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Relationships between rill sediment and flow time varying with freezing, groundcover, compaction and slope on a Prince Edward Island (Canada) fine sandy loam

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Abstract Rill erosion tests were conducted in the laboratory on a fine sandy loam under varying freezing, groundcover, surface compaction, and slope regimes. Using a 20-min test period of rill flow, runoff samples were taken at six sampling times to measure sediment dry mass. Freezing, groundcover, and slope had a significant ($P \leq 0.05$) effect on the mass of sediment in the flow at all sampling times. There was a general decline ($R^2 = 0.611$) in sediment dry mass with progressively later sampling; although treatment units subjected to freezing-and-thawing (frozen at the start of the tests) or compaction showed an initial rise, and thus better defined nonlinear ($R^2 = 0.822$ to 0.927) than linear regression models. In examining sediment size grades between 600 and <38 μm, only <38 μm showed significant differences in individual sample mass among sampling times. For this grade, there was significant decline for 7% slope ($R^2 = 0.901$) and for bare surface ($R^2 = 0.614$) in individual sample mass with later sampling.

INTRODUCTION

One of the major predisposing factors in soil erosion in Prince Edward Island (PEI), in the Atlantic Region of Canada, is the method of farming. Potato land is intensively cultivated, mostly on narrow holdings up-and-down slopes of 8 to 10% in the upper reaches. After harvesting, which involves heavy vehicular traffic and consequent soil compaction, the majority of fields lie bare until the following spring. These fields are mostly fall-disced, and under prevailing conditions their susceptibility to rill erosion could be expected to increase (Foster, 1982; Brown *et al.*, 1989).

PEI experiences an annual precipitation of about 1 000 mm. The cool period is characterized by prolonged gentle rains, frequent snowmelts, and several cycles of freezing-and-thawing, all of which could lead to soil structure deterioration (Edwards, 1991), reduced shear strength at the soil surface (Coote *et al.*, 1988) and, consequently, erosion. Edwards & Burney (1987) found this to prevail consistently for interrill flow from three contrasting PEI soils, particularly from the predominantly cultivated fine sandy loams. However, previously frozen soil is also known to be highly susceptible to rilling even from low-intensity rainfall and runoff (Van Klavern, 1987).

Although sediment in rill flow on non-frozen soil has been studied relative to familiar management factors including groundcover (Brown *et al.*, 1989) and, similarly, sediment in interrill flow has been studied for frozen soil (Edwards & Burney, 1989), little is known of sediment behaviour in rill flow on frozen soil with or without groundcover or other management factors on fine sandy loams under Atlantic Canada conditions. The authors have sought, therefore, to examine the role of selected, prevailing physical and management factors in rilling, and to assess specific relationships between sediment mass and rill flow time under cool-period conditions of PEI as part of a set of related studies (Frame *et al.*, 1992; Burney & Edwards, 1993) of the same soil material under the same circumstances.

In one of the related studies (Frame *et al.*, 1992), the effects of groundcover, slope and temperature on total sediment were found to be significant. Mean sediment dry mass from bare surfaces was over 10 times that from mulched surfaces; from 7% slope it was more than twice that from 3½%; and with freezing-and-thawing it was about 25% more than without freezing.

Sediment fractions in another related study (Burney & Edwards, 1993) showed that all size grades responded significantly to groundcover, yielding from 6 to 34 times more dry mass from bare than from mulched surfaces; size grades < 106 μm had a 22 to 47% greater mass with freezing-and-thawing than without; grades < 106 μm had a 13 to 41% greater mass from uncompacted than from compacted surfaces; and 7% slope had a 120 to 150% greater mass than 3½% slope.

METHOD

The experimental design was a randomized complete block of four treatments: (a) ***temperature*** (i) *freezing-and-thawing* and (ii) *no freezing,* (b) ***groundcover*** (i) *incorporated straw mulch* and (ii) *bare surface*, (c) ***layering*** (i) *surface compacted* and (ii) *non-compacted*, and (d) ***slope*** (i) *7%* and (ii) *3½%*. The study was done in a temperature controlled room using narrow, insulated troughs of galvanized steel in sets of four (Fig. 1). Each trough (3.6 m long, 200 mm wide, 150 mm deep) was fitted with a bottom pipe to facilitate drainage or saturation, and with an outflow gate that was vertically adjustable as rill development occurred. The downslope 3.41 m of the trough served as the test section, designed to handle an overland flow rate of 3 l min^{-1}, and be sufficiently long for adequate rill development (Van Klavern, 1987) by allowing the type of headcutting and undercutting with sidewall sloughing that occurs under field conditions. The upslope 250 mm of the trough was separated from the test section by wire mesh and filled with clean, crushed stone to dissipate energy and ensure smooth, uniform transition of inflow from the supply pipe. The test section was uniformly filled with a Charlottetown fine sandy loam (Edwards & Burney, 1989) and the surface was formed into a vee-shaped furrow (side slopes: 1:1.4, vertical:horizontal) as used by Van Klavern (1987). Chopped barley straw in 50-75 mm lengths was incorporated into the surface of appropriate treatment units. Soil compaction was uniformly achieved with a

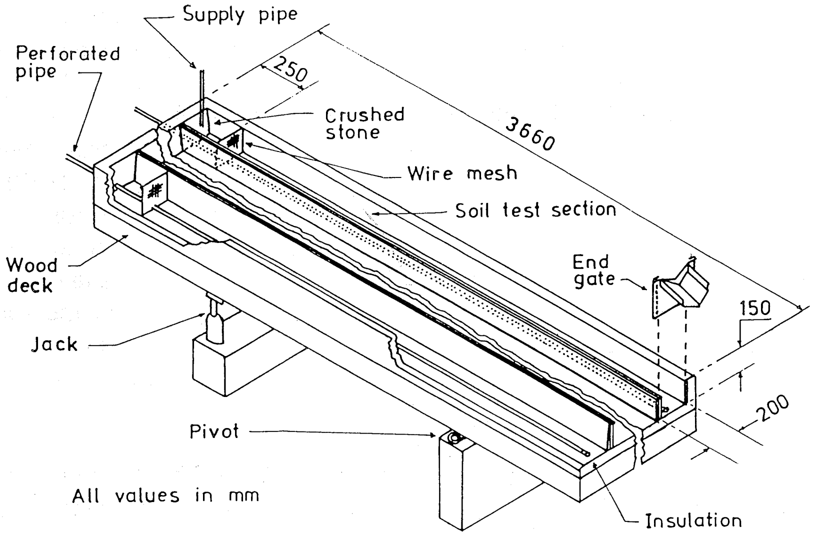

Fig. 1 A set of four contiguous, insulated soil troughs, showing far end trough (with exploded end gate) and sectioned near end trough only.

vee-shaped roller pulled, identically, along the surface of appropriate units using an electric motor. All units were saturated via the bottom pipe then drained in a horizontal position. The freezing treatment was applied by subjecting designated units to −5 °C for 12 h followed by thawing for 12 h (one freezing-and-thawing cycle) four times before applying the erosion tests at the end of the last freezing period.

Facilitated by jacks upslope and a pivot downslope, troughs were set at the appropriate steepness then subjected to 20 min of flow at an application rate of 3 l min^{-1}. Each runoff sample was collected for 14 s at the mid-point of each of six time increments: 0-2, 2-4, 4-8, 8-12, 12-16 and 16-20 min. Each sample was filtered through a nest of six sieves comprising: 600, 250, 106, 53 and 38 μm, and filter paper to collect <38 μm; and sediment dry mass determined for whole sediment and for each size grade. Sediment data were examined to study the relationship of treatments and treatment interactions with flow time, discretely (discrete temporal distribution of sediment) and cumulatively (cumulative temporal distribution of sediment). The level of significance observed throughout this study was $P \leq 0.05$.

RESULTS AND DISCUSSION

Cumulative temporal distribution of sediment

All treatments showed significant linearity in cumulative sediment increase over the 20-min sampling period (R^2: 0.976 to 0.999). Cumulative sediment totals ranged from 0.15 kg for mulched surfaces at 3½% slope to 6 kg for non-compacted bare, surfaces at 7% slope (Fig. 2). There was, therefore, a far steeper incline for *bare surface* variables than for *mulched surface* variables, indicating the contrastingly strong tendency for surface incorporated straw to suppress soil loss.

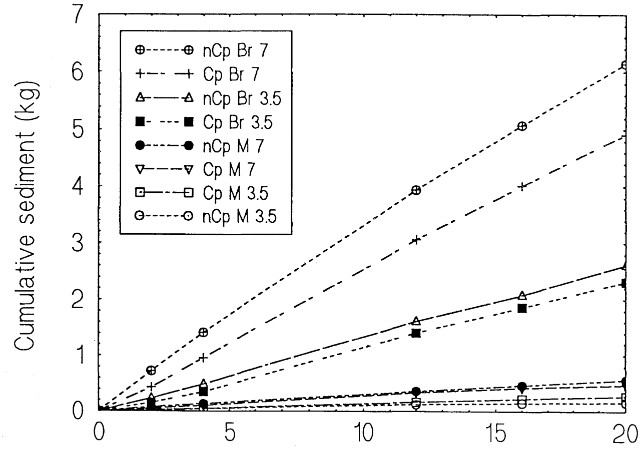

Fig. 2 Interaction effects of treatment on cumulative temporal distribution of sediment averaged over freezing and non-freezing treatments.

There were significant increases in sediment mass for all size grades studied (R^2: 0.961 to 0.989), a general reflection of the temporal trend of the unfractioned (whole) sediment.

The patterns of cumulative temporal distribution of sediment in this study were similar to those commonly reported on larger scales of observation or experimentation, and are thus discussed in far less detail than are the patterns of discrete temporal distribution of sediment.

Discrete temporal distribution of sediment

Whole sediment Temperature, groundcover and slope were significantly effective on sediment dry mass at virtually all sampling times (Table 1). There was a common tendency towards a decline at the end; but the simple effects of most of the treatment variables showed nonlinear patterns of distribution of sediment mass against sampling time (Fig. 3).

Both the *freezing-and-thawing* and *surface compacted* data showed significant convex quadratic patterns of distribution (R^2: 0.807 and 0.803 respectively) (Table 2), thus indicating an initial slow release of sediment, a subsequent increase and a final decrease (Fig. 3). Further examination even revealed a dominant critical exponential (right sense) (Payne *et al.*, 1987) component of regression for *freezing-and-thawing* (R^2: 0.967) and *surface compacted* (R^2: 0.866), thus indicating an equilibrium state after about the 14 min sampling time. This initial pattern of change in these two treatment variables, could be attributed to high soil shear strength at the initiation of the test runs: frozen for the freezing-and-thawing treatments, and compacted for the compaction treatments. In contrast, *no-freezing* had a significant, concave quadratic component (R^2: 0.857); although the variation due to regression was dominated by the linear-divided-by-linear (Payne *et al.*, 1987) component (R^2: 0.980), thus showing the largest sediment mass at the beginning and a subsequent decay to an asymptote, indicating an equilibrium in sediment mass after about the 14 min sampling time. *Non-compacted* also had a

Table 1 Effect of treatment on sediment dry mass over six sampling times (discrete samples).

Treatment	Mean sediment dry mass (g)					
	1 min	3 min	6 min	10 min	14 min	18 min
Temperature						
Freezing-and-thawing	71.4	113.4	132.9	143.1	126.0	116.1
No freezing	134.7	101.7	94.5	84.0	78.3	78.9
LSD (P=0.05)	39.9	NS	27.0	22.5	19.8	19.8
Ground cover						
Bare surface	182.4	196.5	206.4	205.5	184.5	181.2
Straw mulch	23.7	18.6	21.3	21.6	19.8	14.4
LSD (P=0.05)	39.9	30.6	27.0	22.5	19.8	19.8
Compaction						
Non-compacted	120.6	117.9	122.1	116.7	107.1	105.0
Compacted	85.5	97.2	105.0	110.4	97.2	90.3
LSD (P=0.05)	NS	NS	NS	NS	NS	NS
Slope (%)						
7	150.9	153.0	153.0	153.0	138.3	129.6
3½	55.2	62.1	74.1	74.1	66.0	65.7
LSD (P=0.05)	39.9	30.6	27.0	22.5	19.8	19.8

NS: Not significant at P=0.05.

significant concave quadratic component (R^2: 0.803) in contrast to *compacted*; but also showed a significant, descending linear trend (R^2: 0.767), and thus a gradual reduction in soil loss from start to finish.

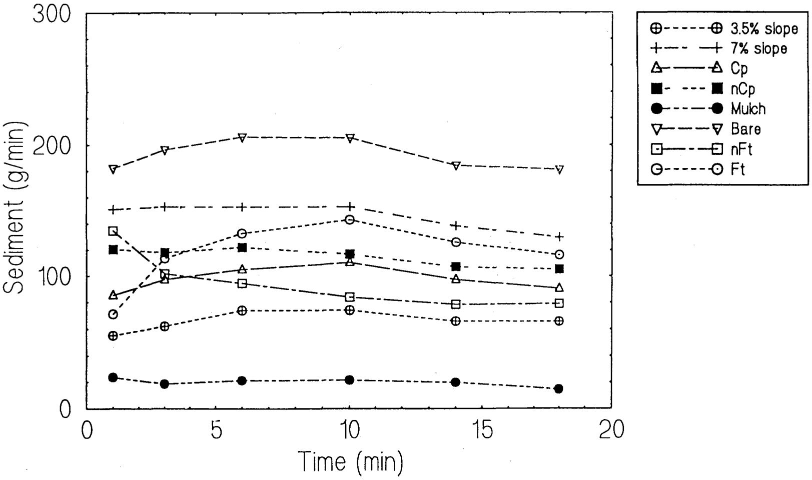

Fig. 3 Main effects of treatment on discrete temporal distribution of sediment.

Ongoing observations in year-round watershed and erosion plot studies in PEI (Burney & Edwards, 1994a,b) show relatively small amounts of sediment in erosion flow from frozen soil.

Where interaction effects were examined, especially for *temperature*, it was evident that all treatment units subjected to *freezing-and-thawing*, and thus frozen at the start of the test runs, had an initially increasing rate of soil loss followed by a decrease with time (Figs 4(a) and (b)), as was much the case for the simple effects of *freezing-and-thawing*. These treatments thus showed a significant quadratic component in the variation due to regression (R^2: 0.629 to 0.993), but was generally dominated by a critical-exponential (Payne *et al.*, 1987) component (R^2: 0.637 to 0.989), having a tendency to flatten near the end. In contrast, *non-frozen* soils showed an overall decreasing trend in the rate of soil loss (Figs 4(c) and (d)), and was generally of a decaying exponential fit (R^2: 0.716 to 0.999) (Table 3).

Groundcover showed the greatest effect of all treatments; and apart from the obvious contrasts in the means of sediment mass between *bare surface* and *mulched surface* shown in Table 1, there were great contrasts between these two treatment variables in regression variation of sediment against sampling time. The simple effects of *bare surface* best described an exponential model (Fig. 3) with a significant R^2 of 0.779 (Table 2), and its interaction effects also showed exponential tendencies with significant R^2 of 0.716 to 0.993 (Table 3). In contrast, for *mulched surface*, neither simple effects nor interaction effects data showed significant variation due to regression against sampling time. With straw, sediment mass was much the same from the beginning to the

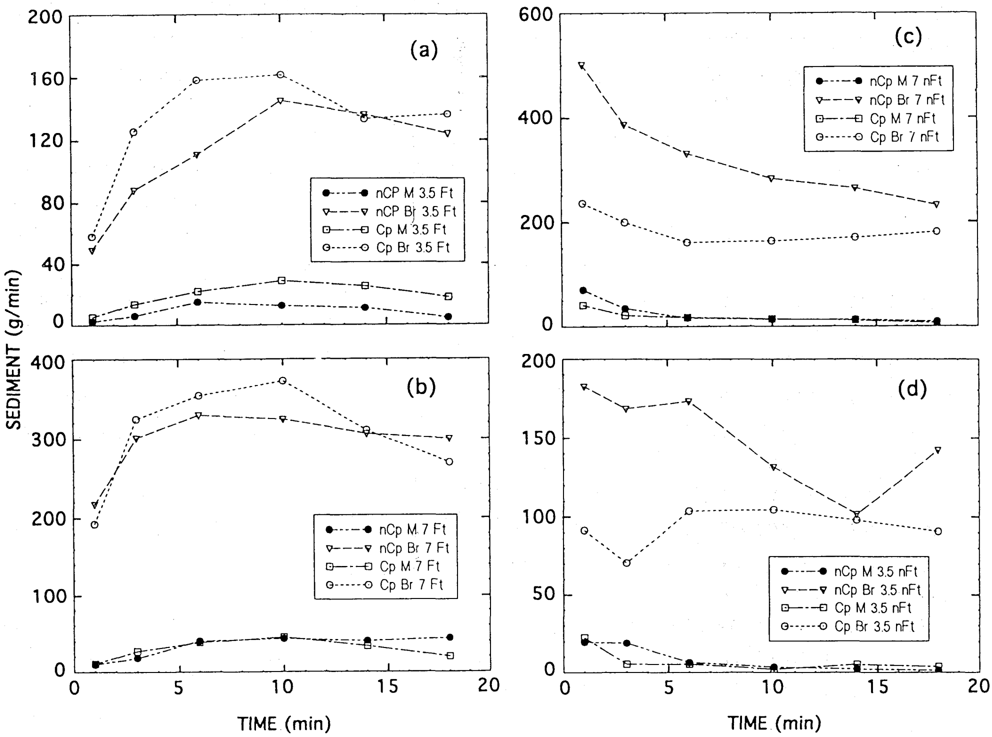

Fig. 4 Interaction effects of treatment on discrete temporal distribution of sediment.

Table 2 Significant ($P \leq 0.05$) regression relationships between sediment flow rate (S) and sampling time (t) for four treatments.

Treatment	Model[1]	Equation	r^2/R^2
Temperature			
Freezing-and-thawing	Quadr.	$S = 67.3 + 14.1t - 0.649t^2$	0.807
	C-exp.	$S = 76.65 + (-34.21 + 28.91t)\ 0.8689^t$	0.967
No-freezing	Quadr.	$S = 135 - 8.48t + 0.304t^2$	0.857
	LDL	$S = (188.8 + 62.23t)/(1 + 0.868t)$	0.980
Groundcover			
Bare surface	C-exp.	$S = 147.2 + (20.64 + 18.64t)\ 0.874t$	0.779
Mulched	-		-
Layering			
No-compaction	Linear	$S = 123 - 0.982t$	0.767
	Quadr.	$S = 120 + 0.16t - 0.0608t^2$	0.803
Compaction	Quadr.	$S = 82.2 + 5.36t -0.280t^2$	0.822
	C-exp.	$S = -3.799 + (80.60 + 15.29t)\ 0.9283^t$	0.866
Slope (%)			
7	Quadr.	$S = 150 + 1.57t - 0.153t^2$	0.927
	C-expl	$S = -137.6 + (285.7 + 13.52t)\ 0.963^t$	0.904
$3^1/_2$	C-exp.	$S = 47.0 + (-0.882 + 8.92t)\ 0.884^t$	0.753

[1] Payne et al., 1987.

(C-exp.): Critical exponential; (LDL): Linear divided by linear (rational function); (Quadr.): Quadratic; Where S = sediment in grams per minute; t= Time in minutes.

end of the runs (Figs 3 and 4). This capability of incorporated straw to significantly dampen variation in sediment over time, indicates its importance in the planning and practice of rill erosion control under the circumstances of this study.

Sediment fractions In examining sediment size grades, significant differences in individual sample mass among sampling times were found only for $<38\ \mu m$, declining ($R^2 = 0.691$ to 0.947) from about 0.40 g s^{-1} to 0.30 g s^{-1}. This size grade also showed uniquely significant interaction with *slope* or *groundcover.* Differences in mass between slopes (*7% > 3½%*) ranged from 237% at the first sampling time to 114% at the last sampling time. Only the 7% slope showed any significant decline ($R^2 = 0.901$) in individual sediment sample mass with later sampling. Differences in mass due to *groundcover* (*bare surface > mulched surface)* ranged from 8- to 13-fold from the first to the last sampling time. Only *bare surface* showed a significant decline ($R^2 = 0.614$) of sample mass with later sampling time.

The unique sensitivity of the $<38\ \mu m$ size grade to treatment has important practical and economic implications. It comprises the finest and most mobile fractions in the runoff. It is the most difficult to control in any system of soil conservation, and is mostly blamed for reduced productivity of the inland/inshore fisheries of PEI; as streams, rivers and estuaries suffer contamination by suspended sediment and silt.

Table 3 Significant ($P = 0.05$) coefficients of determination (R^2) for regression relationships between sediment flow rate and time for treatment interactions.

Treatment interaction			Model[1]	r^2/R^2
Cp	Br	3nF	C-exp.	0.716
Cp	Br	7nF	QDQ	0.994
Cp	Ml	3nF	LDL	0.943
Cp	Ml	7nF	L-exp.	0.998
nCp	Br	3nF	C-exp.	0.911
nCp	Br	7nF	QDL	0.993
nCp	Ml	3nF	QDQ	0.999
nCp	Ml	7nF	L-exp.	0.994
Cp	Br	3F	C-exp.	0.941
Cp	Br	7F	QDL	0.922
Cp	Ml	3F	Quadr.	0.993
Cp	Ml	7F	C-exp.	0.943
nCp	Br	3F	Quadr.	0.966
nCp	Br	7F	C-exp.	0.952
nCp	Ml	3F	Quadr.	0.744
nCp	Ml	7F	C-exp.	0.989

[1] Payne *et al.*, 1987
(Br): Bare surface; (Ml): mulched
(Cp): Compaction; (nCp): no compaction
(F): Freezing-and-thawing; (nF): no freezing
(C-exp.): Critical exponential
(L.exp.): Line plus exponential
(LDL): Linear divided by linear
(Quadr.): Quadratic
(QDL): Quadratic divided by linear
(QDQ): Quadratic divided by quadratic

PERSPECTIVE

Both freezing-and-thawing and surface compaction treatments are considered to have created a resistant soil surface. Under bare surface conditions, however, flow velocity would have been sufficient to erode this surface and, with time, come to less resistant soil material. By this time, rill development would have been active, thus resulting in high sediment loads. Sediment generation would then have declined as the rill developed a mature and stable shape. In similar regard, Loch (1984) reported substantial, initial increases in sediment concentration, which later declined, during rill development on rainfall simulator plots. In the present study, rill development for uncompacted or non-frozen treatments was observed to occur at the initiation of flow, with active cutting, followed by a mature profile.

With mulching, flow velocity was seen at every time to be substantially lower, and flow depth greater than it was for bare surface. There was, therefore, no concentrated cutting action; thus, soil loss was spread over a wider flow area, and tended towards uniformity as with interrill erosion. It is, however, considered that, with sufficient flow velocity under appropriate conditions of slope and time, rilling would have developed in the mulched surfaces. There is, therefore, little surprise from field observation in PEI that, conversely, mulched surfaces show hardly any rilling with snow melt erosion throughout the entire cool period on slopes of up to 10% (Edwards *et al.*, 1994).

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