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Interrill and Rill Erosion on a Tropical Sandy Loam Soil Affected by Tillage and Consolidation

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ABSTRACT

Short and long-term consolidation affect rill and interrill erosion processes. Soil under no-tillage usually has increased consolidation and surface residue, which reduce erosion and runoff. The effect of soil consolidation and soil-surface residue must be evaluated to use physically based erosion models. In this study, we used a sandy-loam (surface texture) Hapludalf, with about 8.5-10% slope, and evaluated erosion and runoff for: 1) recent conventional tillage (RCT), 2) consolidated (2 months) conventional tillage (CCT), 3) no-tillage (6 years) with residue (NTR), 4) no-tillage without residue (NTB), with 6 replications. For interrill erosion, simulated rainfall of 65 mm h^{-1} was applied for 90 min on 0.5 by 0.75 m plots delimitated by metal borders. For rill erosion, plots of 0.2 by 6.0 m with metal borders were prewetted with simulated rainfall and water flow (12 to 60 L min^{-1} for CT, and 24 to 120 L min^{-1} for NT) were applied sequentially during 4 minutes for each flow rate. Runoff and sediment were collected at the lower end of the plots where a collecting device was installed. Rill and interrill erosion parameters were calculated using WEPP procedures. For interrill area, the detachment rate, sediment concentration, and total soil loss were greater for RCT and CCT than for NTR and NTB, due to high soil shear strength and soil aggregation under no-tillage. For RCT, interrill erodibility (K_i) was 1.77 x 10^6 kg s m^{-4}, rill erodibility (K_r) was 0.0129 kg N^{-1} s^{-1}, and critical shear stress (τ_c) was 2.21 Pa. For CCT, K_i was 1.44 x 10^6 kg s m^{-4}, K_r was 0.0038 kg N^{-1} s^{-1} and τ_c was 2.63 Pa for CCT. The mean weight diameter of eroded sediment was greater for RCT than for CCT, NTB and NTR. For most rill flows, the flow regime was turbulent (Reynolds number > 2000) and supercritical (Froude number > 1). Efficient erosion control on tropical soil occurs on no-tillage only with adequate surface residue, and natural consolidation modifies soil erodibility and shear strength.

INTRODUCTION

Erosion studies and predictions in Brazil are usually done by using the Universal Soil Loss Equation (USLE), while erosion studies based on physically based models are scarce and model parameters need to be determined in situ to use such models, including the Water Erosion Prediction Project Model (WEPP) (Elliot et al., 1989).

Only a few studies using WEPP methodology (Elliot et al., 1989) have been conducted in Brazil, primarily by Cassol and associates, where tropical soils predominate. Giasson and Cassol (1996) determined rill erodibility (K_r) of 0.0077 kg N^{-1} s^{-1} and critical shear stress (τ_c) of 1.13 Pa for a plintic sandy clay loam soil, while Braida and Cassol (1996) determined K_i of 5.10 x 10^6 kg s m^{-4}, K_r of 0.0104 kg N^{-1} s^{-1} and τ_c of 4.81 Pa for a sandy-loam dark-red podzolic soil. Thus, besides the few studies using WEPP for Brazilian tropical soils, little is known about the effect of soil management on rill and interrill erosion processes in these soils. Soils and climate are quite different from those occurring in temperate conditions.

Soils in the tropics are highly weathered with primarily kaolinite and Fe and Al oxy-hydroxides in the clay fraction, changing the well-established relationship between rill and interrill erodibility and soil properties for temperate climates such as in the USA (Elliot et al., 1989). The high temperature increases soil-surface residue decomposition and intense rainfall increases soil erosion.

This experiment had the objectives of studying rill and interrill erosion, with different methods of soil tillage and with consolidation, and determining erodibility and critical shear stress on a tropical soil with predominantly kaolinite and Fe and Al oxy-hydroxides in the clay fraction.

MATERIAL AND METHODS

The experiment was conducted at the research station of the Soils Department, UFSM, Brazil, on a red-yellow podzolic, with a sandy loam soil surface texture (19% clay, 24% silt, and 57% sand) and with 10% slope for rill and 8.5% for the interrill area.

For rill and interrill areas, the treatments consisted of: recent conventional tillage (RCT); consolidated (2 months) conventional tillage (CCT); no-tillage (6 years) bare without residue (NTB) and no-tillage (6 years) with residue (NTR, 94% coverage), using a completely randomized experimental design, with six replicates.

Intact soil cores were collected to determine bulk density (Blake and Hartge, 1986). Total porosity was calculated and macroporosity was obtained using a tension table. Partially disturbed soil samples were used for determining aggregate stability through wet-sieving (Kemper and Chepil, 1965) and the mean weight diameter (MWD) and D_{50} of stable aggregates were calculated. The soil shear strength (τ_s) was

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measured with a Torvane (Holtz and Kovacs, 1981) immediately after the rain.

For interrill erosion, simulated rainfall of 65 mm h^{-1} was applied for 90 min on 0.5 by 0.75 m plots delimitated by metal borders. For rill erosion, plots of 0.2 by 6.0 m with metal borders were prewetted with simulated rainfall until steady-state runoff was reached, and then inflow water was applied sequentially during 3 minutes for each flow rate without rain. These extra inflows were applied in ascending order: 12, 24, 36, 48 and 60 L min^{-1}, for the treatments RCT and CCT, and 24, 48, 72, 96 and 120 L min^{-1}, for NTB and NTR. Higher flows were applied on the no-tillage treatments since high shear stress is needed to cause soil erosion (King, 1992).

On the rill area, three runoff samples, one minute apart, for each inflow were collected to determine runoff rate, soil loss, and sediment concentration, and one sample to determine the particle size (MWD) of the eroded sediment. For interrill erosion, during rainfall one 1-L sample was collected every 5 minutes to calculate soil erosion, soil concentration, and runoff. At the end of the rain, a 3-L sample was collected to determine the particle size distribution of eroded sediment. Total soil loss and total runoff were obtained by integrating values during rain, and steady-state rates by averaging values for the last three samples in a given rain, when rates where almost constant. All samples for rill and interrill area were collected at the end of the plots where collecting troughs were installed.

The flow velocity, width, and depth were determined using procedures describe in King (1992) and used to calculate the flow parameters, such as shear stress (τ), Reynolds (Re) number and Froude (F) number (Chow, 1959).

Interrill erodibility (K_i), rill erodibility (K_r), and critical shear stress (τ_c) were calculated using WEPP procedures (Elliot et al., 1989), using the equations:

$$K_i = D_i / (S_f I^2)$$

$$K_r = Dc / (\tau. - \tau_c)$$

where: D_i = interrill detachment rate, S_f = slope factor, I = rainfall intensity, Dc = detachment capacity; $\tau.$= flow shear stress, and τ_c = critical shear stress.

ANOVA and means comparison (Duncan Multiple Range test) of soil properties and erosion parameters were done using SAS procedures.

RESULTS AND DISCUSSION

The effects of consolidation and surface residue on conventional and on no-tillage (Cogo et al., 1984; Nearing et al., 1988a, 1988b; Brown et al., 1990; Norton and Brown, 1992; Brown and Norton, 1994) and erodibility parameters for WEPP (Elliot et al., 1989; Liebenow et al., 1992) are well established for temperate soils. However, little is known for tropical soils, where climate and soil mineralogy are quite different from those occuring on temperate soils. The results of this study contribute for the understanding of erosion processes and their relation to soil properties for tropical conditions.

Interrill erosion

For the most erodible condition (RCT), interrill erodibility (K_i) was, on average, 1.77 x 10^6 kg s m^{-4}. For conventionally tilled consolidated soil (CCT), K_i was 1.44 x 10^6 kg s m^{-4}, clearly showing a reduction in soil interrill erodibility with consolidation.

The interrill detachment rate (D_i) was greater for RCT and CCT than for the other treatments (Table 1), possibly due to soil disturbance and aggregate breakdown under conventional tillage treatments, thus changing the soil shear strength, aggregate size and stability, bulk density and porosity (Table 2) of the soil surface. Low shear strength and smaller aggregate sizes and low stability favor detachment and transport of sediments. Total runoff was greatest and total infiltration was least for RCT and NTB.

For the NTR treatment, the surface residue intercepted raindrops and dissipated their kinetic energy, thus avoiding detachment and surface sealing. In addition, surface residue acted as a barrier to runoff and increased water infiltration.

Steady-state infiltration rate and runoff rate behaved similarly to total amount of water infiltration or total runoff, respectively, while increased sediment concentration was associated with increased detachment rate and total soil loss (Table 1).

Soil strength measured with a Torvane was greatest for NTR and NTB, intermediary for CCT and lowest for RCT due to soil tillage prior to rain. For the CCT, the soil after tillage consolidated for two months, while for NTR and NTB the soil consolidated under no-tillage for six years.

Soil conditions with high detachment rates had low soil shear strength and produced high sediment concentrations and total soil losses. The steady-state infiltration rate was negatively correlated to steady-state runoff rate and total

Table 1. Interrill detachment rate (D_i), steady-state infiltration rate (Ic), steady-state runoff rate (Rc), sediment concentration (SC), total soil loss (TSL), total runoff (TR), and total infiltration (TI), for four management systems.

Treat	D_i	Ic	Rc	SC	TSL	TR	TI
	kg m^{-2} s^{-1}	cm h^{-1}	cm h^{-1}	g L^{-1}	kg ha^{-1}	m^3 ha^{-1}	cm
RCT [†]	0.0002090 a [‡]	1.13 b	4.66 a	11.81 a	7632 a	602 a	2.65 b
CCT	0.0001810 a	2.62 a	3.44 b	12.47 a	5877 a	418 b	4.92 a
NTB	0.0000514 b	1.50 b	4.62 a	2.88 b	2450 b	668 a	2.50 b
NTR	0.0000096 b	2.70 a	3.53 b	0.48 b	322 b	375 b	5.60 a

[†] RCT: Recent conventional tillage; CCT: Consolidated conventional tillage; NTB: No-tillage without surface residue; NTR: No-tillage with surface residue.

[‡] Means followed by the same letter do not differ significantly (Duncan's P=0.05).

Table 2. Soil bulk density (Bd), total porosity (Pt), macroporosity (Mp), mean weight diameter (MWD) and D_{50} of water stable aggregates, and soil shear strength (τs) measured with Torvane, for four management systems.

Treatment	Bd	Pt	Mp	MWD	D_{50}	τs
	Mg m^{-3}	.... %	....	.... mm	....	kPa
RCT [†]	0.99 c [‡]	60 a	33 a	0.72 b	0.31 c	2.17 c
CCT	1.28 b	49 b	16 b	1.52 b	1.43 b	3.42 b
NTB	1.38 a	43 c	5 d	3.42 a	2.64 a	6.33 a
NTR	1.34 ab	47 b	12 c	4.00 a	2.89 a	5.77 a

[†] RCT: Recent conventional tillage; CCT: Consolidated conventional tillage; NTB: No-tillage without surface residue; NTR: No-tillage with surface residue.

[‡] Means followed by the same letter do not differ significantly (Duncan's P=0.05).

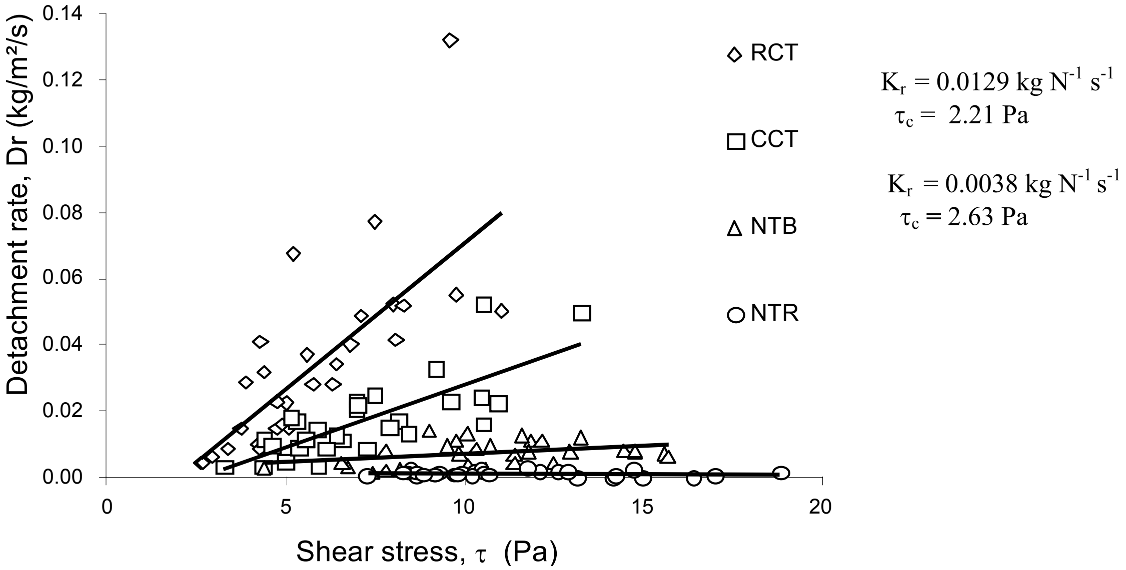

Figure 1. Detachment capacity (Dc) versus shear stress (τ), for four soil management systems.

runoff. The steady-state runoff rate was correlated positively to total runoff and negatively to total infiltration. A negative correlation was observed between sediment concentration and soil shear strength.

Rill erosion

For the conventional tillage, the soil consolidation produced lesser rill erosion and greater critical shear stress (Figure 1). Thus, soil susceptibility to erosion was increased by soil tillage and rain events on freshly tilled soils. For RCT, detachment rates increased rapidly with increasing shear stress; for CCT, this effect was lesser. For NTB and NTR, little or even no increase in the detachment rate occurred with increase in shear stress. Thus, for no-tilled soils, K_r and τ_c could not be calculated, similarly to results obtained by Norton and Brown (1992).

For the most erodible condition (RCT), rill erodibility (K_r) was 1.29 x 10^{-2} kg N^{-1} s^{-1}, and critical shear stress (τ_c) was 2.21 Pa. For conventionally tilled consolidated soil (CCT), K_r was 0.38 x 10^{-2} kg N^{-1} s^{-1} and τ_c was 2.63 Pa.

The flow regime (Figure 2) was initially (low flows) transitional (Reynolds number (Re) = 500 to 2000) and afterwards turbulent (Re > 2000) (Figure 2). For all treatments and flows, the flow was supercritical (Froude number (F) > 1), except for the lowest flow for NTR, which was subcritical (F < 1), thus indicating that surface cover reduced flow velocity and modified the flow regime from supercritical to subcritical.

The mean weight diameter (MWD) of eroded sediments shows that the eroded sediments for RCT were greater than those eroded from the other treatments, and that with increasing flow the MWD increased rapidly at first and then at an increasing rate. For the CCT, a small decrease in MWD occurred at the beginning, probably due to the transport of large loose particles present at the soil surface, but with flow increase, the sediment size increased again. For NTB and NTR, the MWD increased slowly and reached equilibrium at high flows.

The soil loss rate (q_s) and sediment concentration (SC) for the RCT treatment, increased linearly with flow increase. For CCT, both q_s and SC increased rapidly with flow increase and, afterwards, decreased, and were lower than for RCT. For NTB and NTR, there was a small increase in q_s and SC with flow and, afterwards, a small decrease. Soil loss occurred in the following order: RCT > CCT > NTB > NTR.

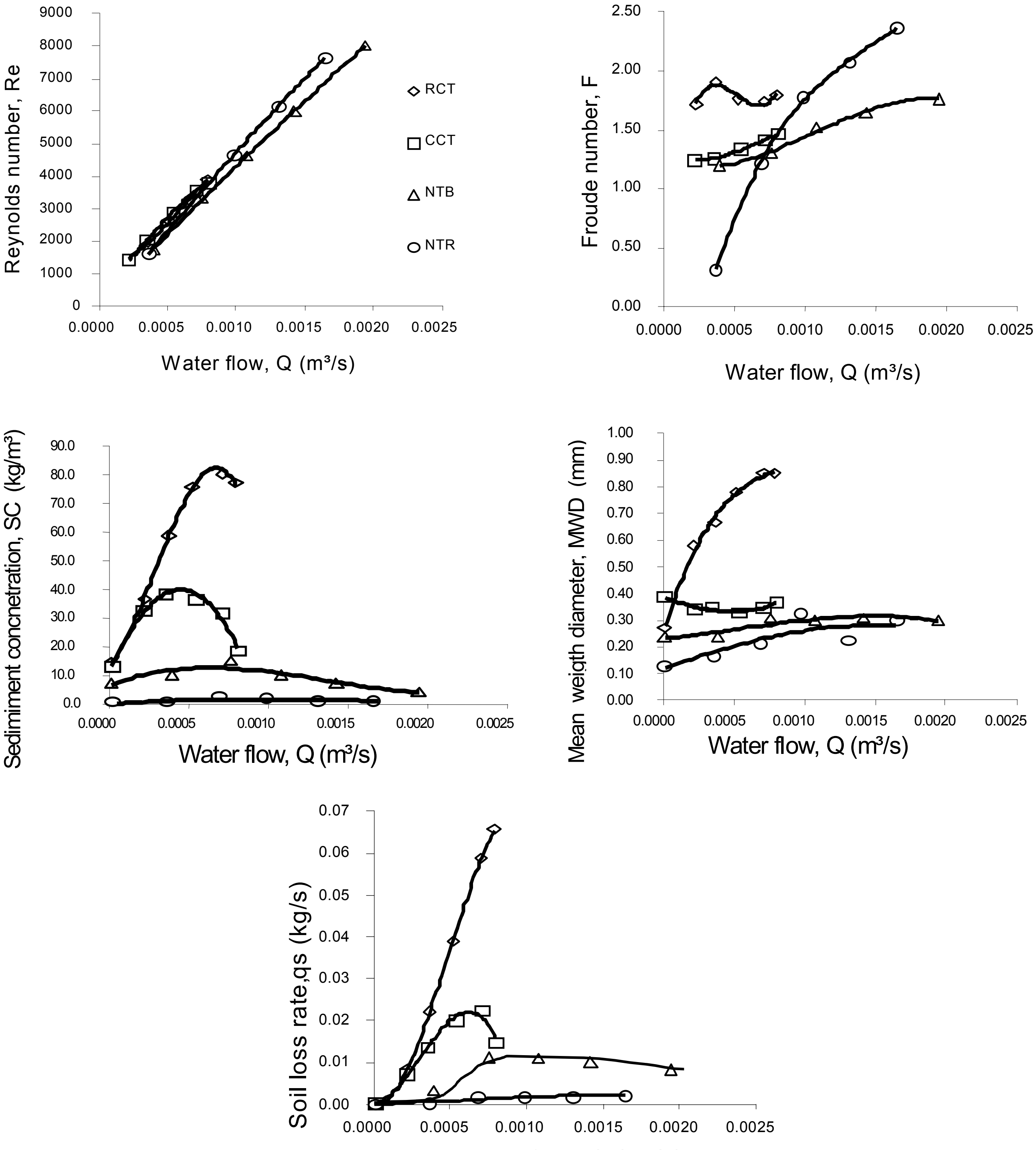

Figure 2. Reynolds (Re) and Froude (F) numbers, sediment concentration (SC), mean weight diameter (MWD) of eroded sediment, and soil loss rate (qs) versus water flow (Q), for four soil management systems.

CONCLUSIONS

For tropical soils, soil surface residue, soil consolidation, and soil aggregation are essential to controlling erosion and runoff, and their effects are complementary.

For the sandy loam tropical soil studied, with recent conventional tillage the interrill erodibility (K_i) was 1.77 x 10^6 kg s m^{-4}, rill erodibility (K_r) was 1.29 x 10^{-2} kg N^{-1} s^{-1}, and critical shear stress (τ_c) was 2.21 Pa. For conventionally tilled consolidated soil, K_i was 1.44 x 10^6 kg s m^{-4}, K_r was 0.38 x 10^{-2} kg N^{-1} s^{-1} and τ_c was 2.63 Pa for CCT.

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