Depth of Surface Soil-runoff Interaction as Affected by Rainfall, Soil Slope, and Management[1]

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ABSTRACT

The effective depth of interaction (EDI) between surface soil and runoff (the thickness of surface soil in which the degree of interaction is equal to that at the soil surface) was determined for five soils of varying physical and chemical properties under simulated rainfall, in order to quantify the effect of rainfall and soil characteristics on EDI. For all soils EDI increased (1.30–37.43 mm) with an increase in rainfall intensity (50–160 mm h^{-1}) and soil slope (2–20%), although the magnitude differed between soils. The effect of rainfall intensity was attributed to increased runoff energy enhancing mixing in the surface soil and was also a function of soil aggregation. The magnitude of the EDI increase with increasing soil slope was independent of soil type being a function of runoff energy alone. An avg 73% reduction in EDI following the incorporation of 100 kg wheat straw (*Triticum aestivum* L. sp.) ha^{-1} and 80% reduction with a 0.5-mm^2 mesh screen, simulating crop cover, was obtained compared to the control (3.36 mm). For all soils the logarithm (ln) of soil loss was linearly related to the ln EDI. This is to be expected since factors affecting EDI (rainfall intensity, runoff energy, and soil aggregation) also influence soil loss. Regression slope of the logarithmic relationship was similar (at the 5.0% level) for all soils, and regression intercept was related to soil aggregation. Thus, EDI and the effect of rainfall and soil management can be estimated from soil loss. This relationship will improve the prediction of adsorbed chemical (P and pesticides) transport in solution, since chemical transport models presently use a fixed EDI value.

Additional Index Words: **adsorbed chemicals, eutrophication, pesticides, dissolved P, water quality modeling.**

Sharpley, A.N. 1985. Depth of surface soil-runoff interaction as affected by rainfall, soil slope, and management. Soil Sci. Soc. Am. J. 49:1010–1015.

PHOSPHORUS (P) and other adsorbed chemicals, such as pesticides, are released from a thin layer of surface soil that interacts with rainfall and runoff. In chemical transport models, the thickness of the interaction zone is determined by model calibration with experimental data, with depths ranging between 2.0 and 6.0 mm (Donigian et al., 1977), or is fixed at 10 mm, assuming that only a fraction of the chemical present in this depth interacts with rainfall water (Frere et al., 1980).

Recent studies placing ^{32}P as a tracer at several soil depths, have shown that the degree of interaction between soil and rainfall-runoff water was maximum at the surface, and decreased very rapidly with depth (Ahuja et al., 1981). In addition, Ingram and Woolhiser (1980), using $CaSO_4$ in soil boxes under simulated rainfall showed that the mixing zone depth was influenced by slope, rainfall intensity, and runoff energy. Thus, the zone of uniform interaction assumed by Donigian et al. (1977) and Frere et al. (1980) is not realistic. For practical purposes, however, Ahuja et al. (1981) proposed an effective depth of interaction (EDI), defined as the thickness of surface soil in which the degree of interaction is equal to that at the soil surface. In an associated study, Sharpley et al. (1981) calculated EDI using the following model describing the kinetics of soil P desorption by runoff water;

$$P_r = (K\, P_o\, \mathrm{EDI}\, D_b\, t^{\alpha}\, W^{\beta})/V \qquad [1]$$

where P_r is the average dissolved reactive P concentration of runoff (μg L^{-1}), P_o the Bray I P content (mg kg^{-1}) of surface soil (0–10 mm), D_b the bulk density of soil (Mg m^{-3}), t the mean residence (or contact) time of runoff water on the soil box during the rainfall (min), W the water/soil ratio during rainfall (cm^3 g^{-1}), V the runoff volume per unit area during the event (mm cm^2), and K, α, and β constants for a given soil.

The EDI's determined by both the physical (Ahuja et al., 1981) and chemical (Sharpley et al., 1981) methods agreed closely for Bernow (Glossic Paleudalfs) (2.1 and 2.2 mm, respectively) and Houston Black soils (Udic Pellusterts) (2.4 and 1.8 mm, respectively) under a 30-min rainfall of 60 mm h^{-1} and 4% soil slope. This agreement substantiates the use of the chemical method to investigate the effects of certain soil and experimental variables on EDI. These studies found that EDI increased with an increase in rainfall intensity and soil slope, concluding that as rainfall and runoff energy increased, EDI increased. For example, Sharpley et al. (1981) calculated an increase in EDI from 2.21 to 6.02 mm when rainfall intensity and soil slope were increased from 60 to 120 mm h^{-1} and 4 to 8%, respectively.

Ahuja et al. (1982) presented a conceptual model for the dependence of EDI on rainfall energy, soil slope, slope length, and runoff rate, which is analogous to a physical soil erosion mechanism. Their experimental data on the effect of these variables on P concentration in runoff were in agreement with the terms in the model. Further experimental measurements are needed, however, to determine the constants in this model and test their generality or relationship to some easily measured soil properties. Since a constant EDI is presently used in chemical transport models, inclusion of relationships describing EDI variability will improve model versatility and prediction.

This paper reports an investigation of the effect of rainfall intensity, soil slope, crop residue incorporation, and crop cover on EDI for several soils under simulated rainfall.

MATERIALS AND METHODS

Surface soil (0–100 mm) samples of Durant loam (Vertic Argiustolls), Houston Black clay (Udic Pellusterts), Kirkland silt loam (Udertic Paleustolls), Pullman clay loam (Torrertic Paleustolls), and Ruston fine sandy loam (Typic Paleudults) were collected from Oklahoma and north Texas locations. Air-dried and sieved (2 mm) soil was packed in impermeable-bottomed boxes (1-m long, 0.3-m wide, and 0.15-m

[1] Contribution of the Agronomy Dep., Oklahoma State Univ., Stillwater, Oklahoma in cooperation with USDA-ARS, Durant, OK. Published with the approval of the Director, Okla. Agric. Expt. Stn as Journal no. 4634. Received 19 Nov. 1984. Approved 15 Feb. 1985.

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deep), with 95 mg P kg soil^{-1} added as K_2HPO_4 to a 40-mm depth during packing (equivalent to surface applications of 50 kg P ha^{-1}). The soils were slowly wetted by a drip system to saturation, with a 3-d period allowed before application of rain by a capillary-tube-type rainfall simulator (Munn and Huntington, 1976). Rainfall was applied for 30 min at intensities of 50, 70, 90, 110, and 160 mm h^{-1} to soil at 2, 4, 6, 8, 12, and 20% slopes. Wheat straw (*Triticum aestivum* L. sp.) was ground (2 mm) and mixed with Durant, Houston Black, and Ruston soil at rates of 0.4, 1.0, 2.0, 3.0, and 4.0 g straw kg soil^{-1} (equivalent to incorporations of 0.5, 1.25, 2.5, 3.75, and 5.0 Mg ha^{-1} to a depth of 150 mm). The wheat straw–soil mixture was brought to field capacity with water and rewet when dry. At the end of a 182-d incubation period at 25 ±2°C, wheat straw-soil mixture was packed in runoff boxes and prewetted to saturation before rainfall application at several intensities and soil slopes. Screens of 0.5-, 1.0-, 4.0-, and 9.0-mm^2 mesh were placed 50-mm above and parallel to the soil surface and rainfall applied at several intensities and soil slopes. It is suggested that these screens, by intercepting varying amounts of rainfall, will simulate varying degrees of rainfall energy reduction by vegetative soil cover (Ahuja et al., 1982).

Surface runoff samples (50 mL) were collected at the initiation of runoff, and subsequently once every 5 min for determination of reactive P concentration by the colorimetric method of Murphy and Riley (1962). Sample analysis was initiated within 10 min of collection, by centrifugation (266 km s^{-1}) to facilitate filtration (0.45 μm). The Bray I extractable P content of a soil sample (0–10 mm) taken from each box immediately before a rainfall, was determined by shaking 2-g soil in 20 mL of 0.03 *M* NH_4F and 0.025 *M* HCl for 5 min (Bray and Kurtz, 1945). Sediment concentration of runoff was measured as the difference in weights of duplicate 250-mL aliquots of unfiltered and filtered samples after evaporation to dryness.

The particle-size distribution was determined by pipette analysis (Day, 1965), following dispersion of the samples with sodium hexametaphosphate. Undispersed samples were analyzed after shaking with water on an end-over-end shaker for 15 min. The degree of soil aggregation is represented by the ratio of the proportions of clay-sized material (< 2 μm) in dispersed and undispersed soil.

Values of the constants K, α, and β of Eq. [1] were calculated from the ratio of percent clay/organic C content of each soil (Sharpley, 1983).

RESULTS AND DISCUSSION

Physical and chemical properties of the soils used varied widely (Table 1). For each soil and rainfall-runoff event, EDI was calculated using Eq. [1]. The mean flow weighted soluble reactive P concentration of runoff, P_r, was calculated from samplings during each event, storm duration, t, was 30 min, and constants K, α, and β used for each soil are presented in Table 1. The value of W for each runoff event was determined as the ratio of runoff volume (V) and mass of interacting soil (ie. EDI $\cdot$ D_b). The mean residence time of runoff water on the soil box during each rainfall was determined as the time from the start of rainfall to runoff initiation. All treatments were duplicated and the following results are average values.

Rainfall Intensity and Soil Slope

The effective depth of interaction between surface soil and runoff increased linearly with an increase in rainfall intensity at each soil slope used (Fig. 1 and 2). At a given rainfall intensity, however, EDI increased exponentially with increasing soil slope (Fig. 1 and 2). Houston Black and Ruston are given as examples since they represent the minimum and maximum EDIs obtained at each rainfall intensity and soil slope (summarized in Table 2). Similar relationships between EDI and rainfall intensity and soil slope were also obtained for Durant, Kirkland, and Pullman soils (data not presented).

The observed increase in EDI with increasing rainfall intensity and soil slope, results from more turbulent mixing in the zone of interaction. However, a positive interaction between rainfall intensity and soil slope was observed (Fig. 1 and 2). For example, EDI at 160 mm h^{-1} rainfall intensity and 2% slope plus 50 mm h^{-1} intensity and 20% slope (8.49 and 27.17 mm for Houston Black and Ruston, respectively) was less than the EDI at a 160 mm h^{-1} intensity and 20% slope (13.34 and 37.43 mm for Houston Black and Ruston, respectively).

Regression slopes of the linear relationship between rainfall intensity and EDI (representing the relative effect of increasing rainfall intensity on EDI) (summarized in Table 3) were significantly related (at the 5% level) to the degree of soil aggregation at each soil slope used (R^2 of 0.76, 0.80, 0.85, 0.90, 0.75, and 0.82 for 2, 4, 6, 8, 12, and 20% slopes, respectively). Thus, the relative increase in EDI with increasing rainfall intensity is greater in well aggregated compared to poorly aggregated soils. In addition, regression slope for each soil increased with an increase in soil slope (Table 3). The magnitude of this increase in regression slope was significantly related (at the 5% level) to soil aggregation (R^2 = 0.73). Consequently, the increased effect of rainfall intensity on EDI with increasing soil slope was also a function of soil aggregation. Regression slopes of the linear relationship between soil slope and logarithm EDI (representing the effect of increasing soil slope on EDI) (summarized in Table 3), were similar for all soils at each rainfall intensity, except for Houston Black (significant at the 5% level as de-

Table 1. Physical and chemical properties of the soils used.

Soil	Clay	pH	Organic C	Total P	Bray P	Degree of aggregation†	Kinetic constants K	α	β
	dg kg^{-1}		g kg^{-1}	mg kg^{-1}	mg kg^{-1}				
Durant l	19(1)‡	7.1	5.2	234	6	19	0.029	0.094	0.794
Houston Black c	50(5)	7.9	22.1	481	10	10	0.071	0.151	0.541
Kirkland sil	13(0.5)	6.0	20.2	303	8	26	0.061	0.319	0.240
Pullman cl	30(2)	6.8	8.3	636	25	15	0.075	0.105	0.702
Ruston (fsl)	10(0.5)	5.6	14.1	327	46	20	0.035	0.195	0.304

† Degree of soil aggregation is the ratio of clay content in dispersed and undispersed soil.
‡ Figures in parenthesis are for undispersed soil.

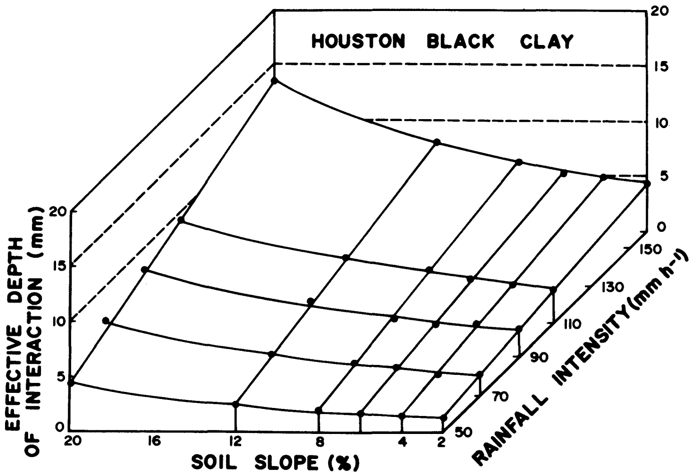

Fig. 1. Effective depth of interaction between surface soil and runoff from Houston Black clay as a function of soil slope and rainfall intensity.

termined by analysis of covariance). Thus, the magnitude of the EDI increase with increasing soil slope was a function of runoff energy rather than soil type, in contrast to the effect of rainfall intensity on EDI.

There are two physical processes involved in the development and maintenance of EDI during a runoff event, raindrop impact on the soil surface initiating turbulent mixing of water in a thin surface zone and energy of runoff as it moves downslope. As the extent of raindrop impact increases with increasing rainfall intensity, the initial formation of EDI will be a function of the degree of soil aggregation. The greater stability of soil structure in well aggregated soils compared to poorly aggregated soils will allow a greater EDI. In poorly aggregated soils the development of a surface seal during raindrop impact and runoff will restrict EDI.

Crop Residue

As the amount of wheat straw incorporated in the surface soil increased, a decrease in EDI was measured (Fig. 3). This decrease was apparent over a range in rainfall intensity, soil slope, and soil type with Houston Black, Durant, and Ruston presented as examples of fine, medium, and coarse textured soils. However, the reduction in EDI with wheat straw incorporation was greater at lower runoff energies. For example, incorporation of 5.0 Mg straw ha^{-1} reduced EDI 86, 82, and 84% for Durant, Houston Black, and Ruston, respectively, compared to no straw at a 50 mm h^{-1} rainfall intensity and 2% soil slope. In comparison, only a 43, 41, and 44% reduction in EDI was obtained at the 160 mm h^{-1} rainfall intensity and 20% soil slope for Durant, Houston Black, and Ruston, respectively. It is apparent, however, that wheat straw incorporation can result in a large reduction in EDI and, thus, affect the transport of P in runoff. Although the magnitude of this effect will differ from that in the field, due to less uniform residue size and incorporation, the same principles should hold.

Table 2. Depth of surface soil-runoff interaction at several rainfall intensities and soil slopes.

Rainfall intensity	Soil slope	Depth of interaction: Durant	Houston Black	Kirkland	Pullman	Ruston
mm h^{-1}	%	mm				
50	4	2.94	1.50	3.27	2.16	3.54
	8	4.19	2.02	4.41	3.13	5.09
	20	15.31	4.46	17.33	13.21	20.61
90	4	4.20	2.86	5.66	3.69	5.13
	8	6.36	3.34	7.00	5.36	7.61
	20	19.44	7.66	23.87	16.73	25.41
160	4	6.93	4.68	8.75	5.83	8.51
	8	10.41	6.52	12.11	8.47	12.83
	20	28.28	13.34	33.74	23.86	37.43

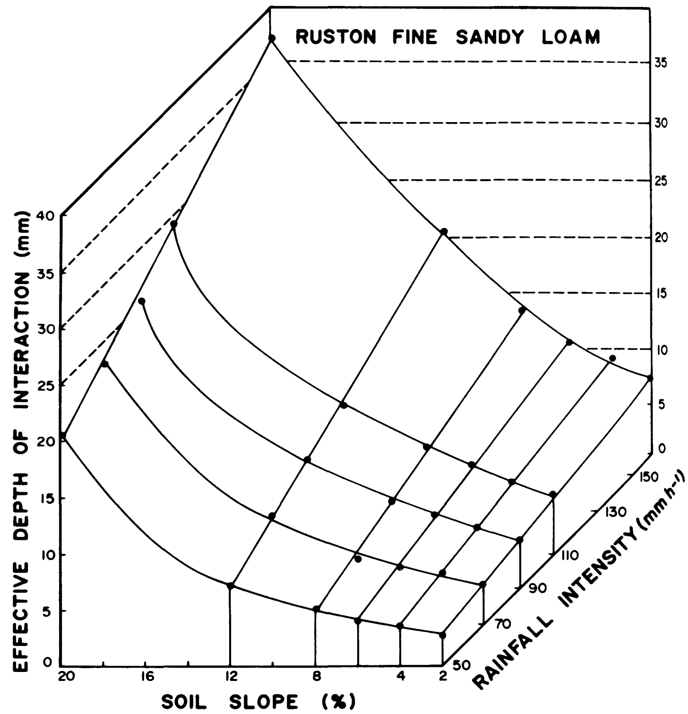

Fig. 2. Effective depth of interaction between surface soil and runoff from Ruston fine sandy loam as a function of soil slope and rainfall intensity.

The reduction in EDI following wheat straw incorporation may be attributed to an increase in water depth caused by greater hydraulic resistance and physical protection of the soil surface by the straw, decreasing the effect of runoff energy on turbulent mixing. In fact at wheat straw applications > 2.5 Mg ha^{-1}, little soil was exposed at the surface. No statistically significant difference in soil aggregation for soils with and without straw incorporation was observed. Consequently, the reduction in EDI following straw incorporation should not be influenced by a change in soil aggregation. When 5.0 Mg straw ha^{-1} was applied on the surface, protecting the soil from raindrop impact, an even greater reduction in EDI was observed for Durant (0.81–0.47 mm), Houston Black (0.54–0.23 mm), and Ruston (0.54–0.23 mm) soils compared to straw incorporation (5 Mg ha^{-1}) at the same rainfall intensity (70 mm h^{-1}) and soil slope (4%).

Soil Cover

As the mesh size of a screen placed 50 mm above the soil was increased, EDI increased (Fig. 4). How-

Table 3. Regression analysis of the relationships between rainfall intensity and effective depth of interaction and between soil slope and ln effective depth of interaction.†

Factor	Durant	Houston Black	Kirkland	Pullman	Ruston
		Rainfall intensity (x)/ effective depth of interaction (y)			
Soil slope (%)					
4	$y = 0.997 + 0.368x$	$y = 0.103 + 0.290x$	$y = 0.757 + 0.517x$	$y = 0.698 + 0.314x$	$y = 1.246 + 0.335x$
8	$1.379 + 0.561x$	$-0.200 + 0.419x$	$0.960 + 0.703x$	$0.844 + 0.479x$	$1.393 + 0.715x$
20	$8.861 + 1.211x$	$0.451 + 0.805x$	$9.782 + 1.524x$	$8.051 + 1.024x$	$12.134 + 1.537x$
		Soil slope (x)/ln effective depth of interaction (y)			
Rainfall intensity (mm h^{-1})					
50	$y = 0.597 + 0.105x$	$y = 0.137 + 0.067x$	$y = 0.720 + 0.104x$	$y = 0.316 + 0.111x$	$y = 0.793 + 0.108x$
90	$1.035 + 0.097x$	$0.763 + 0.063x$	$1.240 + 0.094x$	$0.832 + 0.099x$	$1.242 + 0.100x$
160	$1.580 + 0.100x$	$1.297 + 0.065x$	$1.782 + 0.098x$	$1.333 + 0.103x$	$1.747 + 0.106x$

† All regressions are significant at the 1.0% level.

ever, no consistent difference in the effect of mesh size on EDI was observed between soil types. By reducing rainfall energy and drop size, the different mesh sizes will simulate varying degrees of soil cover by vegetation. In fact, EDI for Durant, Houston Black, and Ruston soils at a 70 mm h^{-1} intensity and 4% slope with the 0.5-mm^2 mesh (0.61, 0.32, 0.72 mm, respectively) was only slightly greater than when 5.0 Mg straw ha^{-1} covered the soil (0.47, 0.23, and 0.62 mm, respectively).

The percent reduction in EDI with the 0.5-mm^2 mesh compared to no mesh, was similar for each soil slope at a 70 mm h^{-1} rainfall intensity and averaged

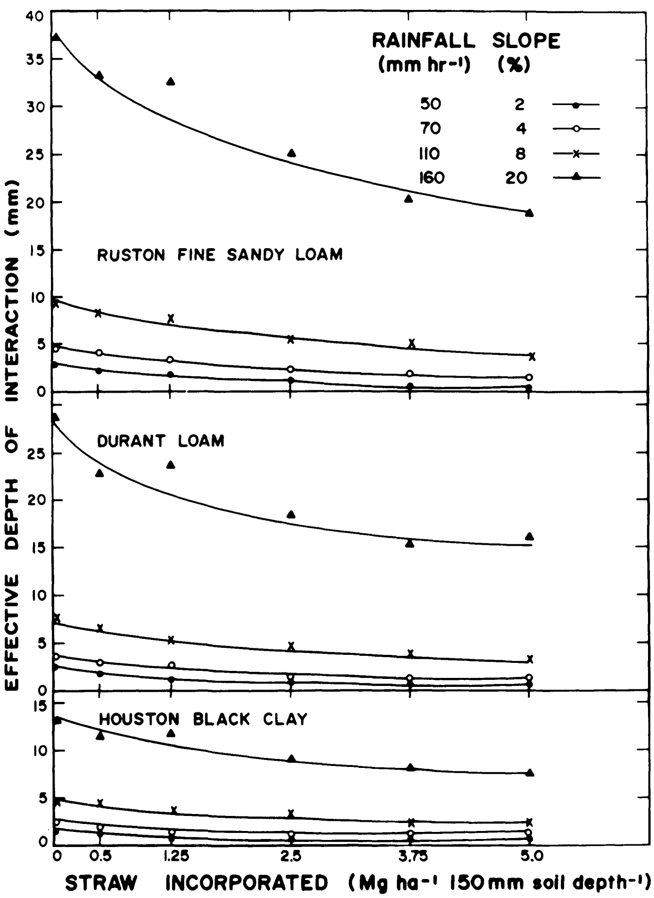

Fig. 3. Effective depth of interaction between surface soil and runoff for Houston Black, Durant, and Ruston soils as a function of wheat-straw incorporation in surface soil (150 mm) at several slopes and rainfall intensities.

67, 88, and 80% for Durant, Houston Black, and Ruston, respectively. Consequently, vegetative cover can have a dramatic effect on EDI and thus, transport of soil-derived P and other adsorbed chemicals in runoff.

Water Quality Modeling

Although the dependence of EDI on rainfall intensity, soil slope and cover, and crop residue incorporation can be described by several relationships, a more simple direct method of estimating EDI and the effect of rainfall and soil management practices is needed for water quality modeling. Since the factors determining EDI, raindrop impact, runoff energy, and soil aggregation will also influence the amount of soil lost in runoff, the relationship between EDI and soil loss was investigated. The ln soil loss was significantly related (at the 0.5% level) to the ln EDI over a wide

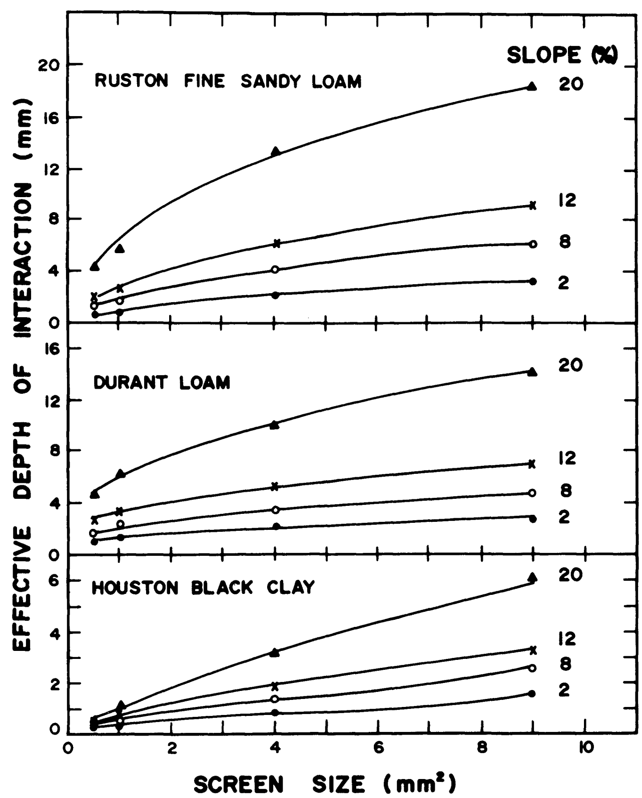

Fig. 4. Effective depth of interaction between surface soil and runoff from Houston Black, Durant, and Ruston soils as a function of screen size at several soil slopes and 70 mm h^{-1} rainfall intensity.

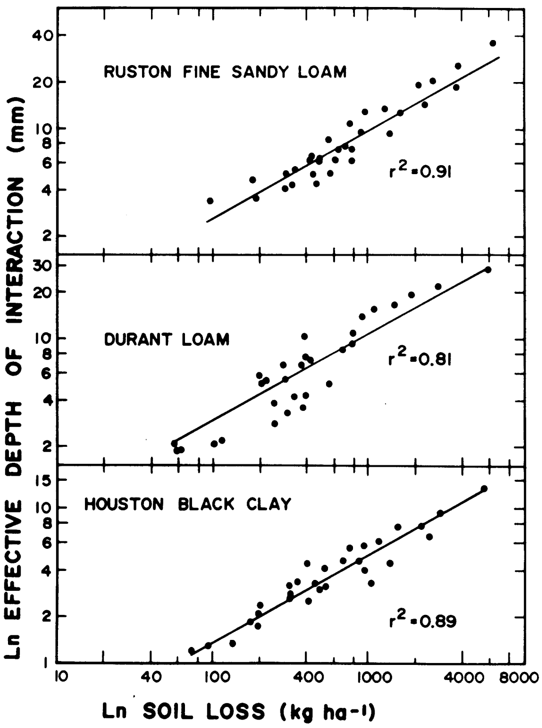

Fig. 5. Relationship between soil loss in runoff and effective depth of interaction for Houston Black, Durant, and Ruston soils.

range in soil loss (50-6000 kg ha^{-1}) (Fig. 5). Slopes of the regression equations, shown in Table 4, were not significantly different (at the 5.0% level as determined by analysis of covariance), consequently the effect of increased soil loss in runoff on EDI was independent of soil type. Regression intercept, however, varied from soil to soil (Table 4). As regression intercept represents the magnitude of EDI for a given soil under certain rainfall and soil conditions, a decrease in the negative intercept value indicates an increase in EDI. A significant relationship (at the 1.0% level) was obtained between the degree of soil aggregation and intercept of the ln soil loss—EDI regression (Fig. 6). This means that as soil aggregation increases the intercept value becomes more positive and, thus, estimated EDI will increase. This increase in EDI with soil aggregation is consistent with the data of Table 2 and earlier work (Sharpley et al., 1981).

The effective depth of interaction between surface soil and runoff can, therefore, be estimated over a wide range in rainfall and soil management practices from the loss of soil in runoff and soil aggregation using the following equations:

$$\ln \text{EDI} = i + 0.576 \ln \text{soil loss} \quad [2]$$

Table 4. Regression analysis of the logarithmic relationship between soil loss and effective depth of interaction for the soils used (n = 30).†

Soil	ln soil loss (x)/ln EDI (y)	R^2
Durant l	$y = -1.676 + 0.594x$	0.81
Houston Black c	$y = -2.457 + 0.597x$	0.89
Kirkland sil	$y = -1.307 + 0.542x$	0.93
Pullman cl	$y = -2.039 + 0.554x$	0.96
Ruston fsl	$y = -1.780 + 0.594x$	0.91

† All regression equations significant at the 0.5% level. Regression slopes not significantly different at the 5.0% level as determined by analysis of variance.

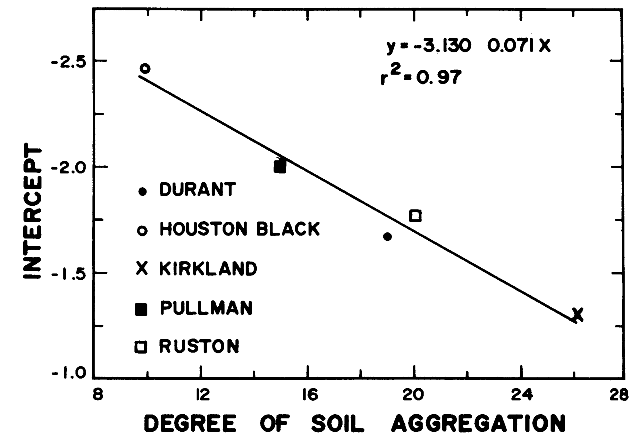

Fig. 6. Relationship between the degree of soil aggregation and intercept of the ln soil loss-EDI regression.

where

$$i = -3.130 + 0.071 \text{ soil aggregation} . \quad [3]$$

The slope of Eq. [2] is the average value for the soils used. These relationships will improve the prediction of both soluble P and herbicide transport in runoff, since earlier modeling efforts used a fixed soil depth from which soil chemicals were extracted (Sharpley et al., 1982; Leonard et al., 1979).

CONCLUSIONS

The effective depth of interaction between surface soil and runoff increased with an increase in rainfall intensity and soil slope and cover. In contrast, a decrease in EDI was observed as amounts of crop residue incorporation in surface soil increased. At high rain intensities ($>$ 110 mm h^{-1}) and soil slopes ($>$ 8%), there is so much disturbance of the soil surface (formation of depressions and rills) that in terms of modeling soluble P transport in runoff, the EDI concept probably fails. Under these conditions eroding soil material is the interacting material. This is especially true in the soil boxes, where a sieved loose soil sample is used. Since EDI is a function of soil loss and aggregation, its inclusion in the predictive equation (Eq. [1]) will still account for rainfall and soil management characteristics. Furthermore, at high soil concentration in runoff, enrichment of fine material will be small and eroded and source soil will, thus, have similar desorption properties (i.e. constants K, α, and β).

A constant EDI does not exist over a watershed area under field conditions, where micro- and macrotopography route runoff through a system of rills and small channels (Khanbilvardi et al., 1983 a, b). As a result, localized erosion can deeply incise the soil and spatially variable discrete areas can contribute to the transport of P in runoff. Application of the EDI concept to the field, therefore, is in its present form, a simplification of complex physical and chemical processes. Its inclusion in user-orientated chemical transport models, however, will improve model versatility and prediction for varying rainfall and soil management characteristics until more complete descriptions are formulated.

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DIVISION S-7—FOREST AND RANGE SOILS

Soil Bulk Density Recovery on Compacted Skid Trails in Central Idaho[1]

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ABSTRACT

In west-central Idaho, the bulk densities of soil in major skid trails were compared with those of adjacent undisturbed soil in order to determine rates of recovery. Five study sites on each of two soils, one formed from granitic material (mixed, frigid, Typic Xeropsamments) and the other from volcanic material (fine-loamy, mixed Dystric Cryochrepts), provided two chronosequences (five 5-yr periods) of time since logging. Bulk density was measured at 5.1-, 15.2-, and 30.5-cm depths. The percent increase in bulk density of soil on a skid trail over that on an adjacent undisturbed area was greater in the volcanic than the granitic soil, but recovery rates (slope of the regression line) for the two soils were not significantly different. Linear regression models showed a significant ($p < 0.05$) recovery trend for all depths except the 15.2-cm depth on the volcanic site. Except for the surface 5.1 cm of the granitic soil, none of the bulk densities in skid trails had returned to the undisturbed values in the 23 yr since logging.

Additional Index Words: **Inceptisols, Entisols, forest soils, logging, volcanic soils, granitic soils, soil compaction.**

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Sci. Soc. Am. J. 49:1015–1017

COMPACTION OF FOREST SOILS is a major effect of ground-based timber harvesting. Undisturbed forest soils typically have high porosity and low bulk density and are easily compacted by logging equipment. Compaction has been shown to have a long-term negative impact on tree growth rates (Froehlich, 1979; Wert and Thomas, 1981). However, because natural soil processes tend to slowly loosen compacted soil, the effect does not persist.

The most rapid rate of complete recovery so far reported (Mace, 1971) was 1 yr after tree-length skidding with rubber-tired skidders on relatively dry, coarse-textured soils in Minnesota. The low initial 7% increase in bulk density in the 5.1- to 15.2-cm layer on medium-use skid trails was reduced to undisturbed levels in one winter. More heavily used trails showed minimal improvment at the same depth.

Also in Minnesota, Thorud and Frissell (1976) traced the recovery of mechanically compacted sandy loam and loamy sand soils. The 0- to 7.6-cm depth recovered within 8.5 yr, but no change was detected in the 15.2- to 22.9-cm soil layer. From regression of data taken within the first several years after logging, Dickerson (1976) estimated recovery of sandy soils compacted by logging in northern Mississipi at 12 yr.

Hatchell and Ralston (1971) measured the densities of compacted and undisturbed soils on 15 areas logged over a 19-yr period in the Virginia Coastal Plain and concluded that surface soils on landings recover to undisturbed densities in 18 yr. Data from primary skid trails had greater scatter, and no statistically significant recovery trend was found. Data were taken with a surface nuclear density probe by the backscatter technique; thus, the soil depth measured was probably

[1] Paper 1866 of the Forest Research Laboratory, Oregon State Univ., Corvallis, OR 97331. Received 12 Apr. 1984. Approved 6 Mar. 1985.

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