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Overwinter Changes to Vehicle Ruts and Natural Rills and Effects on Soil Erosion Potential

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ABSTRACT

Military vehicles used during training maneuvers compact and rut the soils on training lands. The compacted soil produces more surface water runoff for longer periods than adjacent uncompacted soil. The vehicle ruts, similar to natural rills, concentrate the runoff, which increases its sediment transport capacity, thereby increasing the potential for rill formation in ruts. This increased erosion potential on training lands is a major concern to Army land managers. Our objective was to determine the effects of soil freeze-thaw cycling on the hydraulic geometry, density, and strength of ruts and rills. Changes in these soil conditions can increase erosion potential of a soil. Our research results will be useful in simulating soil freeze-thaw processes and seasonal variations in soil erodibility and runoff erosivity in soil-erosion models.

We established research plots on a hillside at the U.S. Army National Guard's Ethan Allen Firing Range in northwestern Vermont. The hill had 12 naturally formed rills and was a good site to test the results we had obtained from previous controlled laboratory experiments on rills and wheel ruts. An Abrams tank, an HMMWV, and an HEMTT were used to form ruts on slopes that varied from 7 to 31%. Rut and rill cross-sectional geometry, frost depths, soil temperatures, soil penetration resistance and shear strength, soil-water content, and standard weather data were collected. Changes in rut and rill geometry and soil strength were related to soil and weather conditions.

Results showed that the penetration resistance in tank ruts decreased by 60%, in wheel ruts by 50%, and in untrafficked soil by 29% over one winter. Scattered sidewall slumps occurred along some of the deeper rills. An 11-cm-deep rill formed in a tank rut on a 31% slope over one winter and spring. Intermittent flows in spring during snowmelt eroded variably sized rills in tank and HEMTT ruts.

INTRODUCTION

Background

The U.S. Army is responsible for about 5,000,000 hectares of training land. The goal of Army trainers is to provide realistic training, while that of Army land managers is to protect plant, soil, and wildlife resources on those training lands as much as feasible within the context of a training facility. Clearly the goals of military readiness and maneuver realism often conflict with those of environmental stewardship. The more knowledge that land managers have about vehicle-on-soil impacts and soil response, the more effectively they can work with trainers to minimize maneuver damage and subsequent soil erosion.

An Army unit with tracked and wheeled vehicles moving over land breaks up soil crusts, ruts the soil surface, and compacts the soils (Gatto, 1997a). Voorhees et al. (1979) reported that ruts could channel surface runoff and increase its sediment transport capacity. Foltz (1993) determined that 200–400% more erosion occurred on rutted roads than on unrutted roads. This is similar to Morgan's results (1977), which showed that rill flows carry far more sediment from a hillslope than unchanneled flows. Compacted soil has reduced infiltration and hydraulic conductivity (Horton et al., 1994), which increases the volume of surface water runoff and the length of time it flows (Mathier and Roy, 1993), which results in more sediment eroded from hillslopes used by off-road vehicles than from unused hillslopes (Iverson 1980). This increased erosion potential on training lands is a major concern to Army land managers.

Freeze-Thaw Effects

Fourteen Army and National Guard training facilities are located in the northern U.S., where the freezing season lasts for 90 days or more. Ice that forms in soil during freezing can push soil grains apart and reduce soil compaction. The amount of soil expansion depends on the soil water available, the soil texture, the volume of water drawn to the freezing zone, the rate of frost penetration, and the number of freeze-thaw cycles (Miller, 1980). A frozen soil with ice in its voids dramatically affects seasonal soil erosion by increasing runoff rates and volumes during rain events and snowmelt. This soil when thawed is often saturated and has low strength because it has reduced particle attachment, interlocking, and friction. A newly thawed soil can be more erodible than at any other time of the year (Gatto, 1997a; van Klaveren and McCool, 1998). This weakened state persists until the excess water drains and cohesion is re-established (Formanek et al., 198; Kok and McCool, 1990a). Soils on training lands that are fine-grained and have available soil water are most susceptible to these substantial seasonal changes in soil strength and erodibility, but studies of the effects of freeze-thaw on vehicle ruts and natural rills are limited.

Frame et al. (1992) reported that the final shape of V-shaped rills in frozen soil in laboratory troughs was deeper and narrower throughout the slope than that of rills in non-frozen soil. Gatto (1997a, b, 1998, 2000) found reduced soil

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strength and hydraulic radius in a rill and wheel ruts after freeze-thaw cycles and also found differences in the rates of freezing and thawing in and out of ruts during controlled laboratory experiments. Van Klaveren and McCool (1998), in experiments with a tilting flume, found that calculated rill erodibility is strongly correlated with soil moisture tension and that it can change rapidly as rills deepen or as soils thaw and drain.

Field studies on freeze-thaw effects on ruts and rills are more rare than laboratory experiments. Schumm (1964) reported that frost-induced soil creep could obliterate natural rills over one winter. Halvorson et al., (1998a,b) measured cross-sectional changes in tank ruts over the winter and differences in infiltration and runoff between tracked and untracked soils at Yakima Training Center in south-central Washington. They found that soil compaction in tank ruts persisted at depth over the winter and that runoff was 67 to 77% higher in ruts than out of ruts. Kok and McCool (1990b) reported that the effects of soil freeze-thaw on soil-erosion mechanics are poorly understood in spite of extensive research on freeze-thaw physics. The inability to model seasonal soil erodibility associated with these effects impedes improvements in soil-erosion predictions (Nearing et al., 1994; VanKlavern and McCool, 1998).

OBJECTIVES

Our field experiments were done in cooperation with those of Halvorson et al., (1998a, b), which were done in a cool, semiarid climate. Our objective in this paper is to report on the freeze-thaw-induced changes in the geometry and soil strength in vehicle ruts and natural rills in a cold, humid climate. On-going studies are defining the differences between compacted and uncompacted soil in terms of frost penetration, thaw progression, and soil-water redistribution during freeze-thaw cycles. A future paper will address those results.

APPROACH

Research Site

We established five vehicle-tracking plots at Ethan Allen Firing Range (EAFR) in northwestern Vermont in October 1996. Twelve variably sized rills were present in five locations near the plots (Fig. 1). Soil at the EAFR sites is a Berkshire Monadnock sandy loam, slopes vary from 7 to 31% from TP1 to TP5 and vegetation is grass and small brush interspersed with unvegetated areas covered with cryptogamic crusts. The EAFR receives about 60 cm of precipitation per year, and the mean length of the freezing season is 115 days (Haugen, personal communication, CRREL, 1997).

Ruts were formed twice, on 25 October 1996 with an Abrams tank and an HMMWV (High Mobility Multipurpose Wheeled Vehicle) and on 17 October 1998 with a tank and an HEMTT (Heavy Expanded Mobility Tactical Truck). The Abrams tank is the Army's main battle tank, the HMMWV replaces the Army's traditional Jeep-sized vehicle, and the HEMTT is an eight-wheeled, all-wheel-drive utility truck about the size of a large dump truck. In October 1996 the tank and HMMWV made two passes along the track locations shown in Figure 2, and in October 1998 the tank and HEMTT made four, six, or eight

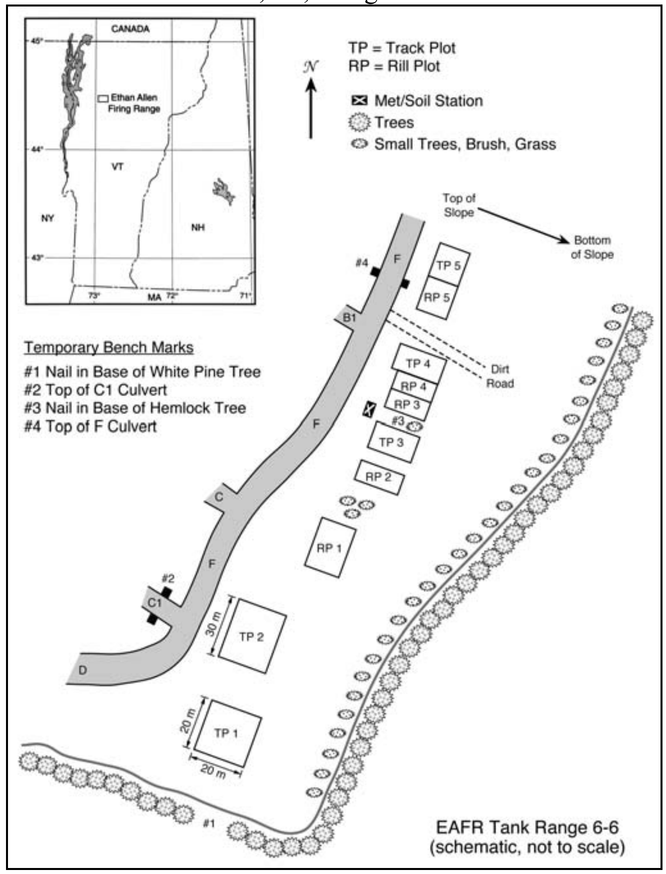

Figure 1. Research plots at EAFR. Track plots are the same as the vehicle plots in Figure 2.

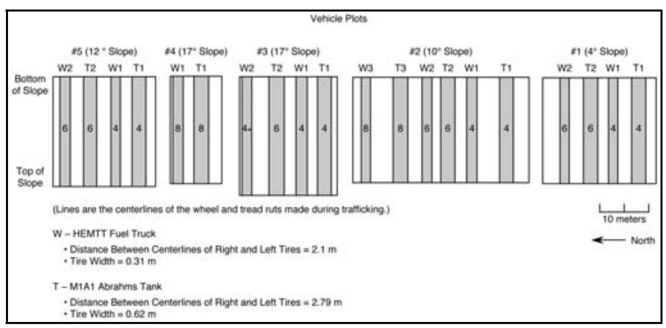

Figure 2. Vehicle passes made in October 1998. Numbers between rut centerlines are the number of vehicle passes; 4+ in plot #3 means that the HEMTT made between 4 and 6 passes because it could not stay on line due to sideslipping. Only two passes were made by each vehicle in 1996 when the HMMWV was used in place of the HEMTT.

passes (Fig. 2) in the same track locations as in 1996. The tank produced 20 4- to 7-cm-deep track ruts perpendicular to the hillslope contours. The HEMTT produced 20 2- to 4-cm-deep wheel ruts. The HMMWV wheel ruts were less than a centimeter deep with no distinct cross-sectional shape.

Volumetric soil-water content at the time of trafficking was 15-38% (33-76% saturation). A standard drop-hammer soil sampler was used to collect one 289-cm^3 core from the soil surface to 7 cm deep in the center of the five track plots (Fig. 1) at the time of tracking. The cores were weighed and dried in an oven at 100°C for several days. The soil water contents per volume of the cores were calculated from the wet and dry weights.

Measurements

We measured rut and rill surface cross-sections as follows. We used a stick marked in millimeters to measure the vertical distances between the soil surface across the ruts and rills and an aluminum bar mounted on 1-m-long rebar driven into the ground on either side of the ruts and rills (Fig. 3). The stick was aligned parallel to marks on the bar to ensure that the vertical measurements were made with the stick in the same orientation. These vertical distances were measured every 2.5 cm horizontally across each rut and rill unless more closely spaced vertical measurements were necessary to adequately define the shape of the soil surface. The estimated maximum error of these vertical measurements was 4 mm. These measurements were used to determine changes in surface geometry across ruts and rills over time. There are 26 rill cross-section locations and 45 rut cross-section locations.

From October 1996 to June 1997, we used a Soiltest pocket penetrometer similar to that used by Kok and McCool (1990b) to measure in-situ unconfined compressive strength of the upper 1 cm of soil in the track and rill plots. Measurements were made on four dates; soil moisture was not measured at the time. Measurements in the vehicle plots were made in the center of each tank and HMMWV rut at upslope, midslope, and downslope locations and in uncompacted soil about 1 m from the center of the ruts. Measurements in the rill plots were made at three upslope, midslope, and downslope locations across the plot. No measurements were made within rills. The individual measurements from the ruts, the unrutted soil, and the rill plots were averaged and plotted to show change over time. No statistical analyses were done on the data.

Beginning in December 1996, we measured on-site air temperature, precipitation, snow depth, wind speed and direction, relative humidity, and solar radiation every 15 minutes. Soil-frost depth in the upper 23 cm of unrutted soil and soil temperature at 10 depths from the surface to 40 cm are measured every four hours near the meteorological station.

Figure 3. Rebar-mounted bar used as datum for measuring rut and rill cross sections. Note the 7-cm-deep rill under the bar on this 14 April 1999 photograph. The rill formed over the 1998-99 winter in the mid-slope part of the south rut of tank rut 2 (T2) in vehicle plot #3, which has a 31% (17º) slope (see Figure 2).

RESULTS AND DISCUSSION

Soil FT Regimes

During the 1996-97 winter, soil froze to 14 cm by late December and to 40 cm by mid- to late January. It remained frozen except for seven thaws of the soil from 0 to 6 cm deep from 16 January to 2 March 1997, and the final spring thaw began on 27 March. The air temperature (T_a) had 41 freeze-thaw cycles above and below 0°C from January through May, while the soil temperature (T_s) cycled 27 times. The soil during the 1997-98 winter started to freeze by mid-January, froze to 30 cm by mid-February, and thawed by late March. The T_a had 91 freeze-thaw cycles, and the T_s, 30 cycles. In the 1998-99 winter the soil started to freeze in late December, froze to 20 cm deep by mid-January, and thawed by late February, although freeze-thaw cycling in the upper 5 cm of soil continued through mid-May. T_a had 75 FT cycles, and the T_s, 26 cycles.

The 0°C isotherm penetrates and retreats rapidly in the sandy loam at the EAFR plots, especially when snow cover is sparse. The soil water content is often not high during the winter, and the amount of heat that needs to be lost to the atmosphere for the soil temperature to drop to 0°C is not great.

Compressive Strength

We measured unconfined compressive strength in the tank ruts, HMMWV wheel paths, untrafficked soil in the track plots, and untrafficked soil in the rill plots on 25 October 1996 and three subsequent dates after spring thaw (Fig. 4). The average compressive strength was highest in the soil compacted by the tank (Fig. 4a). Over the winter the strength of the tank-rut soil decreased by 60%, the wheel-path soil by 50%. The untrafficked soil in the track and rill plots was 20-40% less resistant to compression in April after thaw and generally regained strength as the soil dried in June. The soil-freeze-thaw cycling had reduced the compaction in the upper 1 cm of soil, as was observed by Gatto (1997b) in laboratory experiments on wheel ruts.

Halvorson et al., (1998a,b) and Voorhees et al., (1979) found that compressive strength (penetration resistance) persisted in the soil below 10-20 cm over the winter because freeze-thaw cycling did not reduce the density of the compacted soil. This residual compaction resulted in more runoff in tank ruts than in uncompacted soil during rainfall simulator experiments at the Army's Yakima Training Center (YTC) in Washington (Halvorson et al., 1998b). On several occasions during spring thaw at EAFR, 1- to 5-mm-deep flows were observed in the ruts when there was no surface flow on the adjacent, unrutted soil. This suggests that infiltration is reduced in the ruts because of the residual compaction as observed at YTC. The resulting increased snowmelt runoff changes the geometry in ruts more than in rills.

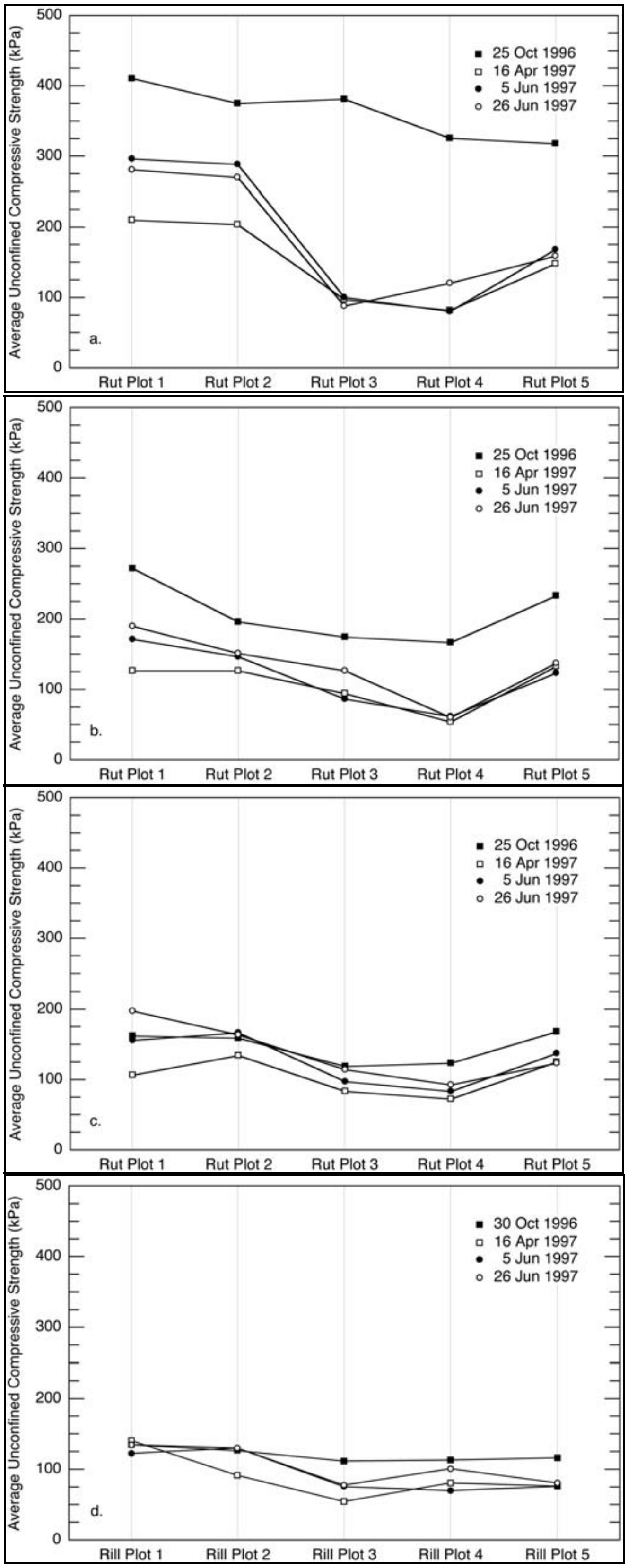

Figure 4. Over-winter changes in unconfined compressive strength; (a) tank ruts, (b) HMMWV ruts, (c) untrafficked soil in rut (vehicle) plots, and (d) soil in rill plots; n = 12 for each average plotted in (a) – (c), n = 9 in (d).

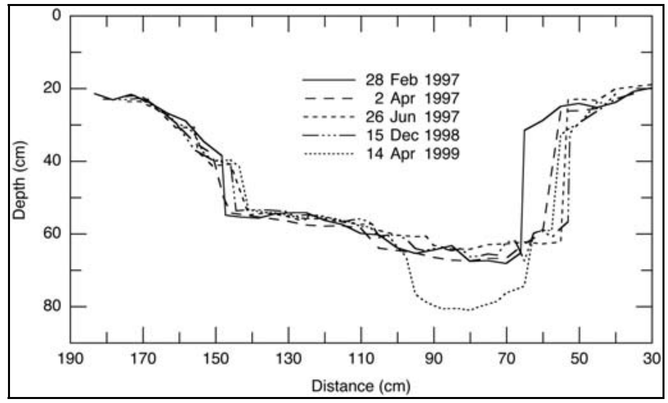

Figure 5. Changes in the cross-sections in the mid-slope part of rill 2 in rill plot #5 over three winters. The slope of rill plot #5 is 22%.

Figure 6. Slumped soil (right of the knife) along a rill on a 24% slope on 18 March 1999; runoff was flowing under the snow.

Rut and Rill Cross-Sectional Geometry

Frost heave in some of the tank ruts was 2 to 3 cm over the 1996-97 winter because of ice formation in the soil, but rill profiles showed no frost heave. Only a few scattered soil slides occurred along the sidewalls of deeper rills during spring thaw, and some of that soil was removed by subsequent snowmelt flows in the rills. The profiles of most of the rills did not change during the three winters, although a rill in plot #5 on a 22% slope showed areas of erosion and deposition and slumping of the sidewalls (Fig. 5). Slumped soil was observed on 18 March 1999 (Fig. 6), when the soil was saturated after a three-day thaw.

The HMMWV path surfaces did not change from October 1996 to October 1998 in any of the track plots. The HEMTT ruts in track plots #1 and #2 were not eroded over the 1998-99 winter and 1999 spring, while the tank ruts showed rills less than 2 cm deep through the walls between the track pad depressions and pockets of deposited sediment in those depressions from the intermittent flows within the ruts. These same features were observed after the 1996-97 winter in track plots #1 and #2.

However, in the spring of 1999, distinct v-shaped rills as much as 11 cm deep had formed in the eight-pass tracks in track plot #4 (31% slope), while adjacent untrafficked soil showed no evidence of rill initiation. The HEMTT eight-pass ruts had 1- to 10-cm-deep rills (Fig. 7). Rills 2 to 4 cm deep had formed in the four- and six-pass tank ruts in track plot #5 (Fig. 8a), while portions of the tank ruts had been frost heaved (Fig. 8b). The HEMTT six-pass ruts in track plot #5 showed no-to-little erosion and scattered patches of frost-jacked surface.

Figure 7. Rills formed over the 1998-99 winter in HEMTT ruts (W1) in vehicle plot #4, which has a 31% (17°) slope; (a Top) south rut with 1- to 2-cm-deep rills scattered along its length, (b Bottom) north rut with a 7- to 10-cm-deep rill in the mid-slope part of the rut, note the tape measure for scale. Photographs taken on 14 April 1999.

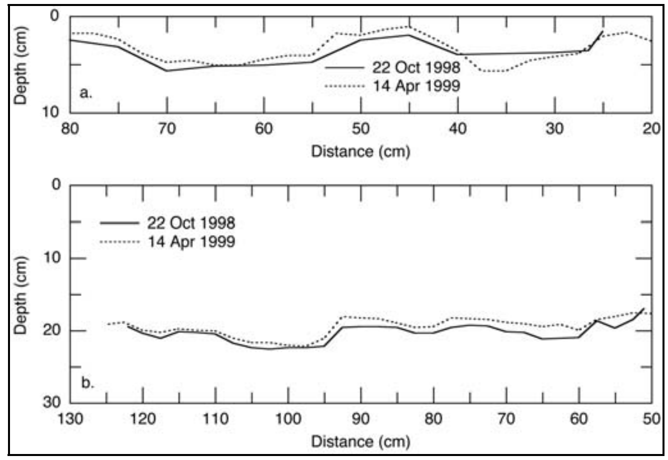

Figure 8. Changes from 22 October 1998 to 14 April 1999 in tank ruts in vehicle plot #5, which has a 22% slope; (a) a 3- to 4-cm-deep rill formed in the mid-slope part of the south rut of T1 (see Figure 2); (b) no distinct rills formed in the south rut of T2 but the soil surface on 14 April appears to be frost heaved.

SUMMARY AND CONCLUSIONS

EAFR observations and measurements show the following. Soil-freeze-thaw cycling over one winter reduced the unconfined compressive strength of soil in the upper 1 cm of tank and HMMWV ruts. Scattered sidewall soil slumps occurred along deep rills when soil thawed in the spring but did not occur along small rills. The slumps changed rill cross-sectional geometry. Small rills and pockets of deposited sediment had formed in most ruts after one winter because of runoff from snowmelt and early spring rains. Distinct v-shaped rills up to 11 cm deep formed in tank ruts on the 31% slope, while the soil adjacent to those ruts showed no evidence of rill initiation. Freeze-thaw cycling loosens the compacted surface soil in ruts, making it more erodible, and the persistence of soil compaction at depth leads to higher runoff in ruts than in adjacent untrafficked soil and exacerbates surface soil erosion in ruts. Predictions of soil erosion potential must account for the residual subsurface compaction below the zone of significant soil-ice formation because surface soil measurements used in soil-erosion models could be different and misleading.

Our future research will address the erodibility of newly thawed soil, the different soil freeze-thaw regimes in tank and wheel ruts and in unrutted soil, the spatial and temporal variability of freeze-thaw regimes at different landscape positions, and the impacts of soil moisture on freeze-thaw-induced soil deformation along ruts and rills.

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