elimination System (NPDES) Phase II program. This paper summarizes the results of hillslope erosion testing conducted at the American Excelsior Company's ErosionLab Rainfall Erosion Facility (REF). Soil loss rates were determined for hillslope plots using three different soil types (sand, loam, and clay). The framework within which the data from this study is analyzed and interpreted is based on the Revised Universal Soil Loss Equation (RUSLE).

A primary goal of this research effort is to establish the numerical value of the soil-erodibility factor "K," used in RUSLE, for each of the three soil types. Baseline soil loss rates thus established are then used to quantify the effectiveness of a variety of erosion and sediment control best management practices (BMP's). In particular, surface protection treatments consisting of blown straw and a manufactured biodegradable erosion control blanket were examined.

Tests were conducted at the ErosionLab REF using portable rainfall simulators. The sprinkler-type simulators produce near-uniform rainfall at target intensities of 51, 102, and 152 mm/hr (2, 4, and 6 in/hr) over the test plots. Tests were conducted in accordance with the procedures described in ASTM D-6459, "Standard Test Method for Determination of Erosion Control Blanket (ECB) Performance in Protecting Hillslopes from Rainfall-Induced Erosion."

The Revised Universal Soil Loss Equation (RUSLE) accounts for the erosive energy of rainfall and overland flow runoff using a function of both intensity and depth of rain. The rainfall-runoff erosion tests indicate that the testing protocols achieve reliable and repeatable results for each soil type. The test data also indicate that the RUSLE framework provides a suitable method for the analysis and interpretation of measured soil loss. Data collected for BMPs indicate that some surface cover treatments consistently reduce soil loss while others can actually increase soil loss under certain test conditions.

Introduction

The tests summarized in this paper provide quantitative, performance-based assessments of three types of soil under bare conditions, a biodegradable erosion control blanket called Curlex® I ECB, and pneumatically applied straw as erosion control BMPs for reducing soil erosion caused by rainfall and runoff from hillslopes. Curlex® I ECB will hereafter be referred to as Curlex I and pneumatically applied straw will be called "Blown Straw."

The ErosionLab REF consists of 12 test plots constructed of three soil types (sand, loam, and clay), with four test plots dedicated to each soil type. The test plots consist of an 18-inch thick veneer of test soil overlying compacted onsite native soil. The native soil is Chetek sandy loam, a fine- to medium-grained, noncohesive soil which is well drained and exhibits rapid infiltration rates. Each plot is 8 feet wide by 40 feet long (2.4m by 12.2m), on a slope of 3H:1V (33 percent).

The plots are tested individually with a network of portable rainfall simulators patterned after those developed at Colorado State University (Holland 1969). The design and spacing of the simulator risers achieves near-uniform rainfall distribution over the test plot at target intensities of 2, 4, and 6 in/hr (51, 102, and 152 mm/hr). For the blown straw test program, only 2 and 4 in/hr intensities were used. Water is supplied to the simulators from a nearby pond that is fed by shallow groundwater.

The framework within which the data from this study was analyzed and interpreted is based on the Revised Universal Soil Loss Equation (RUSLE) (USDA-ARS Agricultural Handbook 703). The erosive energy of rainfall and overland flow runoff is a function of both intensity and depth of rain. It is therefore important to use a measure of erosive energy as a baseline for comparing soil loss from hillslope plots during tests at differing intensities, durations, or both. To accomplish this, the rainfall-runoff erosivity factor "R" of the RUSLE method was calculated for each increment of a simulated storm to normalize the variations in actual measured intensity and test duration.

A primary goal of this research effort is to establish the numerical value of the soil-erodibility factor "K," used in RUSLE, for each of the three soil types (Ayres Associates 2000a). Baseline soil loss rates thus established are then used to quantify the effectiveness of a variety of erosion and sediment control best management practices (BMP's). In particular, surface protection treatments consisting of Curlex I (Ayres Associates 2000b) and blown straw (Ayres Associates 2000c) were examined using these test protocols.

Other hydrologic variables of interest are Soil Conservation Service (SCS) curve number (CN) used for computing runoff volume, and the runoff coefficient (C) used in the Rational Method for computing peak discharge. These hydrologic parameters are readily determined from the data collected at the ErosionLab REF.

Test Set-Up and Procedure

ErosionLab personnel prepared the test plots, conducted the tests, and collected the data using the procedures described in ASTM D-6459, "Standard Test Method for Determination of Erosion Control Blanket (ECB) Performance in Protecting Hillslopes from Rainfall-Induced Erosion." Each soil type was tested a minimum of three times to confirm repeatability of test results and to report mean and standard deviation of both calculated and measured variables.

<u>Material Descriptions:</u> 1. Curlex I: Curlex I is a biodegradable erosion control blanket (ECB) made from curled aspen wood fibers, weighing 0.73 pounds per square yard and having a thin, photodegradable polypropylene netting on the upper surface all secured together with 4-inch stitches placed 4 inches apart using 600-denier HT polypropylene thread. The blanket was installed using 1"x6" soil staples spaced according to the manufacturer's specifications. A new roll of product was used on each plot tested. Because the product is supplied in standard rolls 8 feet wide and 80 feet long, no splices down or across the plot were required.

2. Blown Straw: Dry oat straw mulch was applied to each test plot at a target application rate of 2,500 lbs/acre with a FINN model C15 straw blower (approximately 19 pounds per plot). Once applied, the test plots were covered with polyethylene sheets to minimize surface drying or damage from natural rainfall until the tests could be run.

Testing Procedure: Each test typically consisted of applying rainfall for a minimum duration of 20 minutes at each of three target intensities thus simulating a "storm" with intervals of progressively increasing intensity. Blown Straw tests were conducted with only the 2 and 4 in/hr storm increments. The entire amount of runoff and sediment was collected in a large volume stock tank or a PVC collection trough installed at the toe of each plot. During a test, runoff water in the collection tank was decanted and pumped into a portable, graduated polyethylene tank. The saturated sediment from the stock tank (or collection trough) was transferred to five-gallon buckets and weighed. The water content of a representative sample taken from the saturated sediment was determined gravimetrically, and the total dry weight of sediment collected during a test was then determined.

Grab samples of runoff were collected at intervals of approximately 3 minutes. Sampling commenced when runoff started and continued until runoff stopped. Samples were taken from the plot collection apron in 250 ml (8.5 oz) laboratory sample bottles and analyzed for total sediment concentration by the gravimetric method.

Runoff hydrographs were determined by measuring the discharge into the collection tank during blown straw and bare soil control testing was measured by bucket and stopwatch at intervals of approximately 1 minute. During Curlex I testing, the volume in the graduated holding tank was recorded at intervals of approximately 3 minutes. For each test, six rain gauges were placed to obtain representative rainfall depths on the upper, mid, and lower third of the plot. Rainfall intensity for each test is calculated as the average depth collected in the six rain gauges divided by the duration of the test.

Before and after each "storm," the soil surface was photographed. **Figure 1** is a photograph of a clay plot with Blown Straw after the 2 and 4 in/hr storm increments. For comparison, **Figure 2** shows a clay plot after completion of the 2 and 4 in/hr target intensities during bare soil control testing. The photograph is taken at the start of the 20 minute, 6 in/hr target intensity portion of the "storm."

Analysis and Interpretation of Data

The data from plot testing were used to determine relevant parameters typically used in hydrologic analysis and design of erosion and sediment control plans. This evaluation included determination of the parameters used with the RUSLE soil loss prediction method as well as the runoff Curve Number (CN), and the Rational Method runoff coefficient (C) for estimating peak discharge.

Figure 1. Clay plot after 2 and 4 in/hr tests with Blown Straw.

Figure 2. Clay plot after 2 and 4 in/hr tests on bare soil.

RUSLE Factors

Soil Loss "A": One hundred percent of the runoff and sediment produced during a test is collected and weighed. Samples of the wet sediment are weighed, dried, and weighed again to determine the moisture content. The total sediment collected is reported on a dry-weight basis in pounds, and converted to tons per acre based on the area of the test plot.

Rainfall-Runoff Erosivity Factor "R": To normalize the variation in rainfall intensity and duration for each test, the rainfall-runoff erosivity factor "R" was calculated for each increment of the "storm" based on the following equations, as described in Agriculture Handbook 703:

$$R = \sum EI_{30}(10^{-2}) \tag{1}$$

where: R = Rainfall-runoff erosivity
E = Total storm kinetic energy
I_{30} = Maximum 30-min rainfall intensity

and

$$EI_{30} = \left(\sum_{k=1}^{m} e_r \Delta V_r\right) I_{30} \tag{2}$$

where: e_r = Rainfall energy per unit depth of rainfall per unit area ft · tonf · acre^{-1} in, for the rth increment of the storm, and
ΔV_r = Depth of rainfall for the rth increment of the storm hyetograph which is divided into m parts, each with essentially constant rainfall intensity (in)

Unit energy, e, is a function of rainfall intensity and is computed as

$$e_k = 1099\left[1 - 0.72e^{(-1.27i_r)}\right] \tag{3}$$

where

$$i_r = \frac{\Delta V_r}{\Delta t_r} \tag{4}$$

where: Δt_r = Duration of the increment over which rainfall intensity is considered to be constant (h), and
I_r = Rainfall intensity (in/hr)

The maximum 30-minute rainfall intensity, I_{30}, is calculated from the test data by one of the following two methods:

1. Multiply the rainfall intensity times its corresponding duration (usually 20 minutes) divided by 30 minutes, and add the product of the previous test intensity times the amount of additional time needed to equal 30 minutes total duration (e.g., 10 minutes). Following is an example:

Using the information from a test conducted on Curlex I where the largest rainfall intensity is 7.4 in/hr for 20 minutes (0.333 hrs) and the preceding intensity is equal to 4.5 in/hr for 0.333 hrs.

$$I_{30} = \left(7.4 \ \text{in/hr} * \frac{0.333 \ \text{hrs}}{0.5 \ \text{hrs}}\right) + \left(4.5 \ \text{in/hr} * \frac{(0.5 - 0.333) \ \text{hrs}}{0.5 \ \text{hrs}}\right) = 6.4 \ \text{in/hr}$$

2. If the duration of the test is greater than or equal to 30 minutes, the actual measured intensity is used.

Soil Erodibility Factor "K": Bare soil control plots exhibit no cover-management or support practice improvements; therefore, both "C" and "P" of RUSLE are numerically equal to 1.0 by definition. The RUSLE soil-erodibility factor "K" can be determined for each (cumulative) stage of a "storm" based on the corresponding measured amount of erosion "A", as follows:

$$K = \frac{A}{R(LS)CP} = \frac{A}{R(2.78)(1.0)(1.0)} = \frac{A}{2.78R} \tag{5}$$

where: A = Cumulative measured amount of erosion in tons/acre
R = Cumulative rainfall-runoff erosivity factor, calculated as described above

Plotting the measured amount of soil loss "A" in tons/acre as the dependent variable, versus the rainfall-runoff erosivity factor "R" as the independent variable, the slope m of a least-squares regression line fitted through the origin is thus:

$$m = K(LS)CP \tag{6}$$

or, rearranging for K,

$$K = \frac{m}{(LS)CP} = \frac{m}{2.78(1.0)(1.0)} = \frac{m}{2.78} \tag{7}$$

Length-Slope Steepness Factor "LS": For all tests, the slope length and steepness factor (LS) is a constant with a value of 2.78, corresponding to a horizontal slope length of 38 feet (plot length 40 feet) at a 33 percent slope (Agriculture Handbook 703, Table 4-3).

Cover-Management Factor "C": Determining the value of the RUSLE cover-management factor "C" for any surface treatment (e.g., Curlex I or Blown Straw) requires a comparison of soil loss occurring with the treatment in place to that which occurs in the bare, unprotected condition. Establishing paired data sets (bare soil control vs. treatment) is not practicable given the test protocols established by ASTM D-6459 and described in this paper, for reasons of: (1) the physical scale of the tests; (2) equipment requirements; and (3) data collection demands.

Therefore, the method for determining the numerical value of the cover-management factor "C" for a surface treatment uses the least-squares linear regression technique described above in the discussion of the soil-erodibility factor "K," except that equation 6 is rearranged for C as follows:

$$C = \frac{m}{(LS)KP} = \frac{m}{2.78(K)(1.0)} = \frac{m}{2.78K} \quad (8)$$

In this case, the value of the soil erodibility factor "K" is assumed to be independent of the surface treatment, and numerically equal to the value derived from the bare soil control tests. The support practice factor "P" is still equal to 1.0 by definition.

Thus, a regression-based determination of the soil-erodibility factor "K" yields a similarly-derived calculation of the cover-management factor "C," within the framework of the RUSLE, for each of the three soil types used in the bare soil control and Curlex I and Blown Straw test programs.

<u>Support Practice Factor "P":</u> No support practices, such as contour furrowing or slope terracing, were incorporated into any of the test programs. Therefore, the support practice factor P by definition has a numerical value of 1.0 for all tests described in this paper.

Tables 1 and 2 provide the mean and standard deviations for measured soil loss, sediment concentrations, rainfall intensities, and calculated RUSLE parameters for bare soil control (Table 1) and Blown Straw and Curlex I (combined in Table 2).

Table 1. Summary of Erosion, Rainfall-Runoff Erosivity, Soil Erodibility, and Maximum Sediment Concentrations for Bare Soil Tests.

Target Intensity (in/hr)	No. of Tests	Cumulative Soil Loss (tons/acre)		Calculated RUSLE R-Factor[1]		Calculated RUSLE K-factor[2]		Maximum Sediment Concentration (mg/l)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
SAND									
2	5	0.2	0.50	20.5	12.0	0.257	0.304	47,690	106,630
4	3	74.4	25.75	98.8	26.5	0.257	0.065	562,110	491,540
6	3	170.1	51.00	235.4	85.3	0.257	0.047	781,550	58,880
LOAM									
2	3	2.2	0.98	10.6	1.4	0.150	0.098	243,040	87,700
4	3	54.1	17.24	97.5	21.2	0.150	0.061	617,600	86,590
6	3	114.0	15.20	272.1	86.0	0.150	0.040	453,610	75,260
CLAY									
2	3	1.2	0.83	9.7	1.4	0.061	0.038	198,760	101,150
4	3	14.7	6.28	83.0	19.1	0.061	0.052	401,220	194,570
6	3	43.9	13.08	235.4	63.1	0.061	0.042	366,980	107,780

Note: 1) Values for RUSLE "R" factors represent cumulative measured storm amounts.
2) Values of RUSLE "K" factors based on linear regression of cumulative soil loss "A" to rainfall-runoff erosivity factor "R." Standard deviations calculated by normalizing the dependent variable "A" by the parameters "C" and "LS" of the RUSLE soil loss equation for tests at each target intensity.

Figure 3 depicts measured soil loss amounts "A" in tons/acre versus the rainfall-runoff erosivity factor "R" for loam soils. This plot show both bare soil control results and results obtained using Blown Straw and Curlex I, with the associated least-squares regression line for each data set. Soil-erodibility factor "K" and cover-management factor "C" based on the regression analyses are also shown on the plot.

Table 2. Summary of Soil Loss, Rainfall-Runoff Erosivity, Cover-Management Factor, and Maximum Sediment Concentrations for Plots Protected with Blown Straw and Curlex I.

Target Intensity (in/hr)	No. of Tests	Cumulative Soil Loss (tons/acre)		Calculated RUSLE R-factor[1]		Calculated RUSLE C-factor[2]		Maximum Sediment Concentration (mg/l)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
BLOWN STRAW									
SAND									
2	6	0.0	0.00	26.6	14.7	0.003	0.003	0.0	0.0
4	3	0.27	0.48	136.0	16.3	0.003	0.005	15,212	26,348
LOAM									
2	3	0.31	0.05	12.4	3.14	0.810	0.915	36,319	10,736
4	3	30.53	7.69	89.3	16.8	0.810	0.057	438,787	129,220
CLAY									
2	3	1.81	3.14	12.5	2.14	1.0	2.62	243,730	422,153
4	3	34.75	37.34	71.6	15.4	1.0	3.41	414,849	254,270
CURLEX I									
SAND									
2	5	0.0	0.00	46.7	31.0	0.010	0.012	0.0	0.0
4	4	0.67	0.85	209.8	103.4	0.010	0.010	32,944	38,124
6	4	3.55	3.72	437.5	130.7	0.010	0.012	86,194	54,939
LOAM									
2	3	0.0	0.00	38.6	13.0	0.018	0.031	2,117	1,485
4	3	0.69	0.45	127.9	37.3	0.018	0.014	28,422	7,263
6	3	2.29	1.00	277.3	41.7	0.018	0.013	35,883	14,640
CLAY									
2	3	0.0	0.0	11.4	1.2	0.222	0.385	91,305	86,317
4	3	4.84	0.43	77.3	6.4	0.222	0.262	212,701	109,082
6	3	8.85	1.22	250.1	39.7	0.222	0.023	99,681	19,085

Note: 1) Values for RUSLE "R" factors represent cumulative measured storm amounts.
2) Values for RUSLE " C" factors based on linear regression of cumulative soil loss "A" to rainfall-runoff erosivity factor "R." Standard deviations calculated by normalizing the dependent variable "A" by the parameters "K" (assuming "K" factors for each soil type from Table 1) and "LS" of the RUSLE soil loss equation for tests at each target intensity.

As stated previously, grab samples of runoff were collected at 3-minute intervals after runoff started during each "storm" increment. Although the RUSLE does not address the issue of sediment concentration in runoff, valuable information can be obtained from rainfall-runoff testing under controlled conditions regarding concentrations of sediment in runoff. Quantifying this information and comparing results of bare soil tests with tests of erosion-control products and materials will improve the effectiveness of Best Management Practices and their application to earth disturbance activities, reclamation projects, and land management planning.

Figure 4 provides a bar chart showing the maximum measured concentration of sediment in grab samples of for the various storm increments applied to sand, loam, and clay soils. Results from the bare soil control tests and the tests conducted with Blown Straw and Curlex I are presented. No attempt has been made to correlate maximum sediment concentration with any independent variable or variables; rather, the information is presented simply to provide a quantitative comparison of measured results.

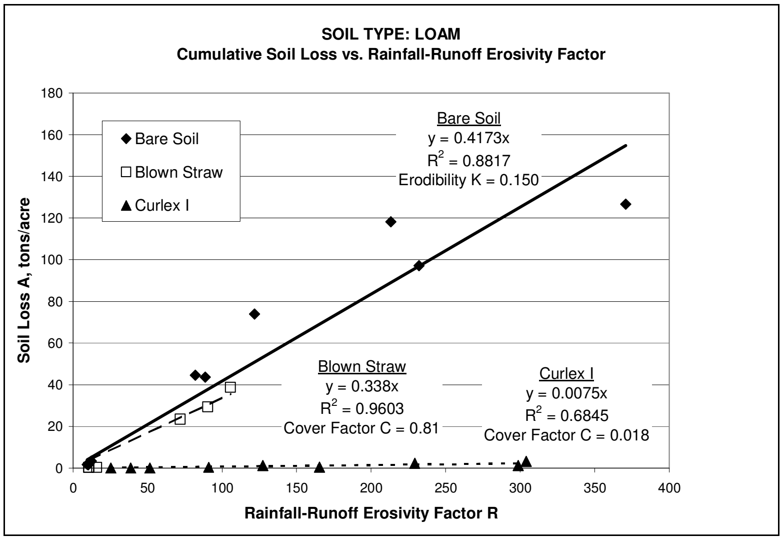

Figure 3. Soil loss "A" vs. rainfall-runoff erosivity factor "R" for loam soil.

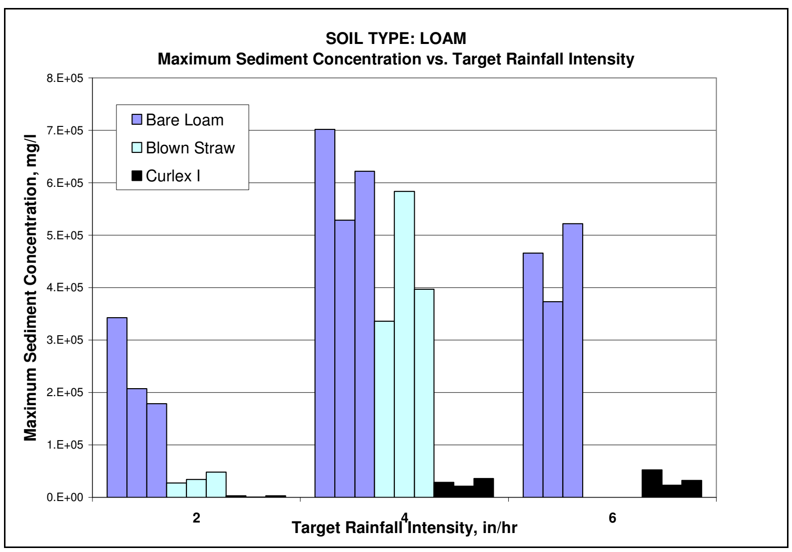

Figure 4. Maximum sediment concentrations in runoff for tests on loam soil.

Conclusions

Based on the results of this testing program, the following conclusions are drawn:

1. The procedures outlined in ASTM D-6459, "Standard Test Method for Determination of Erosion Control Blanket (ECB) Performance in Protecting Hillslopes from Rainfall-Induced Erosion" produce results which we consider repeatable within acceptable limits when applied to bare soil conditions and to soil protected by an erosion-control BMP. A possible exception is the response of the clay soil with blown straw applied which, during several tests, exhibited an episodic pulse in sediment production caused by mass wasting of saturated soils and concentration of overland flow.

2. The concept of a "storm," consisting of sequentially increasing intensities produces soil loss trends consistent with the empirical framework of the Revised Universal Soil Loss Equation (RUSLE). The "storm" concept has also proven to be valid for characterizing the erosion processes associated with a developing rill network on a single-plane hillslope. The test data also indicate that the RUSLE framework provides a suitable method for the analysis and interpretation of measured soil loss.

3. The RUSLE rainfall-runoff erosivity factor R, calculated using intensity and duration data from the test program, are similar to typical R-factors for many parts of the United States. Based on a 10-year event, single-storm R-factors can range from about 10 to 200 (USDA-ARS Agricultural Handbook 703). The cumulative R-value for 4 in/hr tests at the ErosionLab range from 72 to 136, while cumulative 6 in/hr tests typically exceed an R-value of 200.

4. Based on least-squares regression analysis of soil loss vs. rainfall-runoff erosivity, the soil erodibility factor "K" for bare soil was estimated to be 0.257 for sand, 0.150 for loam, and 0.061 for clay (Ayres Associates, 2000b). These values compare well with the mean values derived from calculations performed on data from individual tests which yielded values of 0.268, 0.158, and 0.074 for sand, loam, and clay, respectively (Ayres Associates, 2000a).

5. Curlex I reduced soil loss, runoff volume, discharge rate, and sediment concentration from test plots with all three soil types. Calculated RUSLE "C" factors for sand, loam, and clay were 0.010, 0.018, and 0.222, respectively. The effectiveness of the product appears to be related to four factors: (1) the ability of the product to shield the soil particles from direct raindrop impact and resulting detachment; (2) the direct absorption of water by the wood fibers; (3) the effect of the fiber matrix in slowing overland flow at the soil surface, thus allowing greater opportunity for infiltration; and (4) the ability to delay/reduce the development of rilling, thereby decreasing the delivery of runoff to the toe of the test plots.

6. Blown Straw applied to sand soils substantially reduced soil loss as compared to the bare soil control tests up to the 4 in/hr segment of the "storm." Runoff was produced from only one of the three tests at a target intensity of 4 in/hr. No tests at a target intensity of 6 in/hr were run.

7. Blown Straw applied to loam soils only slightly reduced soil loss as compared to the bare soil control tests, while the testing on clay soil resulted in an apparent increase in soil loss as compared to the bare soil control tests. This apparent increase was due to one test at a target intensity of 4 in/hr where mass wasting of saturated soils caused severe erosion of the plot and a large increase in total runoff volume and runoff discharge rate. Sediment concentrations in runoff were comparable between the blown straw and bare soil control tests. It is believed that the irregularities in straw application and the ability of overland flow to move individual straw fibers caused concentration of overland flow and localized infiltration into the loosely compacted soil, thus initiating rills. During the 4 in/hr test on clay plot 11, a mass failure occurred near the toe of the slope and was collected in the runoff collection tank. Mass failures were also observed during testing on plots 10 and 12, but the pulse of sediment did not reach the collection tank before the test ended.

8. The RUSLE soil loss prediction method does not account for initial abstraction of rainfall or the infiltration capacity of soil. This is most readily apparent in examination of the test data from plots with sand soil, which is highly permeable and well drained. Based on the RUSLE method, a soil with a nonzero erodibility factor "K" should yield sediment and runoff even at very low values of the rainfall-runoff factor "R." The test data indicate that R-values must typically exceed a value of about 20 to 40 to begin generating runoff from bare sand (Ayres Associates, 2000a).

9. Based on least-squares regression analysis of soil loss vs. rainfall-runoff erosivity, the cover-management factor "C" for Blown Straw was estimated to be 0.003 for sand, 0.810 for loam, and 2.6 for clay. The value for clay exceeds the theoretical maximum of 1.0 due to mass wasting and pulses of sediment exhibited by the Blown Straw treatment which were not seen during the bare soil tests.

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