# Laboratory measurement of freeze/thaw, compaction, residue and slope effects on rill erosion

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Frame, P.A., Burney, J.R. and Edwards, Linnell. 1992 **Laboratory measurement of freeze/thaw, compaction, residue and slope effects on rill erosion**. Can. Agric. Eng. **34**:143-149. The effects of alternate freezing and thawing (freeze/thaw) on rill erosion of a saturated Prince Edward Island (PEI) fine sandy loam were tested under complete factorial combinations of straw incorporation, surface compaction and slope. The test apparatus, installed in a temperature-controlled room, comprised troughs of soil (3.66 m long) with controlled inflow, adjustable outflow gates and sub-surface wetting and draining pipes. A uniformly-formed V-shaped depression (1:4.5 side slopes) in the soil surface concentrated rill formation down the centre during initial inflow application. Soil loss was nearly ten times greater from bare soil than from soil with incorporated straw; over two times greater on 7% slope than on 3.5% slope; and 24% greater on frozen soil previously subjected to freeze/thaw cycling than soil with no freezing. Overall compaction was not significant. However, the interaction between compaction and temperature was significant. With no freezing, soil loss was significantly greater without compaction, but with freeze/thaw compaction was not significant. For freeze/thaw treatments, sediment concentration initially increased with flow duration and then decreased; whereas for the treatments with no freezing, sediment concentration continually decreased with time. Bare soil and steeper slope produced deep and narrow rills throughout the rill lengths, whereas freeze/thaw and compaction treatments produced significantly deeper and narrower rills with substantial headcutting only in the upper reach.

Keywords: Rill erosion, laboratory, straw, compaction, freeze/thaw, sediment

Les effets de l'alternance du gel et du dégel sur l'érosion par ruissellement en terrain de silt sableux fin et saturé à l'Île-du-Prince-Édouard, ont été soumis à des essais factoriels complets: incorporation de paille, compactage de surface et pente. L'installation d'essai se trouvait dans une pièce à température régulée et comprenait des goulottes de terre (de 3,66 m de long) avec débit contrôlé à l'entrée, vannes de sortie ajustables et tuyaux de mouillage et de drainage. Une dépression dans le sol en forme de V et uniforme (pentes latérales de 1:4.5) concentrait la formation du ruissellement vers le centre durant les premiers essais. La perte de terre était près de dix fois supérieure pour le sol nu que pour le sol contenant de la paille; plus de deux fois supérieure sur une pente de 7% que sur une pente de 3%; et 24% plus grande sur un sol gelé précédemment soumis à des cycles de gel et de dégel que sur un sol non soumis au gel. D'une façon générale, le compactage n'avait aucune incidence. Cependant, l'interaction entre le compactage et la température eut les effets suivants: sans gel, la perte de sol était très supérieure sans compactage, tandis qu'avec le cycle gel/dégel, le compactage ne changeait rien. Pour les traitements de gel/dégel, la concentration de sédiments a augmenté initialement avec la durée du ruissellement, puis a diminué; alors que pour les traitements sans gel, cette concentration a continuellement décru dans le temps. Les sols nus et les pentes plus raides ont produit des rigoles profondes et étroites sur toute la longueur des ruisselets, tandis que les traitements de gel/dégel et de compactage ont produit des rigoles beaucoup plus profondes et plus étroites avec un creusement marqué uniquement en amont.

## INTRODUCTION

This study is part of a wider research project to assess the effect on soil erosion of selected soil management factors and climatic factors that prevail in Prince Edward Island (PEI) and relate particularly to the production of potatoes, the province's primary crop.

The wider project comprises both field and laboratory investigations. The field investigations include an on-going study of three instrumented, commercially-farmed sub-watersheds of contrasting agricultural characteristics, and associated experimental erosion plots in the upper reaches of the Wilmot River watershed in central PEI. Laboratory investigations have included studies on the effects of freezing, ground cover, and compaction treatments on interrill erosion of some PEI agricultural soils under simulated rainfall (Edwards and Burney 1987, 1989). These studies established the significant advantage of ground cover usage, particularly where the more fragile soils have been subjected to antecedent stresses by freezing or compaction. However, it could not be assumed that the effects would be the same for rill erosion. As noted by Line and Meyer (1989), and implicit in recent erosion prediction technology such as the USDA-Water Erosion Prediction Project (Nearing et al. 1989), soil erodibility and the effects of cropping/management practices may differ substantially for interrill and rill soil losses.

One of the major predisposing factors in soil erosion in PEI is the method of farming. Potato land is intensively cultivated, and much of it historically occupies narrow holdings on slopes of 8 to 10% in the upper reaches (Nowland 1975). Cultivation takes place up-and-down slope in most cases, and is practiced for operational convenience. After harvesting, which involves heavy vehicular traffic and consequent soil compaction, most fields are bare until the following spring. Often to facilitate spring operations, these fields are fall disced. Tillage greatly increases the susceptibility of a soil to rill erosion (Foster 1982; Brown et al. 1989). Furthermore, because this discing or any other tillage operation is done up-and-down the slope, rill formation is greatly facilitated. Rilling is highly evident following snowmelt in spring on bare, sloping PEI farmland (Fig.1).

Prince Edward Island experiences an annual precipitation of about 1000 mm. The cool period is, however, characterised by prolonged rains, frequent snowmelts, and several cycles of freeze/thaw. The cultivated soils are predominantly fine sandy loams which contain a frozen layer at varying depth during the cool period. Thus, with a saturated surface subject to periodic thawing (sitting on a frozen sub-surface), these soils with a weakened structure (Edwards 1991) and lowered shear strength (Coote et al. 1988) are prone to water erosion from late fall until spring, after which the sub-surface becomes permeable once more. As noted by Zuzel et al. (1982), under cool temperate, maritime conditions considerable soil erosion occurs during the cool season.

Previously frozen soil is highly susceptible to rilling even from low intensity rainfall and runoff (Van Klavern 1987) which could occur during much of the PEI cool period (Whiteside 1965). Brown et al. (1989) found that incorporated corn residue was highly effective in reducing erosion in rills under nonfrozen conditions.

A laboratory system (experimental apparatus and procedure) was designed to facilitate the assessment of the effect of selected physical and agronomic factors on erosion in a rill. In this study, the facilities were used to assess the effects of slope, soil compaction, freezing, and ground cover on the amount and temporal variation in soil loss and the resulting rill form.

## EXPERIMENTAL DESIGN

Experimental design comprised a randomized complete block in a factorial arrangement of four replications of four treatments: (1) temperature (freeze/thaw or no freezing), (2) ground cover (incorporated barley straw or bare surface), (3) layering (surface compacted or non-compacted), and (4) slope (7% or 3.5%).

## EQUIPMENT AND METHODOLOGY

The temperature-controlled room described previously by Edwards and Burney (1989) was utilized for the study. Two sets of four narrow troughs, designed to meet dimensional requirements for adequate rill development (Van Klavern 1987), were used. As shown in Fig. 2, each set of troughs was insulated to facilitate a natural pattern of freezing, a pipe was installed down the length of each trough to saturate or drain the soil, and a vertically adjustable gate was fitted at the outflow end of each trough so that rill development would not be impeded.

### Soil troughs

The soil troughs were constructed from sheets of 1.6 mm galvanized steel. Each trough was 3.66 m long, 200 mm wide and 150 mm deep. The downslope 3.41 m of each trough served as the test section. Each trough was fitted with a movable tail section/sampling port which could be vertically adjusted to remain level with the bottom of the rill as it developed during flow application. The lip of this tail section was made to have the same V-shape as that of the uneroded soil surface in cross-sectional profile. The sides and bottom of each set of troughs were insulated with 50 mm styrofoam to allow soil freezing treatment to take effect naturally - from the surface down.

The above trough dimensions were determined through preliminary tests, and based on a minimum flume length of 2.74 m advocated by Van Klavern (1987). The selected section was designed to handle an overland flow rate of 3

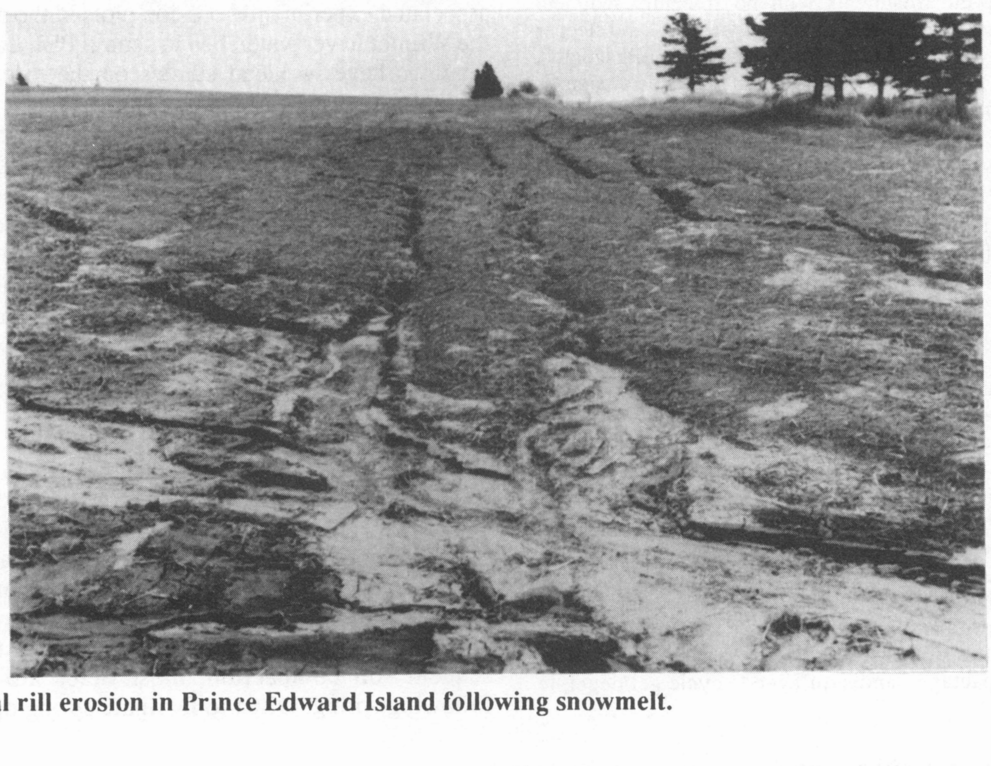

**Fig. 1. Typical rill erosion in Prince Edward Island following snowmelt.**

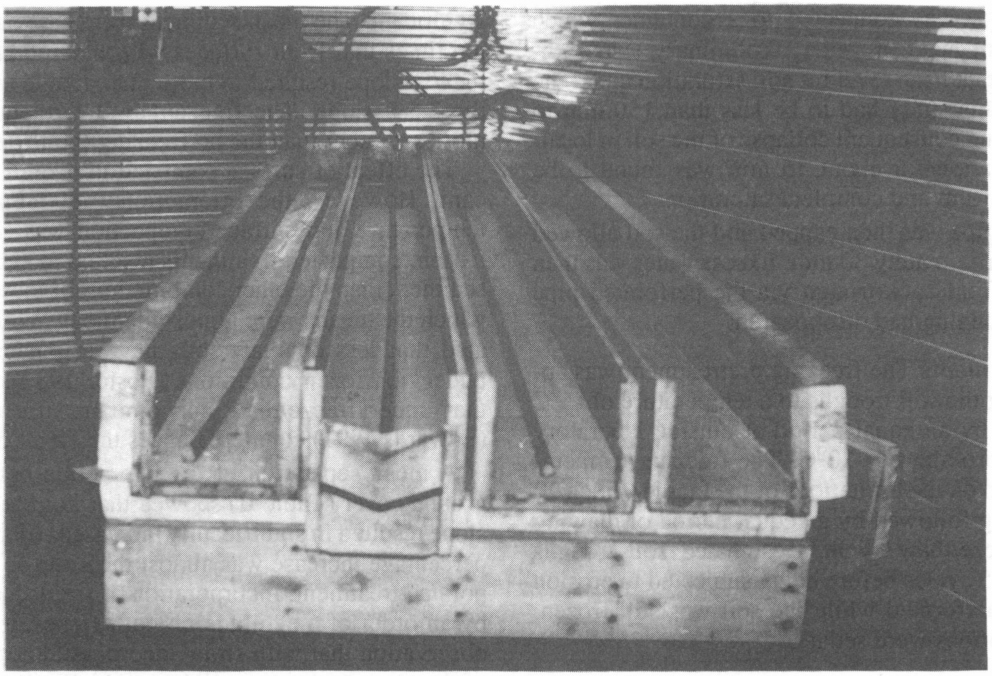

**Fig. 2. Set of soil troughs, looking upslope.**

L•min$^{-1}$, and be sufficiently long to allow the type of head-cutting and undercutting with sidewall sloughing that occurs under field conditions.

A 12.5 mm diameter perforated pipe was installed down the inside length (along the bottom) of each trough (Fig. 2). This pipe was capped at the downslope end, while at the upslope end it passed through the wall of the trough where it could be either connected to a water source for saturating the soil from below, open to allow for drainage, or plugged with a stopper.

Each set of troughs was mounted on a base constructed of 12 mm plywood over 36 by 138 mm joists. Each base was mounted on a pivot at the downslope end and a hydraulic jack at the upslope end to facilitate slope variation between 0 and 9 %.

**Soil preparation**

The soil used was a Charlottetown fine sandy loam of known physical characteristics (Edwards and Burney 1989). The soil was transported in bulk from PEI to the laboratory facilities in Halifax, NS. The soil then was prepared from the bulk pile by mixing to ensure homogeneity, followed by sieving through a 6 mm screen to remove lumps.

The upslope 250 mm of each trough was filled with washed, crushed stone to dissipate energy and ensure a smooth, uniform transition of inflow from the application supply pipe. This section was separated by a vertical fine mesh screen from the soil in the remaining test section of the trough. In later running of each rill test, the supply pipe outlet was inserted vertically downwards into the upper end of this dissipation section to prevent splash over the sides of the trough.

Soil was placed in each trough downslope of the dissipation section. After placement, the surface of the soil was levelled down the trough length. To eliminate sidewall influence, the soil cross-sectional profile was shaped to maintain rill evolution near the centre. To achieve this, the soil surface was shaped to a V-profile with side slopes of 1 (vertical) : 4.5 (horizontal) as used by Van Klavern (1987). Preliminary tests showed that, to achieve consistency, some surface tillage (for all treatments) was essential. This was attained by making three passes with a "weasel" tiller over the soil surface.

**Residue incorporation** For treatments having residue incorporation, barley straw was chopped into lengths of 50 to 75 mm and manually incorporated into the surface 50 mm of the soil at a rate of 3.6 t•ha$^{-1}$ using the "weasel" tiller, as reported by Edwards and Burney (1989) for interrill tests. The incorporation process was continued until the soil surface was in a uniform state and the V-shaped profile restored.

**Surface compaction** For treatments having surface compaction, a mechanical approach was used to ensure consistency and repeatability. The compaction apparatus comprised a 6.8 kg roller having the same surface profile as that of the V-shaped soil surface. The roller was pulled at constant speed along the length of each soil trough by a rope attached to an electric motor. It was established in preliminary tests that a travel speed of 1.25 m•min$^{-1}$ with four repetitions produced consistent compaction of the soil.

In compacting, the roller was positioned above the tail end of the trough and was allowed to settle onto the soil surface just as forward motion started. The soil next to the sampling gate could not be reached by this apparatus and was compacted manually.

**Initial saturation** Preliminary efforts to saturate the soil revealed the necessity for a method that would not disturb the prepared soil surface, or create uneven or partial saturation.

A sub-surface procedure was used with the soil troughs in a horizontal position. The pipe emerging from the upper end of each soil trough was connected to a container which provided a constant head of water. Preliminary tests indicated that the constant head level for soil saturation under the circumstances of this study had to be less than 150 mm to avoid up-welling and consequent collapse of the soil in localized areas. Application for about 45 min was found to be appropriate for uniform and complete saturation.

The perforated pipe was then capped and the soil allowed to stabilize for approximately 30 min. Excess water was then allowed to drain from each trough via the perforated pipe until all signs of ponding had disappeared.

**Freeze/thaw treatments** The freezing pretreatment was applied by subjecting the soil troughs to a temperature of -5°C for 12 h followed by an equal period at outside laboratory temperature of approximately 20°C. The freezing temperature used was based on the limitations of the facility. Each 12 h period of freezing followed by an equal period of thawing was termed a freeze/thaw cycle. Designated soil troughs were exposed to 4.5 cycles before being subjected to erosion tests which were performed while the soil was still frozen. Ambient test conditions were set at 0°C.

### Test procedure

Prior to each test, the application flow rate was calibrated to give 3 L•min$^{-1}$, the supply pipe was positioned and fastened vertically downwards into the energy dissipating section of the trough, the sampling port was adjusted to be level with the soil surface and the required slope was set.

Each trough was subjected, in turn, to a test period of 20 min of overland flow, at the end of which the water inflow was shut off. Six runoff samples were taken, one at each of 1, 3, 6, 10, 14 and 18 minutes, with reference to the time at which overland flow first reached the sampling port. These samples represented flow during the periods: 0-2, 2-4, 4-8, 8-12, 12-16 and 16-20 minutes. Each sample was collected for 14 s centered on the time value, thereby allowing integration of the sample data over the 20 min flow duration to estimate total erosion loss. Sample volumes were measured and each sample was vacuum-filtered. The resulting sediment was oven-dried and weighed for the determination of sediment concentration. A set of soil troughs following test runs is shown in Fig. 3.

The area and perimeter of each rill was measured at the quarter points (2.55 m, 1.70 m and 0.85 m from the sampling port). To achieve this, a 150 by 130 mm metal plate was inserted perpendicularly across the rill at each measurement point. The metal plate was then spray painted and retained for measuring rill cross-sectional area and perimeter. Rill area to perimeter ratio was analyzed as a descriptive measure of rill development.

## RESULTS AND DISCUSSION

An analysis of variance was performed on the total sediment, on the sediment concentration data at each time value and on the cross-sectional rill profiles.

### Total sediment

As shown in Table I the effects of residue, slope, and temperature regime on soil loss over the 20 min test period were significant. The mean sediment from bare surfaces was over ten times that from surfaces with incorporated straw, while the 7% slope resulted in more than double the soil loss from the 3.5% slope. The freeze/thaw treatment produced 24% more sediment than the no freezing (nonfrozen) treatment.

The effect of surface compaction overall was not significant. However, the interaction (not tabulated) between temperature and surface compaction was significant. Nonfrozen, compacted treatments resulted in substantially lower sediment than the other combinations of these treatments, for which the means were almost identical. While this substantiated that less compact soils have a greater rill erodibility under nonfrozen conditions (Foster 1982), it is postulated that under freeze/thaw concomitant structural breakdown (Edwards 1991) counterbalances the effect of compaction.

A mean separation of the interaction between slope and ground cover (Table II) showed that, for bare soil, increased slope resulted in significantly increased soil loss although the percentage increase was almost the same as the straw incorporated treatment. Incorporation of straw decreased soil loss by an order of magnitude on both slopes. It was evident by observation that with straw incorporation, exposed portions of the straw created small dams which substantially reduced

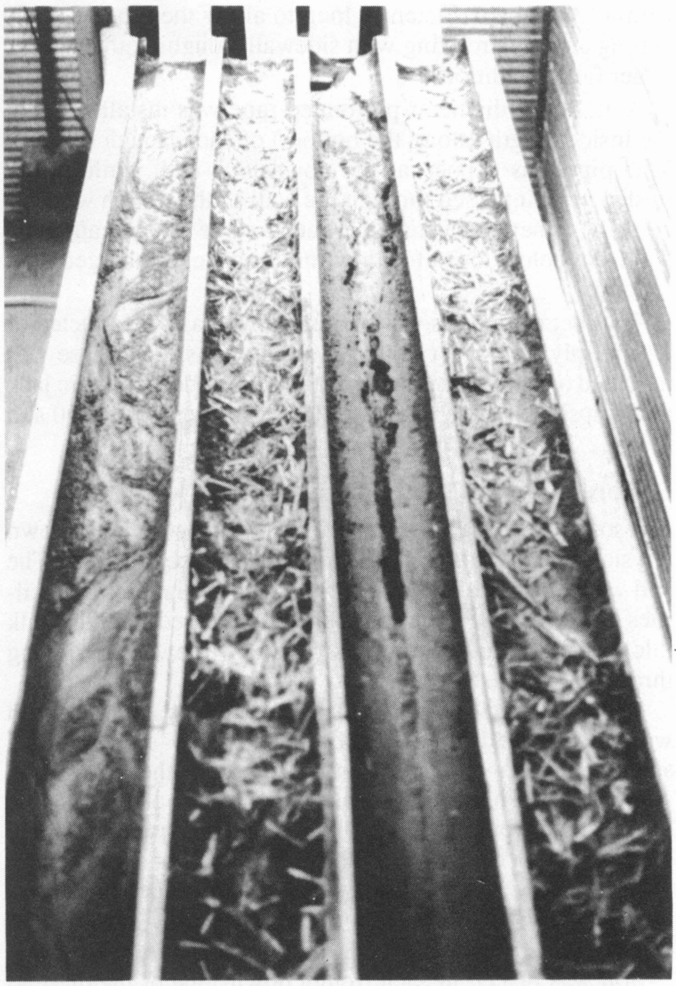

**Fig. 3. Rills developed in troughs at end of a set of test runs, looking downslope.**

**Table I: Effects of treatments on sediment concentration and total sediment.**

| Treatment | Mean sediment concentration at specified times (g/L) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | 1 min | 3 min | 6min | 10 min | 14 min | 18min | sediment (g) |
| Temperature Regime | | | | | | | |
| Freeze/Thaw | 23.8 | 37.8 | 44.3 | 47.7 | 42.0 | 38.7 | 2419 |
| Nonfrozen | 44.9 | 33.9 | 31.5 | 28.0 | 26.1 | 26.3 | 1945 |
| LSD (P=0.05) | 13.3 | NS | 9.0 | 7.5 | 6.6 | 6.6 | 458 |
| Residue | | | | | | | |
| Bare | 60.8 | 65.5 | 68.8 | 68.5 | 61.5 | 60.4 | 3998 |
| Incorporated Straw | 7.9 | 6.2 | 7.1 | 7.2 | 6.6 | 4.8 | 367 |
| LSD (P=0.05) | 13.3 | 10.2 | 9.0 | 7.5 | 6.6 | 6.6 | 458 |
| Compaction | | | | | | | |
| Non-compacted | 40.2 | 39.3 | 40.7 | 38.9 | 35.7 | 35.0 | 2371 |
| Compacted | 28.5 | 32.4 | 35.0 | 36.8 | 32.4 | 30.1 | 1994 |
| LSD (P=0.05) | NS | NS | NS | NS | NS | NS | NS |
| Slope (%) | | | | | | | |
| 7 | 50.3 | 51.0 | 51.0 | 51.0 | 46.1 | 43.2 | 3026 |
| 3.5 | 18.4 | 20.7 | 24.7 | 24.7 | 22.0 | 21.9 | 1339 |
| LSD (P=0.05) | 13.3 | 10.2 | 9.0 | 7.5 | 6.6 | 6.6 | 458 |

NS = not significant at $P \leq 0.05$.
LSD = least significant difference.

flow velocity. This indicated that partially incorporated straw could be an effective treatment to control or reduce soil erosion on long sloping fields.

### Temporal effects

An analysis of variance for sediment concentration at each of the six sampling times (Table I) showed the same effects as for the total sediment mass. However, as shown in Fig. 4, the nonfrozen soils showed a continually decreasing rate of soil loss with time towards an equilibrium rate, whereas the soils subjected to freeze/thaw pretreatment, and which were frozen at the start of the test runs, showed an initial increasing rate of soil loss followed by a decrease.

### Rill profile analysis

Analysis of variance was used to test the effects of the treatments on the ratio of rill area to rill perimeter measured at three positions down the final rill length (Table III).

The most marked effect was that of residue. Deep and narrow rilling occurred down the full length of the profile on bare soil. For treatments with straw incorporation, any rills which formed were shallow and wide.

The two slopes produced markedly different rill profiles at each of the measured locations. The steeper slope produced deeper and narrower rills; however, the difference decreased down the length of the rills.

The temperature and compaction treatments showed significant differences only at the upslope location (Position A). At this location the freeze/thaw treatment produced deeper and narrower rills with marked headcutting, whereas the nonfrozen treatments tended to produce smooth downslope profiles. The freeze/thaw treatments also produced substantial sidewall sloughing and undercutting, leaving an overhanging frozen lip on the surface.

**Table II: Effect of interaction between slope and groundcover treatments on sediment mass.**

| Slope (%) | Bare surface (g) | Incorporated straw (g) |
|---|---|---|
| 7 | 5529 | 522 |
| 3.5 | 2467 | 211 |
| LSD (P=0.05) | 648 | NS |

NS = not significant at $P \leq 0.05$
LSD = least significant difference.

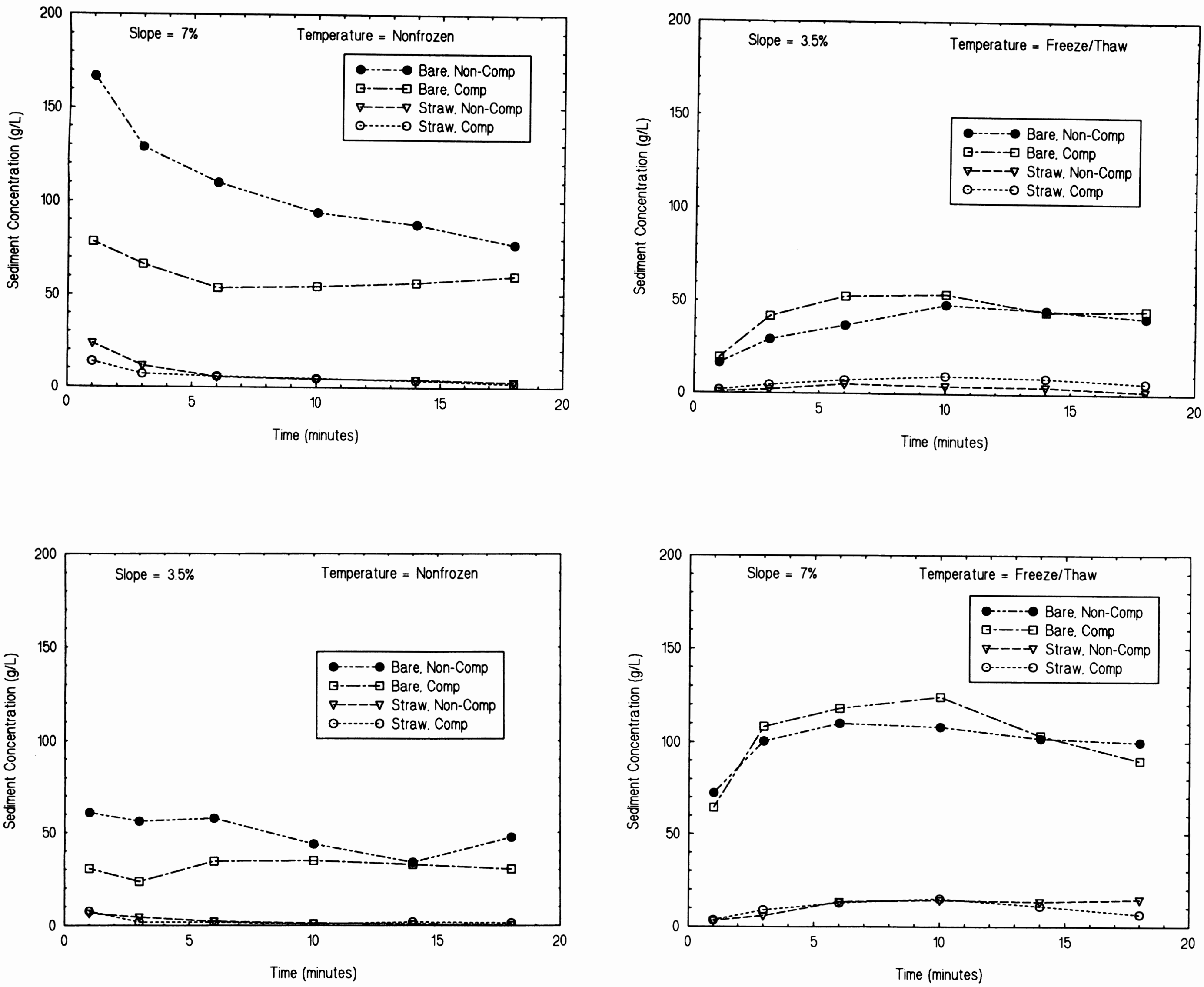


**Fig. 4. Effects of treatments on temporal sediment concentration.**

## CONCLUSIONS

The highly beneficial effect of straw incorporation in reducing sediment loss (by a factor of ten) in rills was clearly evident. When compared with previous interrill tests (Edwards and Burney 1989) in which incorporated straw reduced interrill soil loss by 50%, this indicates that the straw treatment had its major effect in reducing rill erosion.

Equilibrium sediment concentration in the prior interrill study ranged narrowly between 12 and 18 $g \cdot L^{-1}$, whereas in this study sediment concentration ranged widely between 5 and 60 $g \cdot L^{-1}$ (Table I). This indicates that:

1. On bare slopes considerable rill erosion is likely to occur as interrill sediment does not satisfy rill transport capacity. This effect will be most marked on steeper slopes since interrill erosion is little affected by slope, whereas rill erosion increased markedly with increased slope.
2. On slopes protected by straw incorporation, deposition of interrill sediment is likely to occur as the interrill sediment supply exceeds rill flow transport capacity.

Surface compaction had no significant effect on soil loss in rills under freeze/thaw conditions. Although compaction increased interrill erosion in the previous study (Edwards and Burney 1989), it would appear that heavy vehicular traffic used during harvesting of potatoes in PEI has little effect on soil erosion during the cool season.

**Table III: Effects of treatments on rill area - perimeter ratio.**

| Treatment | Mean area-perimeter ratio (mm) | | |
|---|---|---|---|
| | A+ | B | C |
| Temperature regime | | | |
| Freeze/Thaw | 6.49 | 6.10 | 6.49 |
| Nonfrozen | 5.28 | 6.11 | 5.90 |
| LSD (P=0.05) | 0.95 | NS | NS |
| Residue | | | |
| Bare | 7.49 | 7.91 | 8.23 |
| Incorporated straw | 4.29 | 4.30 | 4.15 |
| LSD (P=0.05) | 0.95 | 1.16 | 1.50 |
| Compaction | | | |
| Non-compacted | 6.48 | 6.27 | 6.40 |
| Compacted | 5.30 | 5.93 | 5.99 |
| LSD (P=0.05) | 0.95 | NS | NS |
| Slope (%) | | | |
| 7 | 7.09 | 7.34 | 6.93 |
| 3.5 | 4.68 | 4.86 | 5.46 |
| LSD (P=0.05) | 0.95 | 1.16 | NS |

NS = not significant at $P \leq 0.05$.

+ Positions A,B, and C at 2.55, 1.70, and 0.85 m upslope of outflow gate, respectively.

LSD = least significant difference.


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