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Migration of Water During Winter in West Central Minnesota Soils

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Abstract

Soil freezing influences the amount and quality of our water resources, yet, little is known concerning the impacts of soil texture and water content before freezing on water migration in frozen soils. Columns of Hamerly clay loam and Sioux loam at 3 initial water contents were subjected to the vagaries of the field environment at Morris, Minnesota during the winter of 1993-1994 and then sectioned to determine changes in soil water content. Redistribution of water in the frozen soil layer became more apparent with an increase in initial water content. Little movement of water occurred at the lowest initial water content of 0.21 g g^{-1} (45% pore saturation). Soil water redistribution was more pronounced for the Sioux loam, but only at the highest initial water content of 0.38 g g^{-1} (80% pore saturation). Upward water movement appeared greatest when the rate of descent of the freezing front was slowest. Initial water content had a larger effect on water movement in frozen soil profiles than soil texture. Therefore, soil water content at the time of freeze-up in the fall will determine, to a large extent, the rate of water (and consequently solute) movement in soil profiles during winter.

Introduction

The Midwestern United States is characterized by soils of superior quality for producing food and fiber (1). These soils, valued in terms of fertility and tilth, are affected by seasonal freezing and thawing. The process of freezing can alter soil quality by changing the physical, chemical, and biological properties of soil. Indeed, freezing influences soil physical properties such as porosity, stability, permeability, and structure. Freezing also affects the chemical composition of soils and the function of organisms and plants.

Freezing and thawing is a process involving a phase change in water. This process promotes changes in the unfrozen water content and water potential of soils. The decrease in water potential associated with freezing typically results in an upward migration of water towards a descending freezing front in the soil profile. Movement of soil water alters the water content and solute concentration profiles within the soil, thereby influencing the physiology of soil biota and hydrology of the soil system.

Water movement in frozen soils has been studied mainly in controlled environments where constant temperature gradients are maintained within the soil profile (2, 3, 4). Comparatively few studies have evaluated water movement in response to freezing and thawing in the field environment (5, 6). Although soil physical properties govern water transport within the atmosphere-snow-crop residue-soil system, little is known concerning the effect of texture and antecedent water content on water movement in soil profiles subject to freezing and thawing. This study evaluated water movement in soils of varying texture and water content during a winter in West Central Minnesota.

Materials and Methods

This study was conducted during the winter of 1993-1994 at Morris, Minnesota using a split-plot experimental design with soil type as main treatments and initial water content as sub-treatments.

Hamerly clay loam and Sioux loam with initial water contents of 0.38, 0.29, and 0.21 g g^{-1} were packed into 10-cm diameter, 180-cm long plastic pipes at a density of 1.2 g cm^{-3}. These initial water contents correspond to a water potential of about –0.1, –0.5, and –15 bars for Hamerly clay loam and –0.1, –0.3, and –10 bars for Sioux loam. The columns were sealed at both ends, allowed to equilibrate in a horizontal position for one week, and then wrapped with a 2.5-cm thick blanket of fiberglass insulation about 48 hours before placing in the field.

Soil columns were placed inside larger diameter plastic pipes located in a field devoid of vegetation. Plastic pipes with a diameter of 15 cm and length of 180 cm were capped at one end (to prevent moisture leakage) and placed vertically, capped end first, in the field to a depth of 180 cm. Seals on the soil columns were removed and the columns placed inside the buried pipe on December 15, 1993. The gap between the inner and outer plastic pipes was filled with silicone to prevent moisture leakage. The surface of the soil column remained uncovered to allow infiltration or evaporation.

Frost depth was monitored twice weekly using frost tubes located within the experimental site. Soil columns were extracted from the field on February 15,

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1994 when the frost depth, as measured by the frost tubes, was 60 cm. Columns were sectioned, using a concrete saw, within 1 hour of removing from the field. The columns were cut at 2-cm intervals from the surface to the 50-cm depth, 5-cm intervals from the 50- to 100-cm depth, and 10-cm intervals from the 100- to 180-cm depth. Frost depth in the soil column was determined by the change in resistance of a pointed rod inserted into the column after each cut. The cut sections were placed in a drying oven to obtain soil bulk density and water content.

Redistribution of water in the soil profile was assessed both graphically and using an index of variability (IOV) in soil water content. The IOV accounted for the temporal change in soil water content within a section of the soil column:

$$\mathrm{IOV} = \left\{ \sum_{i=1}^{N} |\Delta w_i| \Delta z_i \right\} \left\{ \sum_{i=1}^{N} \Delta z_i \right\}^{-1} \quad [1]$$

where i is the cut section number indexed from the uppermost cut section at the top of the soil column (i = 1) to the cut section within which the freezing front (i = N) is located, Δw is the temporal change in water content (g g^{-1}), and Δz is the thickness (cm) of the cut section. Differences in IOV among soils of varying texture and initial water content were evaluated using an Analysis of Variance.

Water flux in the soil profile during the 62 days of this study was determined using a mass balance approach:

$$\delta q \, \delta z^{-1} = \rho_b \, \delta w \, (\delta t)^{-1} \quad [2]$$

where q is water flux (g cm^{-2} day^{-1}), z is depth (cm), ρ_b is the soil density (g cm^{-3}), t is time (days), and w is the soil water content (g g^{-1}). Integrating with respect to depth and using the trapezoidal rule of approximation for a linear function, water flux at the midpoint of cut section x is:

$$q(x) = \rho_b \left\{ \Delta t \sum_{i=x}^{L} \Delta w_i \, \Delta z_i \right\}^{-1} \quad [3]$$

where L is the total number of cut sections made along the length of the soil column. This equation assumes an unsaturated profile, negligible vapor flow, and no water flow in response to thermal gradients.

Results and Discussion

The perpetual occurrence of subfreezing air temperatures and continuous snowcover (Fig. 1) resulted in little measured gain (by infiltration) or loss (by sublimation) of water in the soil columns. Therefore, changes in water content were largely a result of redistribution of the initial water within the soil profile.

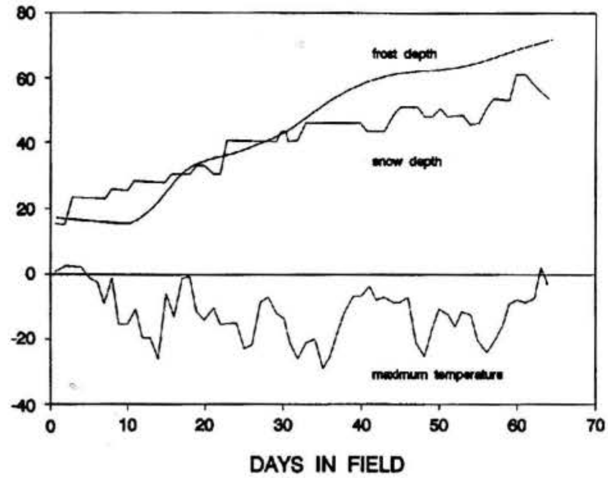

Figure 1. Maximal air temperature, snow depth and frost depth from December 15, 1993 (Day 1) to February 16, 1994 (Day 64) at Morris, Minnesota.

Redistribution of water in a freezing soil subject to the vagaries of the field environment is illustrated in Fig. 2. The greatest change in soil water occurred near the surface of the Sioux loam where soil water content increased from 0.38 to 0.48 g g^{-1} (0.45 to 0.58 cm^3 cm^{-3}) over 62 days. The latter water content corresponds to 105% of pore saturation and indicates the possibility for frost heave of the Sioux loam at high water contents.

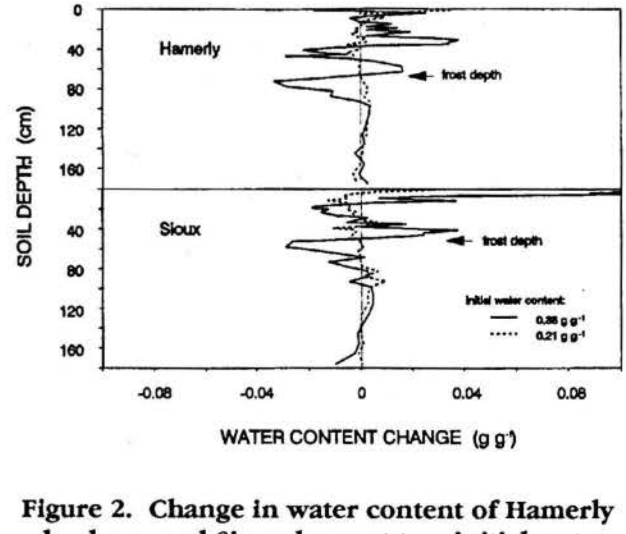

Figure 2. Change in water content of Hamerly clay loam and Sioux loam at two initial water contents occurring between December 15, 1993 and February 16, 1994.

Soil water was depleted from an approximate 20-cm layer below the freezing front at the wettest initial water contents (Fig. 2), indicating an upward movement of water toward the freezing front. The thickness of this layer decreased with a decrease in initial water content and was not apparent at the driest initial water content. The irregularity in the profile water content change within the frozen soil layer (Fig. 2) was representative of data presented by Oliphant et al. (2). They attributed this variation to the uneven distribution of ice lenses forming at the freezing front when a constant temperature gradient was imposed on a soil column. In addition, the irregularity in the data presented in Fig. 2 may be due to the constantly changing soil surface boundary conditions. This was exemplified by a nonuniform rate of frost penetration over the 62 days (Fig. 1).

Initial water content had a large effect on the redistribution of water in a frozen soil profile (Fig. 2). Soils with a wetter initial water content showed a greater redistribution of water than soils with a drier initial water content. The index of variability in soil water content increased with an increase in initial soil water content for both soil types (Table 1).

Table 1

Index of variability for assessing redistribution of water in frozen soils as affected by soil texture and initial water content.‡

Initial water content	Index of Variability	
	Hamerly clay loam	Sioux loam
--- $g\ g^{-1}$ ---		
0.38	1.47 a	2.49 b
0.29	0.99 c	1.22 c
0.21	0.37 d	0.50 d

‡ Means within columns or rows followed by the same letter are not significantly different ($p < 0.05$).

Soil texture influenced soil water redistribution, but only at an initial water content of 0.38 $g\ g^{-1}$ (Table 1). The coarse-textured soil (Sioux loam) had a larger index of variability in soil water content (greater redistribution) than the fine-textured soil. Similar findings were presented by Hoffman et al. (4) who found that the greater hydraulic conductivity of coarse-textured soils resulted in greater water movement when subject to freezing than fine-textured soils. Indeed, the saturated hydraulic conductivity of the Sioux loam was 8.5 cm day^{-1} and of the Hamerly clay loam was 5.5 cm day^{-1}. The apparent lack of an effect of soil textural differences on water redistribution at the drier initial water contents may be attributed to the similarity in unsaturated hydraulic conductivity between soil types. Generally, differences in hydraulic conductivity between soil types are accentuated at wetter water contents.

Water flux was affected by initial water content with little movement of water occurring at drier water contents. For the soils with greater initial water content, the profile of water flux (Fig. 3) indicated that most of the water movement occurred within the frozen soil layer. Water flow was generally positive or upward toward the freezing front. Two regions of peak flow are noted from the profiles in Figure 3. For the Hamerly clay loam, which had a frost depth nearly equal to that indicated by the frost tube, the maximal flow periods occurred at about days 22 and 43 from the beginning of the study and during a time of slow frost penetration (Fig. 1). Water flow toward the freezing front, therefore, appeared to be greatest under conditions of a slowly descending freezing front.

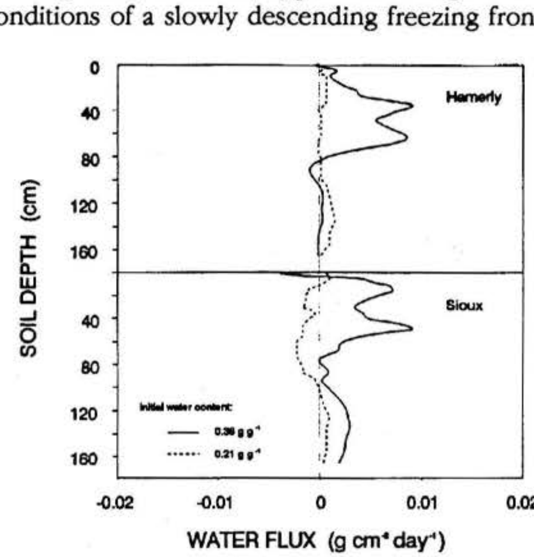

Figure 3. Water flux profile for Hamerly clay loam and Sioux loam at two initial water contents during the period December 15, 1993 and February 16, 1994.

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