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Freeze–thaw effects on vehicular ruts and natural rills: importance to soil-erosion and terrain modelling

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Abstract Overland flows in vehicle ruts and naturally formed rills can be the dominant carriers of sediment down a hillslope. This research addresses the effects of soil freeze–thaw (FT) on rill and rut geometry, soil density, and infiltration, which partially determine water runoff quantity and velocity, and soil erodibility. Laboratory experiments and field observations showed that soil FT (a) decreased the channel hydraulic radius (*R*) of a rectangular rill and wheel ruts up to 33%, (b) increased infiltration in wheel ruts by 62%, (c) decreased unconfined compression strength and shear strength in wheel ruts up to 81% and 57%, respectively, and unconfined compression strength in track ruts up to 60%, and (d) formed a V-shaped, 11-cm-deep rill in a track rut on a 17° slope during spring thaw, while uncompacted soil adjacent to that rut showed no evidence of rill formation. These results can be used in soil-erosion and terrain-evolution models to account for overwinter modifications to hillslope hydrology and soils.

INTRODUCTION

Vehicle ruts, natural rills, and soil erosion

A vehicle travelling overland can rut the soil surface and often can compact soils to some depth. Soil compaction affects hillslope hydrology and soil-erosion potential because the denser soil reduces infiltration and hydraulic conductivity (Horton *et al.*, 1994), which increases surface water runoff volumes (Mathier & Roy, 1993) and lengthens runoff periods (Hinckley *et al.*, 1983). Iverson (1980) measured more eroded sediment from hillslope plots used by off-road vehicles than from unused plots.

Voorhees *et al.* (1979) reported that ruts can channelize surface runoff and increase sediment transport capacity of runoff, and Foltz (1993) measured 200–400% more erosion from rutted than unrutted roads. In addition, Morgan (1977) among others report that rill flows carry far more sediment off a hillslope than unchannelled flows. The erosivity of rill and rut flows is directly related to runoff velocity and volume, which are functions of *R* and infiltration.

Freeze–thaw effects on ruts and rills

Ice that forms in soil can push soil grains apart and reduce soil density. The amount of this soil expansion depends on soil-water content, soil texture, the volume of water drawn to the freezing zone from below, the rate of frost penetration, and the number of FT cycles (Miller, 1980). A soil with ice in its voids often has very low cohesion upon thaw because of excess soil water and reduced particle interlocking and friction. This weakened state persists until the excess water drains and cohesion is re-established. A thawed soil can easily flow and slide downslope.

In some locations, frost-induced soil creep obliterates natural rills over one winter (Carson & Kirkby, 1972); however, detailed studies of FT effects on ruts and rills have not been done. Kok & McCool (1990) report that soil FT effects on soil-erosion mechanics are poorly understood despite extensive research on FT physics, and this inability to model seasonal soil erodibility impedes improvements in soil-erosion predictions (Nearing *et al.*, 1994).

The specific objectives of the laboratory experiments and field studies reported here were to (a) measure the FT-induced changes in the geometry, density, and infiltration in vehicle ruts and natural rills, and (b) understand the differences in frost penetration, frost heave, thaw progression, and soil-water redistribution between compacted rut soil and uncompacted soil.

APPROACH

Lab experiments

Insulated plywood bins, each 1.2 m wide × 2.4 m long × 0.6 m deep, were filled with a clayey silt. Each bin was set horizontally and each was a closed system, with the only water available for freezing being that in the soil at the start of the experiments. The volumetric soil-water content for the rill experiment was 35% (92% saturated), for the first rut experiment (Rut I), 23% (46% saturated) and the second rut experiment (Rut II), 34% (87% saturated). I controlled soil-water content and FT rates during the experiments.

A rectangular, 10-cm-deep × 20-cm-wide rill was dug in the soil surface of one bin for the rill experiment (Fig. 1). Rectangular rills typically form in moderately cohesive silts. For the Rut I and II experiments, an empty pickup truck was driven on the soil to form four ruts, 6–15 cm deep × 22–30 cm wide, one rut per bin (Fig. 1). The rill was frozen and thawed twice, the ruts, three times.

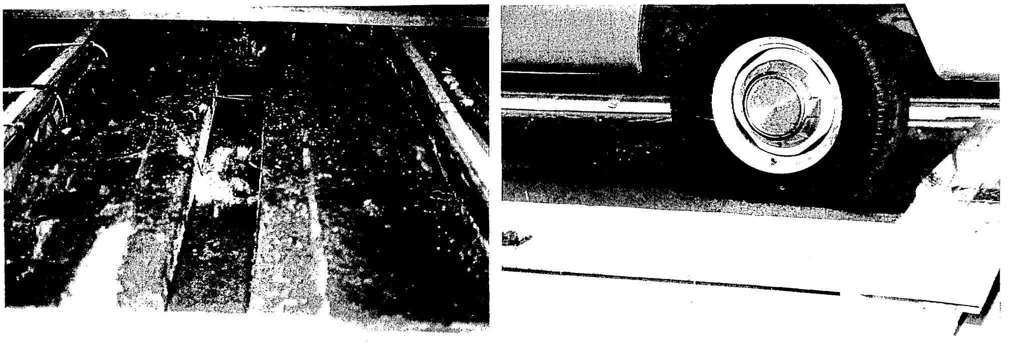

Fig. 1 Rectangular rill at the end of the first freeze (*left*), and wheel rut formed for the Rut I experiment.

Soil-resistivity gauges measured frost depth (Atkins, 1979), thermocouples measured soil temperature and Vitel Hydra probes measured volumetric, soil-water content during FT cycling. I measured surface soil unconfined compressive and shear strengths with a pocket penetrometer (Soiltest CL-700A) and a Torvane shear device (Soiltest CL-600A) and water infiltration with a 5-cm-wide, single-tube infiltrometer. Rill and rut cross-sections were measured from a bar datum mounted above the soil surfaces, and the hydraulic radius was calculated from the rill and rut cross-sections. Gatto (1997a,b) details bin-soil characteristics, preparation, instrumentation, and measurements.

Field studies

I established a field research site on an east-facing hillside with variable slopes from 4° to 17° and with 12 natural rills and gullies at Ethan Allen Firing Range (EAFR), Jericho, Vermont (Fig. 2), in October 1996. Soil at the site is a silty sand and vegetation consists of patchy grasses. An Abrahms tank produced 20 distinct, shallow ruts perpendicular to the hillslope contours, and a wheeled HMMWV formed 18 compacted paths (but no measurable ruts). Volumetric, soil-water content at the time of trafficking was 15–38% (33–76% saturation). Soil-frost depths and soil temperatures, unconfined compressive strengths, soil-water contents, and standard weather data were collected on site.

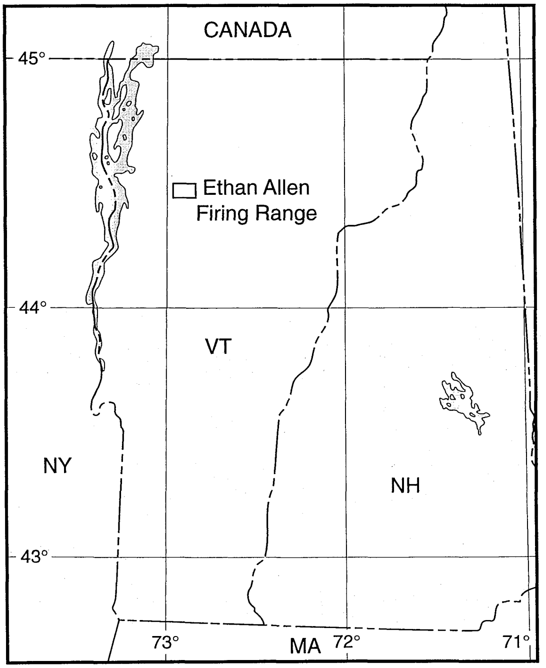

Fig. 2 Ethan Allen Firing Range field site location.

RESULTS

Lab experiments

Rill experiment The first freeze (F1) lasted 9.7 days; the soil froze to 14 cm and took 1.6 days to thaw. F2 lasted 14.8 days; the soil froze to 25 cm and took 3 days to thaw. Upon thaw the water content of the surface soil out of the rill was about 3% higher than before freezing and took 2–3 days to drain. Ice lenses in the surface soil and scattered needle ice on the soil were evident at the end of F1 and F2.

The amount of frost heave that occurs during freezing gives an idea of the volume of water in the soil at the start of thaw, and the degree of FT-induced rill sideslope slumping is directly related to this water volume. Out-of-rill (OR) frost heave averaged 1.5 cm during F1 and in-rill (IR) heave was 0.4 cm. During F2 OR heave was 2.5 cm and IR was 1.4 cm. F2 lasted 5.1 days longer than F1, which caused more water to be drawn to and freeze in the freezing soil.

The rill profiles measured before F1 and after the second thaw (T2) (Fig. 3) show the dramatic change in the rill geometry due to FT cycling. During thaw, the saturated sidewall soil flowed and slid down the rill in variably sized soil masses along its entire length, and tension cracks along the rill crests defined the blocks of soil that had begun to slide or were about to slide. These soil flows and slides changed the rill cross-section sufficiently to reduce the rill R by as much as 33% with a bankfull flow. Such a reduction in R would cause the velocity of the bankfull flow to decrease by 24%, using Manning's equation to estimate velocity.

Rut experiments Rut I is complete; Rut II is underway, so most discussion here refers to Rut I results. F1 lasted 19.2 days, F2, 9 days, and F3, 8.8 days during Rut I. Rut soil started to freeze 1–2 days later; it froze as much as 43% faster once freeze started and thawed slower than adjacent, unrutted soil. The OR soil thawed up to

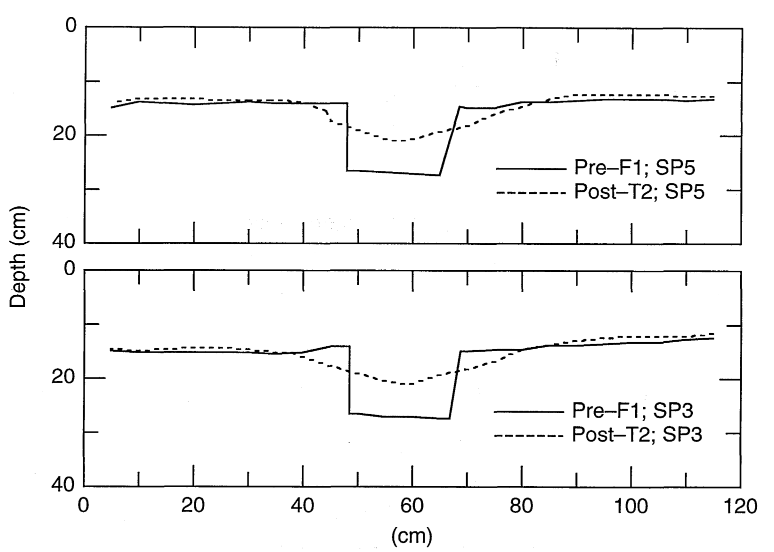

Fig. 3 Typical rill profile changes that occurred during the rill experiment.

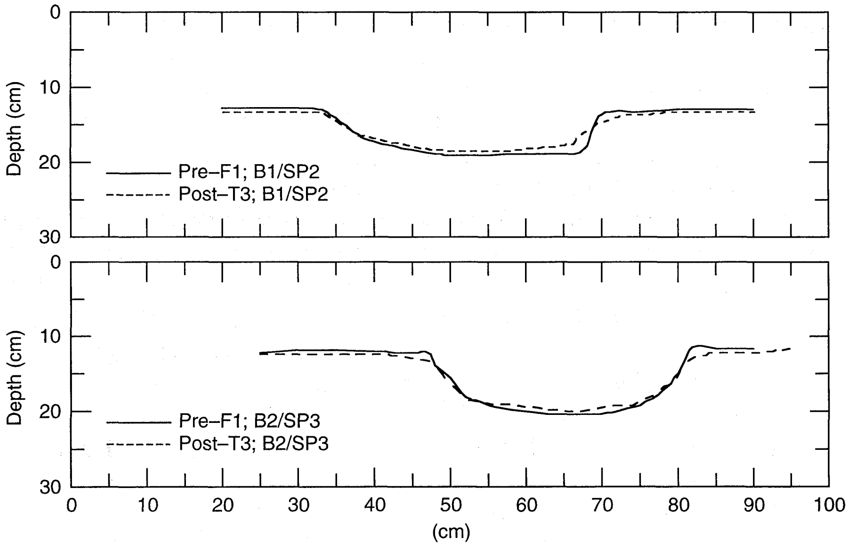

Fig. 4 Typical rut profile changes that occurred during Rut I.

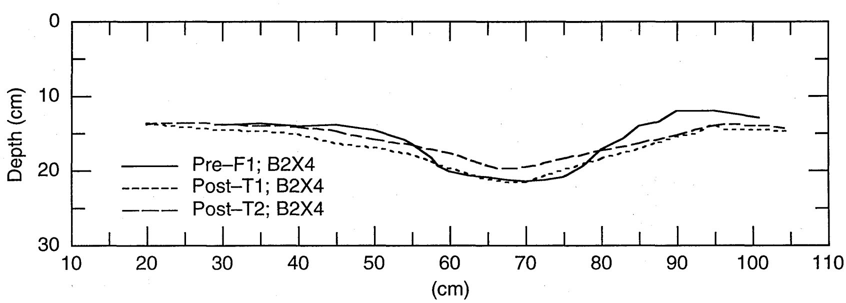

Fig. 5 Typical rut profile changes that occurred so far during Rut II.

44% faster than IR soil. The faster IR frost penetration occurs, possibly because the compacted soil had less air-filled voids, more particle-to-particle contacts per unit volume, and better heat transfer (higher thermal conductivity) to the cold air than the uncompacted soil. OR and IR frost penetration rates were similar after the freezing process loosened the compacted rut soil during F1.

The initial volumetric, soil-water content during Rut I was 23%, which was 12% and 11% lower than during the rill and Rut II experiments, respectively. OR frost heave during Rut I was ≤0.08 cm, and IR heave was 0.02–0.37 cm, about 10 times lower than during the rill and Rut II experiments. Water in the OR surface soil increased by about 5% more than that in IR soil and the OR soil water drains more rapidly than the IR, possibly due to reduced soil-void interconnectedness in the compacted, rut soil.

The unconfined compressive and shear strengths of the compacted rut soil decreased by 35% and 13%, respectively, during Rut I, and by 81% and 57% during Rut II. The reduced strengths reflect the reduced compaction and grain-to-grain contact in the soil caused by soil water expansion in the soil voids during freezing.

Consequently, the infiltration into the less-dense IR soil increased by 62% during Rut I. Infiltration was impractical to measure during Rut II because it was so slow in the wetter Rut II soil. These results suggest that the increased IR infiltration rate could lead to less runoff volume coming off compacted soil after FT cycling, but that runoff would flow over less dense and possibly more erodible rut soil.

The degree of rut cross-sectional change primarily depends on soil-water content. Thus far, less change in rut geometry occurred during Rut I (Fig. 4) than Rut II (Fig. 5), and the *R* of the ruts decreased by a average of only 9% during Rut I. Figure 5 suggests, however, that the *R* during Rut II will decrease by an amount closer to that during the rill experiment because the soil-water content during the rill and Rut II experiments were similar. These experimental results help interpret my field observations.

Field studies

Field observations and measurements from October 1996 through April 1997 show that the frozen, surface soil thawed seven times from 16 January to 2 March 1997 and the final spring thaw began on 27 March. Most rut and rill cross-sections showed minor frost heave over the winter (Fig. 6) and only a few scattered soil slides

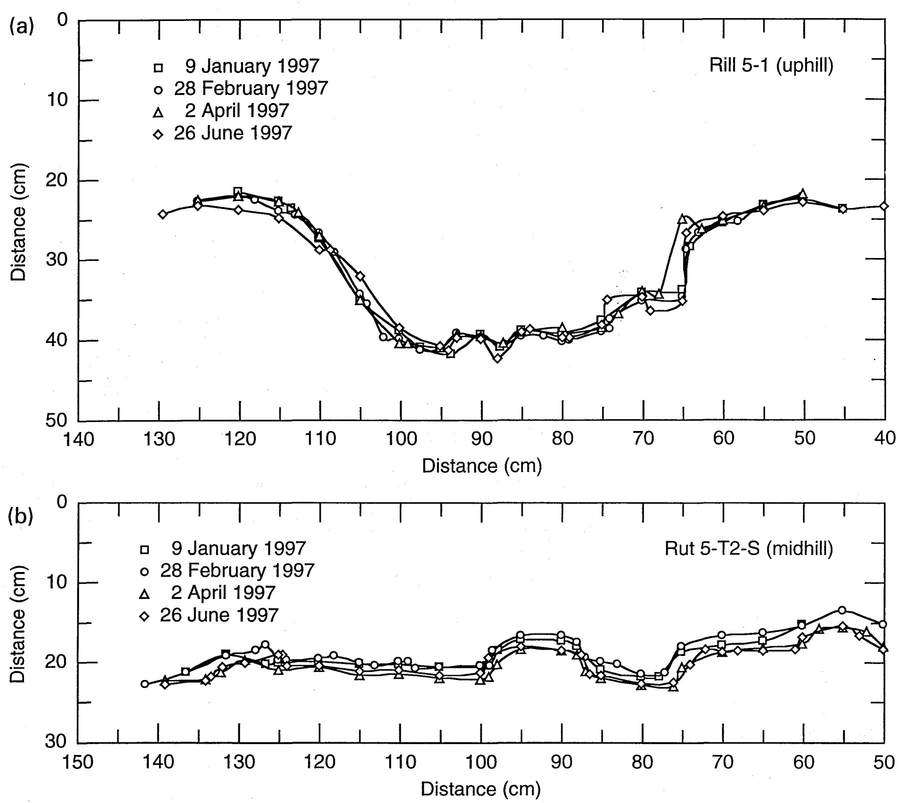

Fig. 6 Typical rill (a) and rut (b) profile changes, January–June 1997.

Fig. 7 Small rill channels formed through track pad depressions.

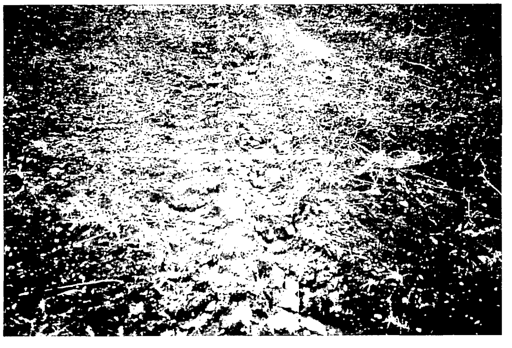

Fig. 8 Rill (11-cm deep) formed in track rut on a 17° slope.

occurred along the sidewalls of the deeper rills and gullies during thaw after 27 March 1997. However, some track ruts on all the slope plots showed rills less than 2 cm deep through the track pad depressions and pockets of deposited sediment in the rut depressions from the intermittent flows within the ruts (Fig. 7). On several occasions I observed 1- to 5-mm-deep flows in the ruts when there was no surface flow on the adjacent, unrutted soil. A distinct V-shaped, 11-cm deep rill formed in a track rut (Fig. 8) on the 17° slope, while soil adjacent to that rut showed no evidence of rill initiation. The wheel path surfaces did not change over the winter.

The coarser texture and the generally lower water content of this EAFR soil cause it to be less frost susceptible than the soil I used in the laboratory experiments. Thus, I expected to observe less FT-induced changes to the ruts and rills. In addition, the vegetation roots at this site hold the surface soil in place. However, I still measured a 60% reduction in the overwinter, unconfined compressive strength of the track-rut soil, 50% in the wheel paths, and 29% in the untrafficked soil (Fig. 9).

CONCLUSIONS

Vehicles travelling overland compact and often rut soils, which can increase hillslope

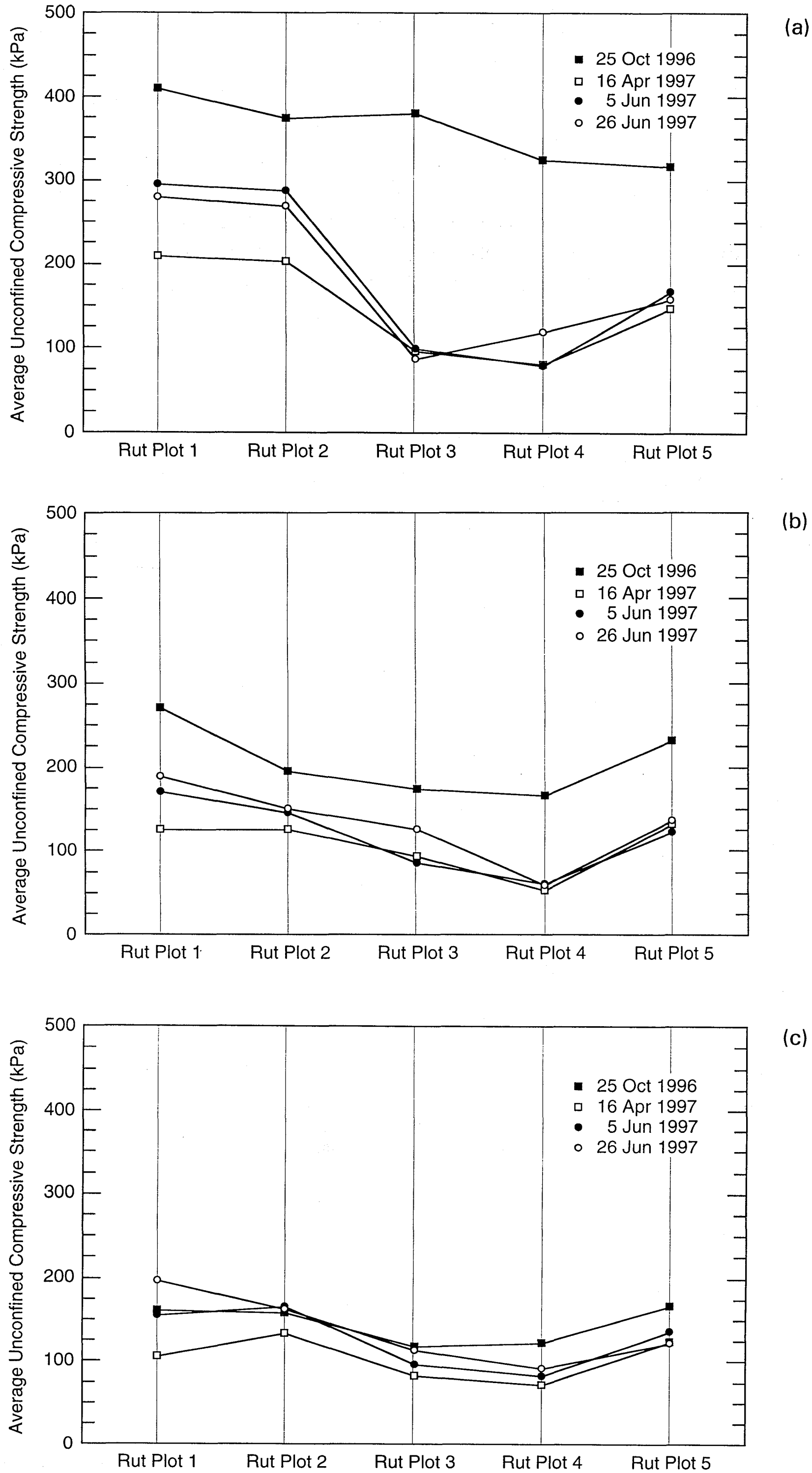

Fig. 9 Soil-strength changes in track ruts (a), wheel paths (b), and untrafficked soil (c).

runoff, concentrate surface flows, and exacerbate natural soil erosion. Results to date show that FT reduces the density of soil in compacted track ruts and wheel paths, increases infiltration into ruts, and induces significant geometric changes in wheel ruts through soil flows and slides when the ruts were formed in wet soil. Such changes can reduce the volume and velocity of flows in ruts, which could lessen rut-soil erosion. However, the reduced soil strength in rut soil could make that soil more erodible and exacerbate erosion. Thus, the relationship between FT cycling and rut and rill soil erosion remains unclear after these initial experiments, and future research will include rainfall-simulator experiments on newly thawed soils to define the effects of FT on rut and rill soil erosion.

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REFERENCES

Atkins, R. T. (1979) Determination of frost penetration by soil resistivity measurements. *Special Report 79-22, CRREL, Hanover, New Hampshire, USA.*

Carson, M. A. & Kirkby, M. J. (1972) *Hillslope Form and Process.* Cambridge University Press, Cambridge, UK.

Foltz, R. B. (1993) Sediment processes in wheel ruts on unsurfaced forest roads. PhD Dissertation, University of Idaho, Moscow, Idaho, USA.

Gatto, L. W. (1997a) Ground freezing effects on soil erosion of Army training lands, Part 1: Initial test results. *Special Report 97-15, CRREL, Hanover, New Hampshire, USA.*

Gatto, L. W. (1997b) Freeze-thaw effects on the hydrologic characteristics of rutted and compacted soils. In: *International Symposium on Physics, Chemistry, and Ecology of Seasonally Frozen Soils* (ed. by I. K. Iskandar, E. A. Wright, J. K. Radke, B. S. Sharratt, P. H. Groenevelt & L. D. Hinzman) (Proc. Fairbanks, Alaska, Symp., June 1997), 189–198. Special Report 97-10, CRREL, Hanover, New Hampshire, USA.

Hinckley, B. S., Iverson, R. M. & Hallet, B. (1983) Accelerated water erosion in off-road vehicle use areas. In: *Environmental Effects of Off-Road Vehicle Impacts and Management in Arid Regions* (ed. by R. H. Webb & H. G. Wilshire), chapter 5. Springer-Verlag, New York.

Horton, R., Ankeny, M. D. & Allmaras, R. R. (1994) Effects of compaction on soil hydraulic properties. In: *Soil Compaction in Crop Production, Developments in Agricultural Engineering* 11 (ed. by B. D. Soane & C. van Ouwerkerk), chapter 7, 141–165. Elsevier, Amsterdam.

Iverson, R. M. (1980) Processes of accelerated pluvial erosion on desert hillslopes modified by vehicular traffic. *Earth Surf. Processes and Landforms* **4**, 369–388.

Kok, H. & McCool, D. K. (1990) Freeze thaw effects on soil strength. In: *International Symposium on Frozen Soil impacts on Agricultural, Range, and Forest Lands* (ed. by K. R. Cooley) (Proc. Spokane, Washington Symp., March 1990), 70–76. Special Report 90-1, CRREL, Hanover, New Hampshire, USA.

Mathier, L. & Roy, A. G. (1993) Temporal and spatial variations of runoff and rainwash erosion on an agricultural field. *Hydrol. Processes* **7**, 1–18.

Miller, R. D. (1980) Freezing phenomena in soils. In: *Applications of Soil Physics* (ed. by D. Hillel), chapter 11, 254–299. Academic Press, New York.

Morgan, R. P. C. (1977) Soil erosion in the United Kingdom: Field studies in the Silsoe area, 1973–1975. *National College of Agricultural Engineering Occasional Paper 4.*

Nearing, M. A., Lane, L. J. & Lopes, V. L. (1994) Modeling soil erosion. In: *Soil Erosion Research Methods.* (ed. by R. Lal), chapter 6, 127–156. St Lucie Press, Delray Beach, Florida, and Soil and Water Conservation Society, Ankeny, Iowa, USA.

Voorhees, W. B., Young, R. A. & Lyles, L. (1979) Wheel traffic considerations in erosion research. *Trans. Am. Soc. Agric. Engrs* **22**, 786–790.