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Influence of Freeze-Thaw Cycle on Silt Loam Soil in Sagebrush Steppe of Northeastern Oregon

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ABSTRACT

Soil freeze-thaw cycles can result in soil surface crusting, pedestaling, and movement. This study was undertaken to quantify the amount of heaving and soil moisture migration in a silt loam soil from the sagebrush steppe. Soil columns containing silt loam soil with moisture treatments of 26%, 34%, 42%, or 50% water content and initial temperatures of 9º C or 20º C were exposed to −7º C for 18 h, which did not completely freeze the soil to full depth. Moisture redistribution amounts of 10% to 20% were observed in treatments above field capacity. Surface saturation was observed after freezing with treatments of 42% and 50% water volume. Soil heaving of up to 0.5 cm was observed after one freezing event.

Introduction

Federal rangeland inventory and monitoring protocols for the assessment of rangeland health and condition require management interpretations of observed soil indicators. Soil surface crusts, pedestaling and hummocking of plants, soil movement, and concentrations of gravel or stones on soil surface have a history of being used by land managers as indicators of range deterioration (Committee on Rangeland Classification, 1994; Pellant et al., 2005). Within the intermountain west, areas of the sagebrush steppe with silt loam soil annually undergo freeze-thaw cycles that can result in these same undesirable soil surface characteristics. If naturally occurring phenomena cause undesirable soil surface morphology, it could result in an incorrect assessment of rangeland health, implying that conditions are the result of management and that modifications in management will mitigate these undesirable soil attributes. Also, knowledge of naturally occurring processes occurring during soil freezing could provide a better understanding of the germination, early growth, and establishment environment of plants leading to more successful rangeland seeding techniques.

Passey et al. (1982) reported that soil flow, crusting, pedestaling, and hummocking naturally occurred during early spring on silt loam soils of the sagebrush steppe in the intermountain west of the United States. Similarly, Hugie et al. (1964) describe observational evidence that these conditions occur naturally and independent of anthropogenic disturbance on silt loam soils in the sagebrush steppe of Southern Idaho. In both cases, the authors observed that rangelands having silt loam soils in arid and semiarid climate do not support complete ground cover and that bare ground surface crusting, accumulation of stones/gravel on the soil surface, polygon surface patterns, localized soil movement, and minor gullying were regularly observed where freeze thaw events occur.

Freezing effects, such as frost heaving, are known to be slight in gravels and coarse sands but increase in magnitude and importance as particle size decreases with the greatest heaving potential occurring in wet silt (Taber, 1929, 1930; Miller, 1980). Soil aggregates that undergo freeze thaw cycles are subject to upward pressures (heaving) derived from the accumulation of ice on the surface of expanding ice crystals and the 9% water volume increase associated with freezing (Brady and Weil, 2017). As ice lenses grow, they displace soil above them, resulting in frost heave, which can be a significantly > 9% increase in molar volume of water because of ice accumulation (Taber, 1929). Under moist soil conditions, segregated ice lenses grow in the freezing zone because of freezing-induced redistribution of moisture within the soil profile through both capillary action and water vapor migration from areas of unfrozen soil toward the freezing zone (Miller, 1980). Total frost heave is equal to the volume of ice lenses formed (Taber, 1930).

Freezing and thawing can also result in soil pores within the freezing zone filling with ice. Subsequent partial surface thawing within the freeze zone yields a layer of soil that loses soil structural integrity and is surfeited

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with melt water (Plaster, 2003). This condition can exceed the plastic limit of the soil, allowing elevational differences at the microsite level to result in flow of soil from higher to lower microelevations.

Crusting and platy soil structure formed under physical conditions, such as those described earlier, dismantle soil aggregates into individual particles. Subsequent freezing and drying can align individual particles into a massive soil structure. Polygonal stress fractures can also form to relieve pressures that occur with drying of the soil surface (Brady and Weil, 2017).

The objective of this study was to describe some of the physical changes that occur in the surface layer of a silt loam soil (20 cm depth) from the sagebrush steppe when subjected to a freezing environment (-7^{o} C) for 18 h.

Soil Description and Environment

Top soil from a fine, montmorillonitic, mesic Abruptic Xerollic Durargid located in the sagebrush steppe of northeastern Oregon was selected for the experiment (Laird, 1997). The soil was derived from basalt colluvium and contains a surface layer that is strongly influenced by the occurrence of volcanic ash and loess. The texture of the surface layer is silt loam (granular structure, ~20 cm depth) underlain by a clay subsoil (~35 cm depth), followed by a duripan (~50 cm depth) and bedrock (occurring below 100 cm). Moist bulk density of this soil is 1.1 g/cm^3. The natural vegetation consists of an overstory of sagebrush (*Artemisia tridentate* Nutt. ssp. *wyomingensis*) with an herbaceous understory of Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Love), sandberg bluegrass (*Poa secunda* Presl) and ~30% bare ground (Passey et al., 1982; Laird, 1997).

Climatic conditions influencing the soil include mesic and xeric regimes (mesic = mean annual soil temperature $8-15^{o}$ C and difference between mean summer and winter temperature > 6^{o} C; xeric = soil dry for 45 consecutive d in the 4 mo following summer solstice and moist 45 consecutive d in the 4 mo following winter solstice) (Soil Survey Staff, 1999). In this case, the annual precipitation is 30 cm (Table 1). The late winter environment of February and March provides favorable conditions for repeated cycles of freezing and thawing of the soil surface followed by periods of surface drying.

Materials and Methods

Top soil from the fine, montmorillonitic, mesic Abruptic Xerollic Durargid was harvested for the experiment. The uniform granular top soil was mixed and placed in Styrofoam containers to form cylinders of soil (780 g) 9 cm deep with a diameter of 10.5 cm. The dry soil was compressed within each container to achieve a uniform dry bulk density of 0.91 g/cm^3. Soil moisture treatments were established by bringing soil moisture content of individual cylinders to 26%, 34%, 42%, or 50% water content by volume. Reference points of soil field capacity and saturation were determined to occur at 25% and 70% water by volume. Thus, soil moisture treatments were designed to measure freeze/thaw changes at 8-unit intervals of soil moisture increase, starting at field capacity. Each container was sealed with polyethylene wrap after the moisture treatment was added and allowed to equilibrate for 72 h. The moisture equilibrated containers were separated to establish two initial temperature treatments (20^{o} C or 9^{o} C) and allowed to equilibrate for an additional 72 h. The two thermal and four soil moisture treatments were organized to form a split plot experiment containing four replications. The polyethylene wrap covers on the containers were removed, and the experiment was placed in a freezer unit exposing the soil to freezing temperature (-7^{o} C) for 18 h. This duration did not result in complete freezing of the soil profile. Data from the freezing event was collected by destructively sampling each cylinder of soil to measure heaving, freezing depth, and the soil moisture content of frozen and unfrozen soil.

Table 2
Influence (cm) of initial temperature and initial moisture (%) content on change in frozen surface elevation and freezing depth of a silt loam soil.

	Initial temperature		Initial moisture treatment			
	20° C	9° C	26%	34%	42%	50%
Elevation (cm)	0.2 a[1]	0.31 b	0.01 a	0.26 b	0.41 d	0.35 c
Depth (cm)	3.1 a	2.5 b	4.2 c	3.0 b	2.1 a	2.0 a

[1] Letter differences in treatment comparisons denote significance at $P = 0.01$.

Results and Discussion

Results from the freezing experiment indicate that the initial temperature of the soil cylinder (before freezing) did not influence the freezing-induced redistribution of soil moisture within the cylinder (data not shown). The initial temperature of the soil cylinder did influence soil surface elevation from heaving during the freezing event and depth of soil freezing ($P = 0.01$) (Table 2). Overall the cooler initial temperature increased the elevation of the soil heave by 33% but reduced the depth of freezing by 20%, possibly resulting from structural differences in ice lenses within the soil pore space. The soil/water environment in this silty soil is structurally and chemically complex, and the specific mechanism that reduced the depth of freezing for the initially cooler soil is unknown at this time. We hypothesize that ice formation in pore spaces could impede heat flux from depth, or it could be a manifestation of the Markovian Mpemba effect (Lu and Raz, 2017). The Markovian Mpemba effect is the process by which hot water can freeze faster than cold water under certain conditions.

The initial moisture content of the soil cylinder also influenced heave elevation and depth of freezing ($P = 0.01$) (see Table 2). The lowest moisture content, which approximated soil field capacity, yielded minimal surface elevation heaving and the greatest depth of freezing. Increasing the soil moisture content from 26% to 34% and then to 42% water by volume resulted in significant increases in heaving elevation and decreasing freezing zone depth. This trend stopped with the final moisture treatment where a decrease in heave elevation was observed relative to the 42% water by volume treatment and freeze zone depth remained constant.

The initial moisture content of the soil influenced the freeze-induced redistribution of soil moisture within the cylinder (Table 3). The freeze-induced redistribution of soil moisture occurred under all soil moisture treatments except field capacity. Increasing the soil moisture content from 26% (field capacity) to 34% and then to 42% water by volume resulted in increasing amounts of moisture redistribution. At an initial moisture content of 34%, freeze-induced redistribution moved 10% of

Table 1
Thirty-yr average precipitation, d with measurable precipitation, and average daily maximum and minimum temperature.[1]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average daily max. temp. C	2.1	5.9	9.9	15.4	20.3	24.9	30.2	29.3	24.9	17.3	8.3	3.1
Average daily min. temp. C	-7.3	-4.7	-3.1	0.0	3.7	7.3	10.2	9.4	5.4	1.0	-2.8	-6.1
Monthly precipitation (cm)	3.0	1.9	2.6	2.3	3.9	3.4	1.7	1.7	1.7	1.7	3.0	3.5
D of mo with measurable precipitation	5	3	4	4	5	4	2	2	2	3	5	5

[1] Data were obtained from the PRISM Climate Group/Climate Source, Inc. (http://www.climatesource.com/).

Table 3
Percent water migration, the increase in water content in the frozen zone, and water content by volume in frozen and unfrozen silt loam under four water content treatments.

Water treatment	Initial moisture (%)	Migration (%)	Frozen (%)	Unfrozen (%)
1 (Field capacity)	26	0.0 a[1]	26.0 a	25.0 a
2	34	3.5 b	37.4 b	29.3 a
3	42	8.0 c	50.0 b	34.5 a
4	50	9.0 c	58.7 b	40.8 a
	Mean		43.6 b	32.7 a

[1] Letter differences in the migration column and across frozen/unfrozen comparisons denote significance at $P = 0.001$.

the moisture from the unfrozen soil into the freezing zone. At 42% moisture content the transfer increased to 20%. The proportion of the moisture transferred in the final treatment remained near 20%.

The resulting differences in total soil moisture content between frozen and unfrozen soil followed a similar pattern (see Table 3). Soil moisture content was unchanged during the freeze thaw cycle when the initial water content was set at field capacity. When the initial moisture content was increased to 34% and 42%, the moisture content of the unfrozen soil was 21% and 30% lower than the frozen zone. Increasing the initial moisture content to 50% did not reduce the percent moisture loss in the unfrozen zone beyond 30%. Surface thawing of the frozen zone from the soil moisture treatments of 42% and 50% yielded a soil slurry surfeited with melt water.

Summary and Conclusions

Results from this study indicate that freeze-thaw characteristics of heaving and freeze-induced moisture redistribution occur in a silt loam soil under moisture conditions that can be observed in the sagebrush steppe Figs. 1 and 2. Freeze-thaw cycles in soils can bring about a freezing-induced redistribution of soil moisture (Miller, 1980) resulting in soil heaving, crusting, saturation, solifluction, and creep (Higashi and Corte, 1971; Passey et al., 1982; Satterlund and Adams, 1992). In this study, conditions of soil heaving and moisture redistribution did not occur when initial soil moisture was below field capacity but increased in intensity above field capacity up to an initial soil moisture content of 42%. Heave elevations of up to 0.5 cm were observed after one freeze event. Long-term precipitation data (Laird, 1997) indicate that annual precipitation for the study area ranges between 23 and 35 cm and that 2 out of 10 yr will receive < 1.2 cm of precipitation during the months of January, February, and March. These data and personal observation suggest that the soil moisture conditions necessary for soil heaving and moisture redistribution do not occur on an annual basis.

The physical changes associated with the freeze-thaw cycle that occurs in the surface layer of a silt loam soil can impact seed germination, establishment, and survival. Moisture migration toward the freezing surface creates a relatively water-rich environment for the seed in an otherwise arid environment, increasing chances for successful germination and the potential for seedling establishment. Thus, seeds exposed to the freeze-thaw environment in moist silt loam would receive the benefit of low water stress and high dissolved oxygen as they imbibe moisture before germination (Fenner, 1985). Field observations, reported in germination studies of hoary cress (*Lepidium draba* L.) and yellow starthistle (*Centaurea solstitialis* L.), indicate that freeze-induced moisture migration helped fulfill moisture requirements for germination (Larson and Kiemnec, 1997; Larson et al., 2000).

Soil crusting and the formation of surface polygons occur when wet massive soil structure undergoes a period of drying (Plaster, 2003). In this study the freeze-thaw cycle under initial soil moistures of 42% and 50% resulted in a structureless surface layer surfeited with melt water. Given a period of soil drying, conditions would be in place to create soil crusting and surface polygons. However, long-term weather data and field observations suggest that these conditions are not present on an annual basis. Prerequisite soil moisture conditions depend on precipitation patterns, so cold-wet winter and spring conditions would be most likely to promote soil crust and polygon formation.

Saturated and super saturated conditions created through freeze-thaw cycles can also create barrier to seedling emergence (Miller and Donahue, 2007). A frozen, saturated soil minimizes particle-to-particle contact and is destructive to soil aggregation. This typically results in the formation of a massive, platy soil structure to the depth of the saturation zone and formation of polygonal units across the soil surface as it dries. Soil interspaces within this sagebrush community can display surface crusting (platy structure), surface polygons, and evidence of soil

Figure 1. This is an example of structural failure due to the loss of particle-to-particle contact, which occurred under moist conditions with repeated freeze-thaw cycles. This occurs because the soil becomes surfeited with melt water above the frozen zone as the soil warms.

Figure 2. Profile view of a fine, montmorillonitic, mesic Abruptic Xerollic Durargid showing soil flow from the surface, which resulted from freeze-thaw events.

flow where micro differences in surface elevation exist (Hugie et al., 1964; Passey et al., 1982). These surface attributes form in late winter under conditions of repeated freeze-thaw followed by a period of drying and will remain visible well into summer and fall months unless physically degraded by rain or mechanical destruction. Under those conditions, effective germination is commonly limited to the cracks separating the polygons with the crusted polygon surfaces being devoid of successful germination (Passey et al., 1982).

In this study, conditions of soil heaving were not observed when the initial soil moisture was at or below field capacity and increased in intensity above field capacity up to an initial soil moisture content of 42%. Heave elevations of up to 0.5 cm were observed under the higher soil moisture conditions after one freeze event. Repeated freeze-thaw events or longer-duration freezing periods would facilitate ice lens formation intensifying the heave process leading to pedestaling that could impact seedling survival through root exposure, breakage, and destruction.

The attributes described earlier are the result of a complex freeze-thaw process impacting a silt loam soil. None of the attributes are dependent on management and, as such, management modification would have limited value as a mitigator of these perceived deteriorated soil conditions.

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