Mechanisms of water erosion in a partially melted, frozen Andisol

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Abstract
Partially melted seasonal frozen soil is susceptible to water erosion. In this study, artificial rainfall was applied to a partially thawed soil and the effects of soil physical conditions on erodibility of partially thawed Andisol was measured. An Andisol from a mountain range area was used. The soil was packed into a plastic box to form an 8-cm thick subsoil. The packed soil was kept in a refrigerator at -30°C for one night to form the frozen subsoil. Before the rainfall, disturbed soil was laid over the frozen subsoil to form 2-cm thick unfrozen layer as a model for a thawing surface soil. During the rainfall experiment, runoff, eroded soil, seepage from outlets at front wall of the down slope end of the box was sampled periodically. In the early stage of the rainfall, impermeable frozen subsoil was the reason for enhanced runoff and soil loss, while surface sealing was the main cause of the runoff during latter half of the rainfall event. Seepage from above or through the frozen subsoil suggested saturation of near surface unfrozen soil, and soil loss was significantly large for the same period, even though the runoff rate was similar through the rainfall experiment.

Key Words
Freeze-thaw, buoyancy force, suction, effective stress.

Introduction
Soil erosion depresses productivity of agricultural lands. An estimate suggests that agricultural production has been reduced 10% worldwide by soil erosion (Lal 1998). In early spring, partially melted frozen soils are subject to accelerated water erosion. In the USA, about 4.2 million km^2 of agricultural lands are affected by soil freezing and thawing (Formanek *et al.* 1990). Similar problems are seen in Norway, Canada and Japan. Additionally, winter irrigation, which is expected to store water as ice, is one of the conventional practices in inland semi-arid regions. This may have a side effect of preventing infiltration of rainfall in early spring. It is still not clear if during the freezing process; aggregate disintegration or reduction of infiltration contributes more to inhibiting infiltration and increasing soil loss. Orradottir *et al.* (2008) discussed changes in infiltration of Andisols in response to vegetation and snow cover. However, it is still not known how the initial moisture condition affects infiltration, runoff and soil loss of partially frozen Andisol soils. The main objective of this study is to clarify the effect on initial, pre-freeze, and moisture condition on runoff and soil loss from a frozen Andisol.

Material and Methods
An Andisol from Tsumagoi, Gunma, Japan was used. Tsumagoi is a mountain range of central Japan that lies at an altitude of 1200m. Average daily temperature from December to February is below 0°C. Texture of the soil was silty clay loam, and loss on ignition was 16%. Soil had natural water content was sieved through 2-mm mesh screen and kept in a plastic bag until the experiment. The soil was packed into a 0.1m (W) × 0.1m (D) ×0.5m (L) plastic box to form 8 cm thick subsoil. Initial, pre-freeze, volumetric water content of the subsoil was 20, 40 and 60%, respectively. The packed soil was kept at -30°C overnight to form the frozen subsoil. Before the rainfall, 2-cm of unfrozen soil was laid over the 8-cm frozen subsoil to form unfrozen layer as a model for a thawing surface soil. Packing dry bulk density of surface and subsoil was 0.6 and 0.7 Mg/m^3, respectively. Slope of the soil box was 8% and experiments were done in duplicate for each condition. Rainfall was applied by using the Norton ladder-type rainfall simulator that was set 2.1m above the soil box. Veejet 80100 nozzle with 41kPa water pressure was employed. Rainfall intensity was 42 ±2 mm/h. Raindrop size distribution produced by the same nozzle with a similar water pressure was similar to a natural rainfall, and kinetic rainfall energy was estimated to be 90% of the natural rainfall (Meyer and Harmon 1979). Four collection troughs were attached down slope end of the box, and drainage, discharge and eroded soil were periodically sampled. Thermocouples were inserted 2.5 and 5 cm from a side wall and 2.5, 5.5 and 8.5 cm in depth near the down slope end of the box, and soil temperature during rainfall event was monitored.

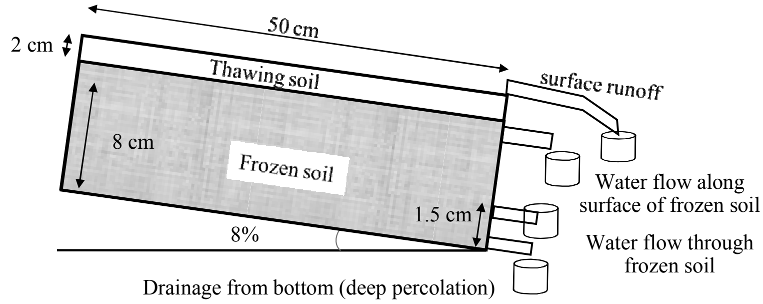

Figure 1. Outline of soil box and collector troughs.

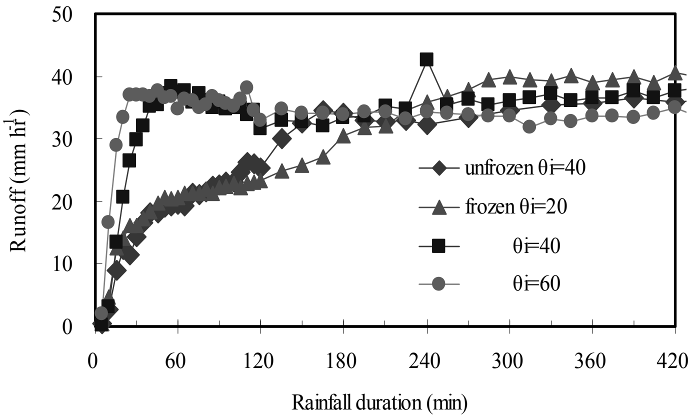

Figure 2. Runoff from soil with and without frozen subsoil with different initial volumetric moisture or ice fraction. Legend denotes treatment and initial volumetric moisture or ice fraction of the subsoil. Packing dry bulk density of the subsoil was 0.7 Mg/m^3.

Results

Runoff with and without frozen subsoil

Figure 2 shows runoff from soils with or without frozen subsoil. Initial volumetric water content was assumed equivalent to initial ice fraction. Subsoil ice fraction of 20% had a similar runoff as the treatment without frozen subsoil, while treatments with higher initial ice fraction of frozen subsoil, 40 and 60%, gave quick runoff initiation, and more than 80% of rainfall was discharged as runoff. The high initial ice fractions, 40 and 60%, also caused seepage from outlets connecting frozen subsoil layer. The seepage was small, but continued 2 hours from the beginning of the rainfall (Figure 3). This suggested soil above the frozen subsoil was saturated during the early stage of the rainfall, and runoff of this period was due to impermeable frozen subsoil. Soil that had no frozen subsoil and initial ice fraction of 20% showed less runoff for the same rainfall duration due to infiltration. After 2 hours of rainfall when melting frozen subsoil was expected, runoff was similar for all the subsoil conditions. From the observation, surface seal formed by raindrops, instead of the frozen subsoil, dominated soil and water dynamics for latter stage of the rainfall event.

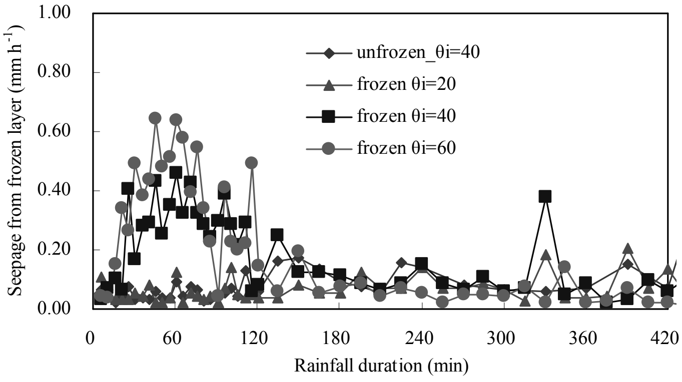

Figure 3. Seepage above and through frozen subsoil. Legend denotes treatment and initial volumetric moisture or ice fraction of the subsoil. Packing dry bulk density of the subsoil was 0.7 Mg/m^3.

Soil loss during rainfall event

Soil loss rate showed similar feature with the runoff. Subsoil ice fraction of 20% resulted to show similar soil loss rate to the one without frozen subsoil while soil had frozen subsoil of higher initial ice fraction gave high soil loss rate at the beginning of runoff. Soil loss rate was significantly high when seepage from the down slope end was observed (Figure 3), and 2 hours of rainfall and later, soil loss rates became similar for all the subsoil conditions (Figure 4). This suggested that soil becomes to be susceptible water erosion when permeability of frozen subsoil is low enough to cause water saturation near surface soil. However, when hydraulic characteristics of surface seal dominate runoff and infiltration, soil loss seems to be controlled by the physical property of the seal.

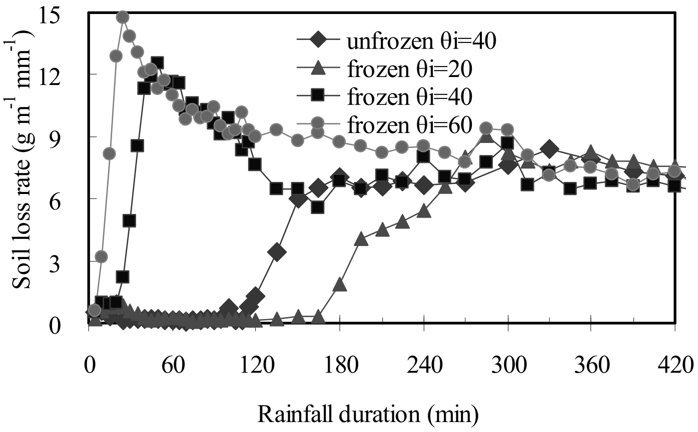

Figure 4. Changes in soil loss with and without frozen subsoil having different initial volumetric ice fraction. Legend denotes treatment and initial volumetric moisture or ice fraction of the subsoil. Packing dry bulk density of the subsoil was 0.7 Mg/m^3.

Mechanisms of soil loss from partially thawed soil

Froese *et al.* (1999) and Cruse and Larson (1977) suggested that from the point of view of soil strength, detachment of particles from soil surface by runoff could be affected by soil shear strength, and therefore by buoyancy force under water saturated condition and matric potential of unsaturated soil water. When surface seal forms, water pressure gradient may form across the seal and the soil beneath, and pore water pressure at shallow depth became negative (Nishimura *et al.* 1993; Froese *et al.* 1999). For example, saturated hydraulic conductivity of surface crust formed on Yamanashi Andisol, Japan was 3 mm/h (Nishimura *et al.* 1993) and smaller than the average percolation rate under shallow surface runoff during late stage of the rainfall event, 5 mm/h, in presenting study. This could cause negative pore water pressure below the seal. Shift of mechanism of producing runoff such as impermeable subsoil of high initial ice fraction frozen subsoil to low permeable surface seal, could be a reason of different soil loss late rate (Figure 4) with similar runoff rate (Figure 2) from soils with different extent of freezing.

Conclusion

Water dynamics in partially frozen soil under rainfall changed depending on the extent of thawing. When the frozen soil layer inhibits infiltration, its low permeability may be the major cause of runoff, while a frozen soil that has partially melted or has enough permeability so that surface seal formation reduces infiltration and produces runoff. Temporal variation in soil loss rate with almost steady runoff suggests soil loss responses to a mechanisms producing runoff. When subsoil with low permeability is the major reason for runoff, buoyancy forces acting on soil particles at the surface saturated region enhances soil loss, while suction of soil water across the surface seal may increase effective stress of surface soil and therefore strengthen the surface soil and reduces erosion. From the results, it is recommended to farmers, if possible, to prevent high moisture condition at initiation of seasonal soil freezing. Fall or winter irrigation to store water in soil for spring cultivation is not recommended from the point of view of erosion of thawing soils.

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