Sediment production under various forest-site conditions

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ABSTRACT   Sediment loss was observed using Coshocton N-1 runoff samplers installed on 0.02 ha plot-watersheds under six forest-site conditions in Texas, USA, during 1980-1981. The soil is a highly erodible Woodtell series of Hapludalfs, supporting a 40 year old forest dominated by loblolly and shortleaf pines. Sediment yields from 19 runoff producing storms over a 9 month period were 0.011, 0.017, 0.156, 0.265, 3.462, and 3.423 t ha^{-1}, respectively, for the undisturbed, thinned (50%), clearcut without site preparation, chopped, KG bladed, and clear cultivated watersheds. Besides storm energy, variation of sediment losses among the treatments was highly related to storm runoff, soil moisture content, cover conditions, and site disturbance. The observed C values of the Universal Soil Loss Equation (USLE) under the various treatments generally fell within the ranges proposed by other investigators. With continued observations and replications on other soils, the USLE can probably provide reasonable estimates of sediment loss in forest land.

INTRODUCTION

Sediment caused by accelerated erosion is by far the largest, and is widely considered one of the most important water pollutants in the United States. This is probably due to the recent findings that sediment delivered to water bodies in the United States, about 4×10^9 t year^{-1}, exceeds sewage load by 500-700 times (Glymph & Carlson, 1966), that sediment is widely responsible for the degradation of the physical, chemical, and biological quality of streams, and that because many chemical and pollutants may be adsorbed on it, sediment has been proposed as a key indicator for water quality conditions (Zison, 1980; Granillo, 1981).

Accelerated sediment production is generally associated with storm runoff, and with agricultural, forestry, mining and construction activities. Because its sources are widespread and often difficult to identify, its occurrence is diffusive and intermittent in nature, and the effective methods of control are through land management practices, accelerated sediment production is commonly attributed to "non-point" sources.

The US Federal Water Pollution Control Act Amendment of 1972 (PL 92-500) requires each state to establish area-wide or state-wide forest practice regulations for control of non-point sources of water

pollution. To develop such regulations, the processes of sediment movement in forested watersheds must be understood, basic data related to soil erosion and sediment produced from forest activities must be collected, and objective methods for estimating these losses must be developed. Unfortunately, knowledge of the effects of forestry operations on soil movement is inadequate for development of sound guidelines. Reported here are some preliminary results of our studies in monitoring soil and water movement caused by forest mechanical clearcutting and site preparation in the southern United States, and testing the applicability of the Universal Soil Loss Equation (USLE), developed primarily for agriculture land, to forest areas.

THE UNIVERSAL SOIL LOSS EQUATION

The Universal Soil Loss Equation (USLE) was developed by the US Department of Agriculture (Wischmeier & Smith, 1978) to estimate sheet and rill erosion from agricultural land under various cultivation activities. The equation estimates the average annual soil loss, A, in $t\ ha^{-1}year^{-1}$ as the product of six variables:

$$A = RKLSCP \tag{1}$$

where the variables are index values reflecting sediment production as modified by:
R   impact energy, frequency and intensity of rainfall,
K   erodibility of soil,
L   length factor of slopes,
S   steepness factor of slopes,
C   cover and cropping management, and
P   conservation practices.
   Forest cover, because of its unique features of canopy, litter layer and root system, is much more effective in protecting soil from loss by water erosion than most agricultural crops. Quantitative effects of various forest conditions on soil movement have not been widely studies and the application of the USLE in forest areas depends on C values derived from analogical consideration (Wischmeier, 1975), or from empirical judgement (Dissmeyer & Stump, 1978). Validity of published C values for forested areas must be determined from observed field data.

METHODS AND PROCEDURES

Study area

The study was conducted at a central location in forested East Texas, about 30 km southeast of Nacogdoches, and 230 km northeast of Houston. The area has a humid subtropical climate with prevailing winds from south and southeast. Winter storms are dominated by frontal systems, while convective storms of short duration, high intensity, low frequency, and afternoon occurrence are most common during the summer. The mean annual precipitation and temperature

(1941-1970) at Nacogdoches are 1207 mm and 18.7°C, respectively.

Physiographically, the area is in the Coastal Plains regions with sediments of Tertiary age deposited by marine and fluvial processes in the ancestral Gulf of Mexico. The soil of the study site is gravelly fine sandy loam of the Woodtell series, a member of the fine, montmorillonitic, thermic family of Vertic Hapludalfs with slopes ranging from 6 to 11% and supporting a 40 year old forest dominated by loblolly (*Pinus taeda*) and shortleaf (*P. echinata*) pines with scattered hardwoods.

Study design

A plot-watershed approach, based on the design used by the USDA in developing the USLE, was employed in this study to monitor soil and water losses under various forest conditions. Originally, the study was planned with six treatments replicated three times with each replicate located on a typical soil type in forested East Texas. However, budget constraints limited the study to one soil type (no site replicates). The six treatments, including the most common methods of timber harvesting and site preparation in the south, are:

(a) undisturbed forest with full crown closure,
(b) thinned forest, 50% of its original crown density,
(c) clearcut, merchantable timber removed, no site preparation,
(d) clearcut and roller chopped,
(e) clearcut, sheared, root raked and slash piled in windrows,
(f) clearcut, clear tilled, continuous fallow, cultivated up and down hill.

A surface plot (9.14 m wide x 22.13 m long) along with a subsurface plot (2.44 m wide x 3.66 m long) are centrally located in each of the treatments to monitor soil movement and surface and subsurface runoff, respectively.

Watershed instrumentation

Each surface plot is bounded by a plywood barrier 15 cm deep with half of its depth above and half below the soil surface. At the lower end of each plot an apron was installed to direct all soil and surface water leaving the plot into an approach section, and a 15.4 cm high H-flume, with a stilling well equipped with an automatic water level recorder. A Coshocton N-1 runoff sampler diverts about 1% of the water flowing from the H-flume into a storage tank as a sample of runoff and sediment. The storage tank capacity is large enough to accommodate runoff produced from 50 year 48 h storms (Parsons, 1954; Chang, 1981). Within each plot, three access tubes were also installed in the soil to a depth of 121 cm for soil moisture measurement. Throughfall on the undisturbed, thinned, and cleared without site preparation treatments was observed with five 5.08 mm improvised PVC raingauges on each plot.

The subsurface plot was a block bounded by a concrete barrier about 8 cm thick and extending to a depth of 38 cm. Outside the barrier was a trench designed to divert surface and subsurface runoff from the surrounding area. At the lower end of each plot a runoff collector was inserted into the soil profile. The upper lip of the collector was about 7.5 cm below the surface, and the lower

lip was at a depth (38 cm) well below the upper boundary of the B
horizon. Eleven per cent of the water from each collector was
diverted by a splitter and drained into a storage tank.

A climate station, equipped with one recording and one standard
non-recording raingauge, two 5.08 cm PVC improvised raingauges, and
one thermohygrograph housed in a weather shelter, was also installed
in the northwest corner of the study site.

Treatments and data collection

The treatments were applied during the summer and fall of 1979, and
site preparation was completed on 10 September 1979. Chopping was
done with a 1.83 m diameter roller chopper pulled up and down the
slope so that the blades made furrows perpendicular to the slope.
The shearing was done with a KG blade and the debris was piled
in a windrow by pushing up slope with a root rake. Cultivation
was performed on 18 October 1979 with a heavy disk harrow pulled
behind a crawler tractor. Additional cultivation was done in
November 1979, and in May and November 1980, with a garden
tiller.

Data collection began on 28 May 1980 and continued until
27 February 1981. Volumes of surface and subsurface runoff were
measured directly in the storage tanks after each storm, and were
later checked against storm hydrographs recorded on the water level
recorder charts. Samples of surface runoff water along with total
deposited sediment were also collected at the end of each storm for
laboratory analyses.

Soil moisture data were measured three times per week at four
different depths from the surface (i.e. 0.15, 0.45, 0.75, and 1.05 m)
in the inserted access tubes using a CPN #503 Hydroprobe, a neutron
moderation instrument. Because of abundant organic matter and roots
in forest soils, the curve (instrument readings *vs.* moisture content)
supplied by Campbell Pacific Nuclear, Inc. was recalibrated by the
gravimetric method and expressed by the following equation for the
undisturbed and thinned treatments:

$$\theta = -0.0466 + 0.32\ R_a \tag{2}$$

where θ is the soil moisture content in g cm^{-3}, and R_a is the ratio
between field count and the standard count. For the other four
treatments the equation was:

$$\theta = -0.1494 + 0.32\ R_a \tag{3}$$

The throughfall gauges were randomly re-located after every
fifth storm. Observations of temperature, humidity, rainfall, and
water level on the H-flume were made from recorder charts once
a week. The rating table to convert water level in the H-flume
into flow rate is available from the US Department of Agriculture
(1979).

Soil texture, organic matter content, bulk density, moisture
content at 1/3 and 15 bars, and per cent slope were also obtained
for each of the six treatment plots.

Sediment analysis

Sediment produced from each storm is the sum of deposited and
suspended soil particles transported from each plot. Thus, all soil
particles deposited in the apron, approach, and H-flume sections
were collected at the end of the each storm and oven-dried at 105°C
for 48 h to obtain their net weights. The surface water in the
storage tanks was agitated thoroughly prior to sample collection.
Sediment suspended in the water was determined gravimetrically using
the procedure described in the Standard Methods by the American
Public Health Association. The sediment concentration thus
obtained (mg l^{-1}) was applied to total storm runoff volume to
estimate total suspended sediment in kg from each plot. Finally,
the suspended sediment was added to the deposited sediment to
compute total sediment (kg ha^{-1}) for each storm.

RESULTS AND DISCUSSION

Preliminary analysis of data collected during the 9 month period
seems to support the hypothesis that different intensities of cutting
and mechanical site preparation cause significant differences in soil
moisture content, runoff, and sediment production in the study area.

Soil moisture

In general, soil moisture content increased with soil depth and with
reduced vegetative cover. The average soil moisture contents of the
four depths during the study period (117 measurements made at two
to three day intervals) were 0.285, 0.367, 0.361, 0.433, 0.424, and
0.489 g cm^{-3} for the undisturbed, thinned, clearcut without site
preparation, chopped, KG bladed, and cultivated plots, respectively
(Fig.1). Thus, the cultivated plot contained about 20% more water
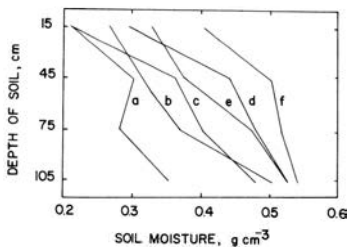than the undisturbed forest plot.

FIG.1   *Average soil moisture contents for six forest-
site conditions (see Fig.2) near Nacogdoches, Texas,
28 May-27 February 1981.*

    Soil moisture content differed most among the six treatments at
the top level (0-30 cm). This is obviously due to the greater root
concentration and the direct exposure of soil to the air. The
average values of the 117 measurements in this layer were, in the
same order, 0.207, 0.266, 0.207, 0.290, 0.325, and 0.402 g cm^{-3}.

Simple Student's t tests showed that all values differed significantly at alpha levels less than 0.01, except those for undisturbed forest and commercial cutting without site preparation.

The data further showed that the soil moisture depletion rate was generally greater for greater forest cover and for greater antecedent moisture content. As the soil became drier, the moisture content was exponentially reduced, and finally approached a constant level at about the wilting point. The trend can be expressed by the following equation:

$$\Delta S_t = S_O \, e^{-bt} \tag{4}$$

where S_O is the initial soil moisture content in mm, ΔS_t is the moisture content t days later, and b is the depletion coefficient. Equation (4) fits the observed average soil moisture content of the upper 1.2 m with r^2 (coefficient of determination) values ranging from 0.993 (undisturbed forest) to 0.729 (cultivated plot). The b values were 0.0109, 0.0092, 0.0098, 0.0068, 0.0070, and 0.0050 for the undisturbed, thinned, clearcut without site preparation, chopped, KG bladed, and cultivated plots, respectively. The calculated coefficient for undisturbed forest is broadly comparable to those derived by Zinke (1975) from published data for loblolly pine (0.0072) and shortleaf pine (0.0129) stands.

Although the average soil moisture content of the chopped plot was a little lower than the KG plot in the top 30 cm level, it became greater at the next three deeper layers and consequently little greater for the overall average (0.433 *vs.* 0.424 g cm^{-3}). The depletion rate was also smaller for the chopped plot, although the difference was small (0.0068 *vs.* 0.0070). This is probably due to the greater slope of the KG plot (8% *vs.* 11%) and the numerous furrows perpendicular to the slope made by the chopper. No comparable rates are available in the literature for the site preparation treatments.

Runoff

Thirty storms occurred during the study period, 19 of which produced surface or subsurface runoff. The storms ranged from 0.5 to 48.4 mm in size with maximum duration of 32 h and maximum 30 min intensity of 69.6 mm h^{-1}. Total surface plus subsurface runoff of the 19 events ranged from 7.4 mm for the undisturbed plot to 137.3 mm for the KG plot (Table 1). Clearcutting alone produced surface runoff 5.3 times greater than that from the undisturbed plot. Additional mechanical site preparation raised the ratio to 10.7 times for the chopped plot and 20.9 times for the KG plot.

Total runoff from the KG bladed plot was almost twice that from the chopped plot, in part due to steeper slopes (11% *vs.* 8%) but probably in greater part to compacted B-horizon surfaces exposed by blading. In contrast, the numerous furrows perpendicular to the slope left by chopping may have increased detention storage and infiltration, consequently reducing runoff. The cultivated plot produced less surface and total runoff than the KG bladed plot, probably because of its loose and friable soil surface created by periodic tillage. Multiple comparisons among treatment means,

TABLE 1   Total net rainfall, runoff and soil loss from 30 storms between 28 May 1980 and 27 February 1981 in Nacogdoches, Texas

Treatment	Net rainfall (mm)	Runoff (mm)			Soil loss (kg ha^{-1})		
		SUR	SUB	Total	SUS	DEP	Total
Undisturbed forest	359.6	6.4	1.0	7.4	4.2	6.5	10.7
Thinned forest	377.8	7.2	9.8	17.0	11.6	5.5	17.1
Clearcut without site preparation	430.4	34.2	7.5	41.7	42.5	113.3	155.8
Clearcut chopped	459.4	68.3	13.1	81.4	75.8	189.2	265.0
Clearcut KG bladed	459.4	133.5	3.8	137.3	2201.6	1260.0	3461.6
Clearcut cultivated	459.4	97.9	21.1	119.0	1009.4	2414.0	3423.4

NOTE: SUR, surface; SUB, subsurface; SUS, suspended; DEP, deposited.

however, showed that differences between the KG bladed and the cultivated plots were not significant, neither were the differences between the means of undisturbed and thinned plots or those between clearcut with no site preparation and chopped plots.

Of the storm and soil characteristics tested, net storm rainfall had the most important effect on total direct runoff (surface and subsurface) of the six treatments. Fig.2 is a plot of the relationships with r^2 values ranging from 0.76 for the thinned and KG plots to 0.34 for the undisturbed plot. In general estimates of runoff produced from smaller storms are better than those from greater storms, for which the errors may exceed 100%. In general, runoff was greater for treatments that resulted in greater
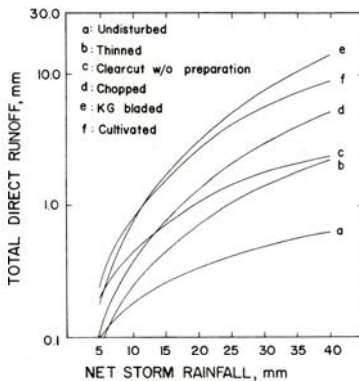

FIG.2   Total direct runoff as a function of net storm rainfall for six forest-site conditions.

disturbance of surface cover.

Antecedent soil moisture condition was slightly correlated with direct runoff, but its inclusion in the prediction equation developed through stepwise multiple regression analyses improved prediction only slightly.

Sediment production

Total sediment production (soil loss) during the study period ranged from about 10 kg ha^{-1} for the undisturbed plot to over 3.4×10^3 kg ha^{-1} for the KG bladed and cultivated plots (Table 1). Statistical analyses of the mean amounts of sediment produced from each storm showed no significant differences between undisturbed and thinned plots and between KG bladed and cultivation. Commercial clearcutting without site preparation, produced much more sediment than thinning. Clearcutting followed by chopping produced significantly more sediment than the commercial clearcutting alone, but significantly less than that from clearcutting followed by KG-blading or continuous cultivation.

Sediment production among the six treatments followed closely the variation of soil moisture content and surface runoff. Treatments most severely depleting tree and ground cover and exposing mineral soil produced the most sediment. Compared to the undisturbed forest, thinning, clearcutting, chopping, KG blading, and cultivation activities increased sediment production by 2, 14, 25, 323, and 320 times, respectively. Sediment production also increased moderately with increases in antecedent soil moisture, due probably to more limited storage capacity with consequently greater runoff. The very heavy sediment increase from KG blading, as compared with roller chopping, appears to result mainly from removal of forest floor organic matter and exposure of more compact, impermeable soil. The chopper, run up and down the slope, creates multiple cross-slope depressions providing temporary storage of rainwater which add to infiltration opportunity. The annual sediment production from US southern forests has been reported to range from trace to 0.18×10^3, trace to 0.13×10^3, 0.13×10^3 - 0.38, and 12.54×10^3 - 14.25 $\times$ 10^3 kg ha^{-1} for undisturbed, thinned, carefully clearcut, and mechanical site preparation, respectively (Yoho, 1980). Since the period of observation covered by this report is too short for estimation of annual sediment production, no comparison was made with those collected in other studies.

Values for the C factor in the USLE

There has been some reluctance to apply the USLE to forest land because of its canopy and forest floor characteristics. These characteristics may uniquely affect a number of erosion processes through differences in organic matter content, mulch and duff cover, biological activity, rainfall impact, infiltration, water storage, and related effects. Some have questioned whether so complex a set of relationships can be adequately expressed in values for a single factor, such as C in the USLE. Although a few C values have been proposed for several forest conditions, they have not been justified through field observations.

The C value in the USLE can be obtained by the following equation, if data on sediment loss A along with the other variables for any particular forest condition are available:

$$C = A/RKLSP \qquad\qquad (5)$$

Using the total sediment collected during the nine month period and inserting appropriate values for RKLS and P in equation (5), the observed C values for each of the six forest conditions are given in Table 2. The observed C values range from 0.000 14 for the undisturbed forest to about 0.10 for the cultivated plot, increasing with decreasing canopy, litter, and residual stand values. Thus the C values for KG blading (0.0242) reflects a 750% increase in sediment production over that for chopping (0.003 25).

TABLE 2   *Observed and previously proposed C values for USLE computations*

Source	Treatment*:					
	a	b	c	d	e	f
Observed	0.00014	0.00019	0.00165	0.00325	0.02420	0.09702
Dissmeyer &	0.0001–		0.0003–	0.001–	0.004–	0.023–
Stump (1978)	0.0034	–	0.010	0.022	0.028	0.068
Wischmeier &	0.0001–	0.002–	0.003–			0.11–
Smith (1978)	0.001	0.004	0.009	0.03	–	0.17

* *See Fig.2.*

The observed C values generally fell within the ranges proposed by Wischmeier & Smith (1978) and by Dissmeyer & Stump (1978) through analogical considerations and empirical judgement. The C values obtained from the field data along with the USLE were further employed to estimate the observed sediment losses from each single storm and for each treatment. Results showed that the estimated values were not significantly different from the observed means at an alpha level of 0.065 or less. It suggests that, with additional data to evaluate C values, reasonable estimates of sediment loss from forest land of various conditions may be obtained by use of the USLE.

CONCLUSIONS

Total soil moisture content, moisture depletion rate, direct runoff and sediment production increase with decreasing forest canopy, litter, and slash coverages and with increasing site disturbance. For the six treatments, the ascending order is undisturbed forest, thinning, clearcutting, clearcutting and site preparations, and cultivation. Because it retains most organic matter *in situ* and leaves numerous furrows perpendicular to the slope, chopping

prepares sites for regeneration with much less sediment loss than KG blading.

The observed C values for the USLE derived from this study are compatible with those proposed by other investigators through analogical considerations. Continued observations over several years, and replication on other soils and topography will be needed to fully evaluate the application of the USLE to estimation of sediment loss from forest land.

REFERENCES

Chang, M. (1981) Characteristic hourly rainfall at Nacogdoches, Texas. *Texas J. Sci.* (in press).

Dissmeyer, G.E. & Stump, R.F. (1978) Predicting erosion rates for forest management activities and conditions sample in the Southeast. USDA, For. Service Southeastern Area State and Private.

Glymph, L.M. & Carlson, C.M. (1966) Cleaning up our rivers and lakes. *Am. Soc. Agric. Engrs* Paper no. 66-74.

Granillo, A.B. (1981) Studies of water quality in small forested streams of East Texas. MSF Thesis, Stephen F. Austin Univ., Nacogdoches, Texas, USA.

Parson, D.A. (1954) Coshocton type runoff samplers, laboratory investigations. *USDA SCS-TP-124*.

US Dept. of Agriculture (1979) Field manual for research in agricultural hydrology. *USDA Agric. Handbook* no. 224.

Wischmeier, W.H. (1975) Estimating the soil loss equations cover and management factor for undisturbed areas. In: *Present and Prospective Technology for Predicting Sediment Yields Sources* (Proc. Sediment-Yield Workshop, November 1972), 118-124, *USDA ARS-S-40*.

Wischmeier, W.H. & Smith, D.D. (1978) Predicting rainfall erosion losses - a guide to conservation planning. *USDA Agric. Handbook* no. 537.

Yoho, N.S. (1980) Forest Management and sediment production in the south - a review. *Southern J. Appl. For.* 4, 27-36.

Zinke, P.F. (1975) The depletion of soil moisture storage in forest soils. In: *Forest Soils and Forest Land Management* (Proc. 4th Am. For. Soils Conf., August 1973), 27-36.

Zison, S.W. (1980) Sediment-pollution relationships in runoff from selected agricultural, suburban urban watersheds. *Environ. Res. Lab, US EPA-600/3-80-022*, Athens, Georgia, USA.