Rill Erodibility Parameters Influenced by Long-term Management Practices

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Abstract. *A field study was conducted to estimate rill erodibility parameters on two paired north central Illinois soils with differing long-term management practices (conventional and no-till) in an effort to support on-going erosion and sediment transport modeling. Simulated rainfall and a sequence of inflows were applied to six treatments: aged tilled conventional, fresh tilled conventional, aged tilled no-till, fresh tilled no-till, undisturbed no-till with residue removed, and undisturbed no-till. Two models (shear stress and stream power) were used to analyze rill detachment rates. Baseline rill erodibilities for fresh tilled conventional (0.00879 g s^{-1} N^{-1}) and fresh tilled no-till (0.00541 g s^{-1} N^{-1}) were significantly different using the shear stress model. Consolidation also produced significant differences in erodibilities for the conventional tilled site (0.0122 g s^{-1} N^{-1} and 0.00879 g s^{-1} N^{-1} for aged and fresh tilled treatments, respectively). When stream power was used to model the response of rill detachment, no significant differences were detected in erodibility and critical stream power for baseline conditions. However, the stream power model accounted for most of the variability in detachment rates within each treatment. Long-term no-till significantly reduced sediment concentrations in the runoff from all other treatments (0.0045 g/g and 0.0067 g/g for undisturbed and undisturbed residue removed, respectively). Sediment concentration was a function of residue and consolidation.* ***Keywords.*** *Rill erodibility, No-till, Conservation tillage, Shear stress, Stream power.*

Erosion by water is a worldwide concern. Each year soil erosion causes billions of dollars of damage in the United States (Committee on Conservation Needs and Opportunities, 1986). In many cases, mitigation efforts for erosion have concentrated on conservation tillage practices. One method, growing in popularity, is no-till farming. No-till farming generally consists of leaving the previous year's crop residue and planting into the undisturbed surface. Advantages of long-term no-till farming over conventional methods include reduced soil loss (McIsaac et al., 1990; Pesant et al., 1987; Lembi et al., 1985), increased surface residue (Norton et al., 1985), improved soil drainage (Edwards et al., 1990), and reduced labor costs (Weersink et al., 1992).

Traditional agricultural practices continue to promote accelerated erosion rates. In order to control erosion, some understanding of the soils susceptibility to erosion must be quantified. Erosion by water may be divided into two components: rill and interrill (Meyer et al., 1975; Foster et al., 1977). Rill erosion is primarily a function of detachment by concentrated flow in small channels while interrill erosion is driven by detachment from raindrop impact. The main objective of this study was to evaluate rill erodibility parameters for no-till and conventional managed systems as influenced by time and tillage. Results of this study will be incorporated into erosion prediction technology.

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Background

The moldboard plow is being used much less in modern agriculture. Much emphasis has been devoted to a new concept in farming practices called residue management. Residue management is a concept which involves leaving crop residue on the soil surface for erosion control (McIsaac, 1990) and increased soil fertility (Geiger et al., 1992). Several research efforts have been focused on no-till conservation management (Zhu et al., 1989; Heard et al., 1988; Cogo et al., 1984; Laflen and Colvin, 1981).

Zhu et al. (1989) studied the effect of no-till soybeans with a winter cover crop on runoff and soil loss. Using natural rainfall plots, they reported runoff and soil loss reductions of approximately 90 and 50%, respectively. The lower soil losses were attributed to an increased soil cover during the critical erosion period. Norton et al. (1985) also reported the role that residue plays in controlling erosion. They analyzed four management systems and reported that residue cover and roughness index were correlated to soil loss (r^2 = 0.76). Most of the variance in erosion was explained by the residue cover factor.

Laflen and Colvin (1981) studied soil loss from three types of tillage (conventional, reduced, and no-till) and found that soil loss, sediment concentration, and residue cover were significantly different for no-till compared to both conventional and reduced tillage systems. Yoo et al. (1987) documented more than a 50% reduction in soil loss for a first-year no-till system when compared to a conventional tilled system. Brenneman and Laflen (1982) and Cogo et al. (1984) concluded that residue cover reduces erosion in one of four ways: 1) dissipation of the energy from raindrop impact; 2) slowing runoff, and increasing flow depth, which in turn reduces the impact of raindrops; 3) absorption of some of the forces from runoff that are usually applied to the soil surface; and 4) creation of small reservoirs of ponded runoff causing deposition.

Methods and Procedures

Sites selected for the study were located in north-central Illinois near Lexington. Soil on the no-till site was classified as a Saybrook silt loam (fine-silty, mixed, mesic Typic Argiudoll) while that for the conventional location was a Corwin silt loam (fine-loamy, mixed, mesic Typic Argiudoll). Both soils were formed in late Wisconsin-aged loess over glacial till. Terrain at both sites was slightly rolling to flat, with an average slope of 3.5%. The Saybrook soil contained 25.6% clay, 69.9% silt, and 4.5% sand. The Corwin soil contained 21.1% clay, 73.2% silt, and 5.7% sand. Organic carbon was 3.01 and 2.66% for Saybrook and Corwin soils, respectively. Cropping history for the no-till site (Saybrook) was 18 years continuous no-till with a corn-soybean rotation. The conventional (moldboard plowed or chiseled, and disked) site (Corwin) had been in a corn-soybean rotation for 15 years and in pasture for an unknown period prior to that. The conventional site was adjacent to the no-till site. Minor differences in soil composition were assumed to be negligible in this study. However any differences in erodibility and critical shear may be due to soil differences rather than management practice.

Artificial rills, 0.2 m wide × 4.0 m long, were formed using 14 gauge metal border on each side and positioned up and down hill. The 0.2 m width was chosen to minimize the interrill contribution. Different treatments for the no-till site included: undisturbed, undisturbed residue removed, aged tilled, and fresh tilled. Aged tillage is defined as using several passes with a garden tiller approximately one month prior to field study. Light precipitation (12 mm) fell on both aged-tilled plots between the time of tilling and the experiment causing some consolidation. Measurements of kinetic energy were not available. Fresh tillage was completed immediately before the simulated rainfall experiment. The freshly tilled condition involved destruction of the surface crust formed from rainfall impact. A garden hoe was used to perform this operation. Treatments for the adjacent conventional site (Corwin) included aged tilled and freshly tilled as described above. Nine replications for each tillage treatment were completed at the no-till site (Saybrook) while six replications were completed for each treatment at the conventional location. Baseline conditions were those of the fresh tilled condition.

Artificial rainfall was applied for 1 h at a target rate of 63.5 mm/h using a programmable rainfall simulator (Foster et al., 1979). Rainfall simulation was discontinued after 1 h and a series of inflows were introduced in sequence at the upslope end of the rill to create a range of flow shear stresses. Target inflow rates of 38, 76, 113, 151, and 189 L/min were used for undisturbed conditions while rates of 11, 23, 34, 45, and 57 L/min were used for all disturbed conditions. Flow rates of these magnitudes were estimated to exceed the critical shear stress of the soil (Smerdon and Beasley, 1961). Each inflow was added with a digital flow meter for an average duration of 3 min. Steady-state flow conditions were assumed to occur after 1 min. The second and third minutes were utilized for the collection of water runoff samples to determine soil and water losses, sediment concentrations, particle size distributions, and flow velocity. Mean flow velocity was measured using the leading edge dye method (Horton et al., 1934) and corrected by using an electrical conductivity method (King and Norton, 1992; King, 1992). Primary particle size, D_{50} (50% passing) and mean weight diameter (MWD) were measured using the Kemper and Chepil (1965) method.

Flow discharge rates along with velocity measurements were used to calculate the cross-sectional area of flow using the relation:

$$Q = \bar{v} A \tag{1}$$

where

Q = flow discharge ($m^3\ s^{-1}$)

$\bar{v}$ = mean flow velocity ($m\ s^{-1}$)

A = cross-sectional area of flow

Assuming a constant 0.2 m effective flow width, mean depth was calculated based on the estimated cross-sectional area.

Erodibility was related to detachment rate by two methods: average hydraulic shear stress (Chow, 1959) and stream power (Bagnold, 1977). Average shear stress was computed by:

$$\tau = \gamma R S \tag{2}$$

where

τ = the shear stress (Pa)

γ = the specific weight of the water ($N\ m^{-3}$)

R = the hydraulic radius (m)

S = the slope of the channel (m/m)

Stream power is defined as the product of shear stress and mean flow velocity:

$$\omega = \tau \bar{v} = \gamma q S \tag{3}$$

where ω is stream power ($kg\ s^{-3}$), q, the flow discharge rate per unit width ($g\ s^{-1}\ m^{-1}$), and all other variables being previously defined.

Average shear stress was related to detachment rate using the equation of Foster and Meyer (1975):

$$D_r = K_r (\tau - \tau_c)^n \tag{4}$$

where

D_r = the detachment rate ($g\ s^{-1}\ m^{-2}$)

K_r = the erodibility factor ($g\ s^{-1}\ N^{-1}$)

τ_c = the critical shear stress ($N\ m^{-2}$)

τ = the effective shear stress ($N\ m^{-2}$)

n = an exponent

For the conditions of this study, the exponent n was assumed to have a value equal to unity (Foster et al., 1984). Stream power was related to detachment rate in a similar manner:

$$D_r = \omega_r (\omega - \omega_c) \tag{5}$$

where

ω_r = erodibility factor ($s^2\ m^{-2}$)

ω_c = critical stream power (kg s^{-3})

ω = effective stream power (kg s^{-3})

Assuming a linear relationship between detachment and shear stress (Foster et al., 1984) or stream power, erodibility becomes equal to the slope of the line and the x-intercept is the critical tractive force or power depending on which model is used. Average values for each treatment are presented.

Results and Discussion

Both the average shear stress (eq. 4) and stream power (eq. 5) detachment models were used to determine erodibility parameters. Calculated rill erodibility and critical hydraulic shear stress for each treatment using the shear stress model (eq. 4) are presented in table 1 while erodibility and critical stream power (eq. 5) are presented in table 2. Graphical representations of detachment rate versus hydraulic shear stress and stream power are presented in figures 1 and 2, respectively.

Erodibility

Assuming any variability between soils is negligible, significant differences in baseline erodibilities were detected when using the average shear stress model (K_r = 0.00879 g s^{-1} N^{-1} and K_r = 0.00541 g s^{-1} N^{-1} for fresh-tilled conventional and fresh-tilled no-till, respectively). However, application of the stream power model indicated no significant differences existed in baseline erodibility (ω_r = 26.67 $s^2\ m^{-2}$ and ω_r = 17.58 $s^2\ m^{-2}$ for fresh-tilled conventional and fresh-tilled no-till, respectively). Similar results were also found between consolidated (aged tilled) treatments. Erodibility of aged-tilled conventional (K_r = 0.0122 g s^{-1} N^{-1}) and aged-tilled no-till (K_r = 0.00728 g s^{-1} N^{-1}) were found to be significantly different when estimated with the average shear stress model. But, when stream power was used for erodibility estimation, no significant differences were present (ω_r = 30.01 $s^2\ m^{-2}$ and ω_r = 20.16 $s^2\ m^{-2}$ for the aged-tilled conventional and no-till site, respectively). No-till residue removed and no-till undisturbed were not significantly different from each other, regardless of which model was used. However, no-till residue removed was not significantly different from no-till freshly tilled.

Table 1. Multiple comparison of rill erodibility and critical hydraulic shear stress using the average shear stress model (eq. 4)

Treatment	Reps†	K_r* (mg s^{-1} N^{-1})	S.D. (mg s^{-1} N^{-1})	C.V.	τ_c* (Pa)	S.D. (Pa)	C.V.	Avg. R^2
Aged-tilled conventional	5	12.20a	3.34	0.27	3.08b	1.11	0.36	0.88
Fresh-tilled conventional	6	8.79bc	2.71	0.31	1.85bc	0.32	0.17	0.90
Aged-tilled no-till	9	7.28bc	2.08	0.29	1.87bc	0.44	0.24	0.91
Fresh-tilled no-till	9	5.41cd	3.51	0.65	1.24c	0.63	0.51	0.88
Undisturbed residue removed	5	3.62de‡	1.85	0.51	1.97bc‡	0.85	0.43	0.76
Undisturbed	5	1.70e‡	0.74	0.43	7.14a‡	2.46	0.34	0.61

* Values in columns followed by same letter are not significantly different for α = 0.05 using Duncan's multiple range test.

† Replications which were not used contained negative values for critical shear stresses.

‡ Shear stress and erodibility were not partitioned for soil and residue roughness.

Note: No-till site (Saybrook); Conventional site (Corwin).

Table 2. Multiple comparison of rill erodibility and critical stream power using the critical stream power model (eq. 5)

Treatment	Reps†	ω_r* (s^2/m^2)	S.D. (s^2/m^2)	C.V.	ω_c* (kg/s^3)	S.D. (kg/s^3)	C.V.	Avg. R^2
Aged-tilled conventional	5	30.01a	4.83	0.16	0.424b	0.201	0.47	0.93
Fresh-tilled conventional	6	26.67ab	9.20	0.34	0.423b	0.101	0.24	0.92
Aged-tilled no-till	9	20.16a	6.45	0.32	0.423b	0.176	0.42	0.92
Fresh-tilled no-till	8	17.58abc	15.22	0.87	0.414b	0.288	0.70	0.90
Undisturbed residue removed	2	9.89bc‡	6.52	0.66	0.370b‡	0.146	0.39	0.78
Undisturbed	3	4.80c‡	2.68	0.56	1.067a‡	0.385	0.36	0.76

* Values in columns followed by same letter are not significantly different for α = 0.05 using Duncan's multiple range test.

† Replications which were not used contained negative values for critical shear stream power.

‡ Shear stress and erodibility were not partitioned for soil and residue roughness.

Note: No-till site (Saybrook); Conventional site (Corwin).

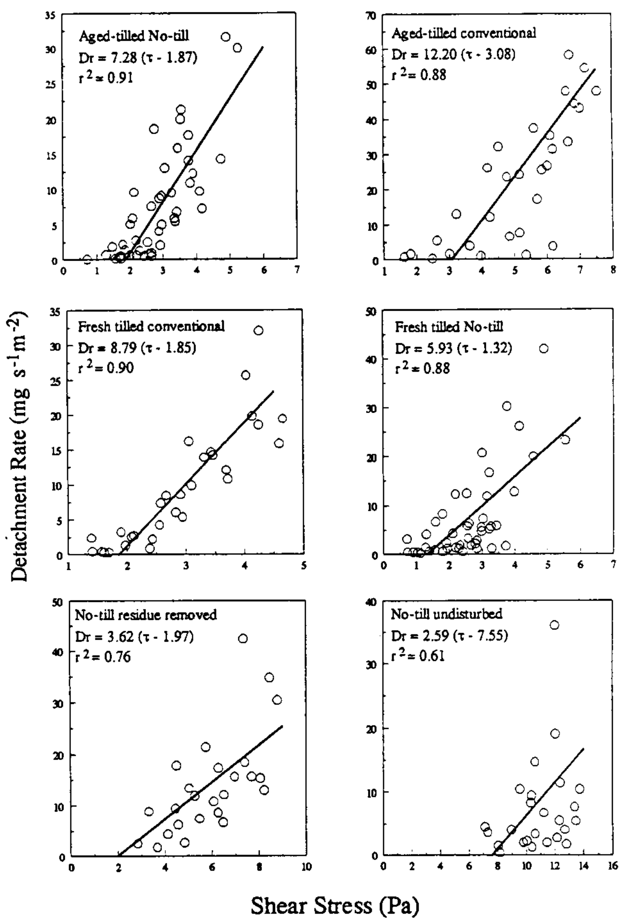

Figure 1–Detachment rate vs. shear stress and average best fit line over all replications for six treatments at two sites. The R^2 is the average coefficient of determination over all replications for the respective treatment.

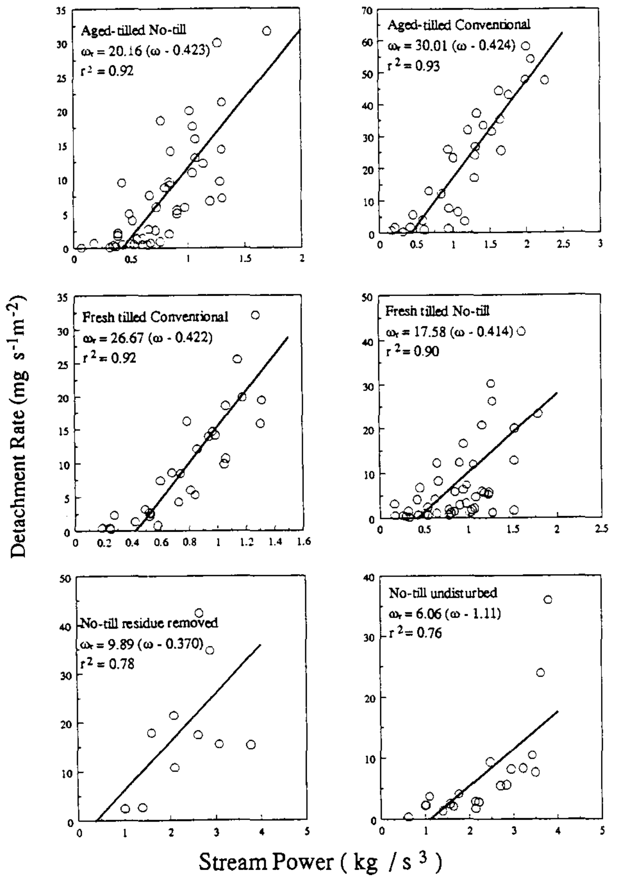

Figure 2–Detachment rate vs. stream power and average best fit line over all replications for six treatments at two sites. The R^2 is the average coefficient of determination over all replications for the respective treatment.

Evaluation and analysis of mean weight diameter (MWD) and D_{50} data (diameter at 50% passing) (table 3) does not lead to any explanation of the significant differences seen in erodibility between sites. Handling of the samples during transport may have affected the stability of the aggregates, thus eliminating any differences which may have occurred.

Earthworm activity may be a factor influencing erodibility. Earthworms feed on surface residue and incorporate it into the top layers of soil, promoting increased organic carbon and permeability (Edwards et al., 1990). Even though no measurements were conducted on earthworm density between the two sites, more earthworm activity was observed at the no-till site. This observation is reflected in the average organic carbon content at both sites (3.01% for no-till and 2.66% for conventional).

Methods and assumptions in measurement may also influence erodibility. Shear stress was calculated under the assumption that rill shape was rectangular and detachment was uniform for the length of the rill. While predominately rectangular, observation of the eroded channels indicated a range of channel shapes: trapezoidal, rectangular, and parabolic. The variance in shape was accounted for, but was assumed over the entire event. Dynamic variance of the rill shape was not estimated. Headcutting was also present in some of the replicates, producing more erosion than would be expected under the assumption of uniform detachment. While the soils were assumed to be similar for pooling and hypothesis testing, the composition differences may be great enough to influence erodibility. This assumption alone could explain the significant erodibility differences.

Figures 1 and 2 show the scatter associated with the replications and the average best fit through those replications. The scatter across the replications proves to be the factor preventing significant differences to occur. However, a look at tillage history (figs. 3 and 4) shows that erodibility decreases almost linearly as long-term management practice progresses to no-till. This indicates that weathering, wetting and drying, consolidation, and residue play a major role in a soils susceptibility to erosion.

Time of consolidation did produce a significant difference in erodibility. Erodibility from aged-tilled conventional (K_r = 0.0122 g s^{-1} N^{-1}) and fresh-tilled conventional (K_r = 0.00879 g s^{-1} N^{-1}) were found to be significantly different when estimated from average shear stress (eq. 4). However, no differences were detected in erodibility with stream power (eq. 5). Aged-tilled and fresh-tilled plots from the no-till site were not significantly different, regardless of the detachment model. The differences detected from consolidation on the conventional managed site may have resulted from the

Table 3. Average mean weight diameter (MWD) and D_{50} (mm) for each treatment at each flow level

	Flow Level									
	1		2		3		4		5	
Treatment	MWD	D_{50}	MWD	D_{50}	MWD	D_{50}	MWD	D_{50}	MWD	D_{50}
Aged tilled conventional	0.44	0.18	0.46	0.18	0.57	0.29	0.58	0.28	0.54	0.24
Fresh tilled conventional	0.33	0.05	0.38	0.32	0.48	0.23	0.46	0.21	0.47	0.13
Aged tilled no-till	0.29	0.11	0.30	0.20	0.51	0.30	0.57	0.30	0.60	0.30
Fresh tilled no-till	0.28	0.11	0.34	0.24	0.46	0.21	0.54	0.23	0.59	0.18
Undisturbedresid ueremoved	0.48	0.11	0.51	0.27	0.54	0.37	0.66	0.36	0.84	0.60
Undisturbed	0.41	0.12	0.44	0.23	0.56	0.27	0.53	0.30	0.71	0.38

Note: Flow rates differ between tilled and undisturbed treatments at same flow level.

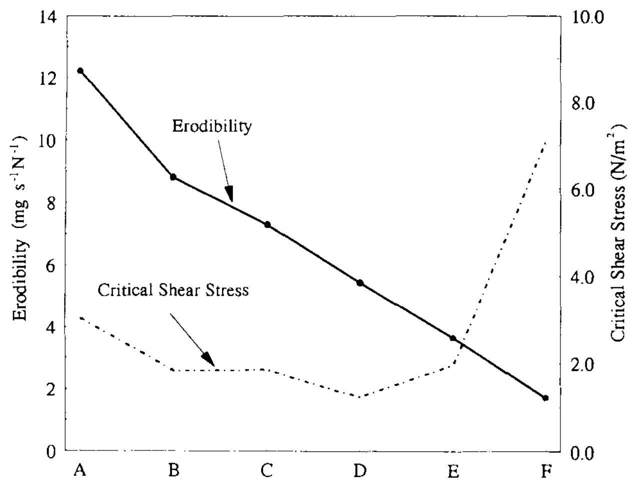

Figure 3–Erodibility and critical shear stress represented as a function of tillage history (A – aged tilled conventional, B – fresh tilled conventional, C – aged tilled no-till, D – fresh tilled no-till, E – undisturbed residue removed, and F – undisturbed).

eroding of a thin surface seal. The seal was developed when precipitation fell on the plot.

Long-term consolidation (no-till residue removed) was significantly different from all other treatments with the exception of undisturbed no-till and fresh-tilled no-till, when shear stress (eq. 4) was used for determining erodibility (table 1). However, when stream power (eq. 5 and table 2) was analyzed, significant differences did not follow along the same lines. Although, as previously indicated from figure 4, the general trend in erodibility was to decrease with tillage history.

Residue serves to absorb shear from the fluid and decrease the velocity of runoff. When residue is combined with long-term consolidation (no-till undisturbed), the decrease in erodibility is more pronounced. Residue reduced erodibility by more than 50% when compared with no-till residue removed, even though the treatments were not significantly different. The transport of residue in some replications translated into high coefficients of variation, preventing detection of significant differences. Nevertheless, observation indicated marked differences in sediment leaving the no-till undisturbed replications.

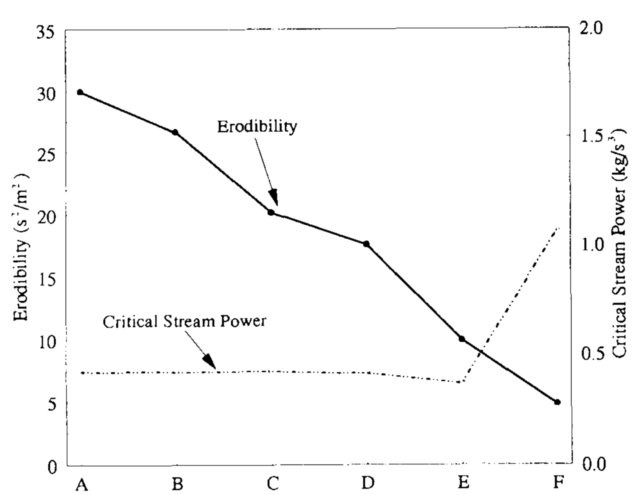

Figure 4–Erodibility and critical stream power represented as a function of tillage history (A – aged tilled conventional, B – fresh tilled conventional, C – aged tilled no-till, D – fresh tilled no-till, E – undisturbed residue removed, and F – undisturbed).

Critical Tractive Forces

Long-term management system did not produce significant differences in critical shear stress for baseline conditions (τ_c = 1.85 Pa and τ_c = 1.24 Pa for fresh-till conventional and fresh-till no-till treatments, respectively) nor for consolidated plots (τ_c = 3.08 Pa and τ_c = 1.87 Pa for conventional and no-till sites, respectively). Similar findings were detected when stream power was analyzed (table 2). Critical tractive force for no-till undisturbed (τ_c = 7.14 Pa and ω_c = 1.067 kg s^{-3}) was significantly different from all other treatments (tables 1 and 2).

Residue appeared to be the major factor influencing critical shear stress. An evaluation of tables 1 and 2 would indicate that residue absorbs about 70% of the shear force applied at this site. Figures 3 and 4 also show a sharp rise in critical tractive force for the undisturbed treatment. This dramatic increase in critical force is a function of residue. Tillage history did not seem to influence critical tractive force in the same manner as it did erodibility. Trends in critical tractive force are similar for each model. Critical forces tend to fall within a range that are not significantly different until crop residue is present. Because the soil characteristics and composition are relatively the same, the intercepts (critical tractive forces) would be expected to be similar. Consolidation and wetting and drying sequences will affect the slope (erodibility) of the curve, not the intercept. In this study, crop residue seems to be the major factor increasing critical tractive forces and reducing sediment losses.

Sediment Concentrations

Sediment concentrations were significantly reduced with long-term no-till management (table 4). Undisturbed and undisturbed residue removed treatments had sediment concentrations significantly lower than the baseline (fresh-tilled conventional) condition by 67 and 51%, respectively. The differences in flow levels should not influence concentrations since the no-till treatments were subjected to much higher shear forces. As with erodibility, sediment concentration decreased with tillage history (fig. 5), but with much more significance. This may be explained by

Table 4. Sediment concentration by treatment over all flow levels

Treatment	Sediment Concentration* (g/g)	Samples
Aged tilled conventional	0.0181 a	29
Fresh tilled conventional	0.0137 b	26
Aged tilled no-till	0.0123 b	39
Fresh tilled no-till	0.0105 b	42
Undisturbed residue removed	0.0067 c	44
Undisturbed	0.0045 c	45

* Values in columns followed by same letter are not significantly different for α = 0.05 using Duncan's multiple range test.

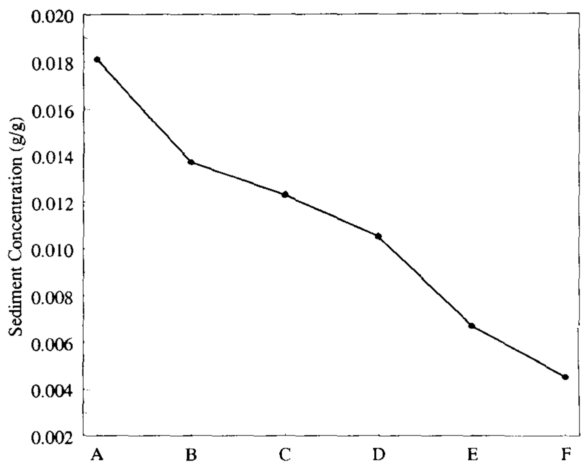

Figure 5–Sediment concentration represented as a function of tillage history (A – aged-tilled conventional, B – fresh-tilled conventional, C – aged-tilled no-till, D – fresh tilled no-till, E – undisturbed residue removed, and F – undisturbed).

the fact that sediment concentration is a measured value and erodibility a derived value. The differences which occur between erodibilities and sediment concentrations for each treatment may indicate some errors in the method used to obtain erodibility values.

SUMMARY

Shear stress and stream power models were evaluated as a means to relate sediment detachment, critical tractive forces, and erodibilities. Both models appeared to predict detachment adequately, with stream power explaining slightly more of the variability.

Long-term management practices produced significant differences in baseline erodibilities. Consolidation, weathering, wetting and drying sequences, and residue were all factors which contributed to variability between treatments. Critical tractive forces were primarily influenced by residue. Sediment losses, indicated by sediment concentrations, were significantly reduced when long-term no-till was the management practice. Discrepancies between differences in erodibility and sediment concentration within the same treatment were attributed to the fact that erodibility is a derived value and sediment concentration is measured. This would suggest that some improvement in methodology of estimating erodibility may be necessary. However, based upon sediment concentrations, it can be concluded that long-term no-till practices are effective and practical in reducing rill erodibility and sediment loss on these two selected sites.

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