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Article

Simulated and *In Situ* Frost Heave in Seasonally Frozen Soil from a Cold Temperate Broad-Leaved Korean Pine Forest

Short Title: Frost Heave in Seasonally Frozen Soil from a Temperate Forest

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Abstract: Frost heave, which is the volumetric expansion of frozen soil, has great ecological significance, since it creates water storage spaces in soils at the beginning of the growing season in cold temperate forests. To understand the characteristics of frost heave in seasonally frozen soil and the factors that impact its extent, we investigated the frost heave rates of forest soil from different depths and with different soil moisture contents, using both lab-based simulation and *in situ* measurement in a broadleaved Korean pine forest in the Changbai Mountains (northeastern China). We found that frost heave was mainly affected by soil moisture content, soil type, and gravitational pressure. Frost heave rate increased linearly with soil moisture content, and for each 100% increase in soil moisture content, the frost heave rate increased by 41.6% (loam, upper layer), 17.2% (albic soil, middle layer), and 4.6% (loess, lower layer). Under the same soil moisture content, the frost heave rate of loam was highest, whereas that of loess was lowest, and the frost heave of the uppermost 15 cm, which is the biologically enriched layer, accounted for ~55% of the frost heave. As a result, we determined the empirical relationship between frost heave and freezing depth, which is important for interpreting the effects of frost heave on increases in the storage space of forest soils and for calculating changes in soil porosity.

Keywords: seasonally frozen soil; frost heave; soil moisture content; soil type; freezing depth; soil porosity

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Introduction

As the most direct effect of soil freezing (Jackson, 1958), frost heave plays an important role in zones that experience seasonally frozen soil and is especially important for the stabilization and development of soils in temperate forests of the northern hemisphere (Groffman, 2001). In addition to having a positive effect on the redistribution of soil moisture, salinity, and nutrients (Outcalt, 1975; Zhao, 1997; Maximov, 2008), frost heave also enhances the diversity of microbial soil communities (Sulkava, 2003; Withingtin, 2007; Tan, 2010) and decomposition of litter (Coxson, 1987). However, few studies have addressed the effect of frost heave or its impact factors in seasonally frozen forest soils.

In addition, previous studies have been restricted to two main topics. The first topic incorporates the quantitative modeling (Jackson, 1958; Nixon, 1975; Outcalt, 1975; Taylor 1978) and analysis of the microscopic mechanisms of frost heave (Harlan, 1973; Konrad, 1981, 1982) under artificial conditions (Konrad, 1982; Padilla, 1992), as well as the effects of heat, moisture, and solutes on the development of frost heave in unsaturated soils (Cary, 1987; Selvadurai, 1999). Meanwhile, other studies have focused on the engineering aspects of frost heave, by simulating and controlling the effects of soil expansion, stretching, displacement, which occur as a result of frost heave, since they directly affect the stability and safety of architectural construction (Miller, 1974; Tong, 1985; Padilla, 1992; Andrew, 2003). However, these studies lack observations and analysis of *in situ* frost heave in forest soils, especially for temperate forests in the northern hemisphere.

Since understanding the extent of frost heave in forest soils and its relationship with major impact factors is necessary for estimating the effects of frost heave on the soil porosity and ecology of cold temperate forest soils, the objective of the present study was to quantify the extent of frost heave in a broad-leaved Korean pine forest and to determine the relationship of frost heave with soil moisture, soil type, and freezing depth using both lab-based simulation and field-based *in situ* measurement.

Materials and Methods

Experimental site

Field experiments were conducted in a broad-leaved Korean pine forest in the Changbai Mountains, which is a typical natural forest ecosystem and seasonally frozen region in northeastern China (12806′E, 4201′N, 738 m elevation). Based on meteorological conditions recorded from 1983 to 2015 at the Changbai Mountain Forest Ecosystem Research Station, Chinese Academy of Sciences, which is ~1 km from the forest, the region is characterized by a humid subalpine climate, with a mean annual temperature of 3.6°C, annual precipitation of 695.3 mm, relative humidity of 75–82%, and average annual evaporation of 1250.9 mm (Wang, 2005; Lin, 2015). In addition, snow cover occurs for up to 158 d each year (November to April), with an average air temperature of -5.5°C during this period, and the average temperature of the coldest month (January) ranges from -16.7 to -18.6°C. Soil freezing begins in late October and ends in early May of the following year, with a maximum freezing depth of ~1.2 m. In broad-leaved Korean pine forest, the frozen soil can be divided into three layers (loam, albic soil, and loess, from top to bottom), with depths of 0 to 13 (±2) cm, 13 (±2) to 32 cm (albic soil), and ≥32 cm, respectively.

Lab-based simulation of frost heave

Twelve sampling points were haphazardly selected in the forest, with at least 10 m between adjacent sampling points, and the soil profile was excavated at each point to a depth of 1.2 m. Subsequently, the 12 soil profiles were divided into four groups (3 points each), saturated, and the moisture content of the four groups was adjusted to approximately 50, 40, 30, and 20% by evaporation over 2–7 d.

Once the desired moisture contents were achieved, we sampled each soil profile at 15 cm intervals from the surface (0 cm) to 1.2 m in depth (i.e., 9 samples per soil profile) using cutting rings (2.5 cm i.d., 6 cm length), and any excess soil that was overflowing the cutting ring cylinders was cut off flatly. Then, to determine the change in soil volume caused by frost heave, we measured the lengths of the undisturbed soil columns (i.e., soil in cutting ring cylinders) before (H_0) and after (H_f) freezing. The lengths of the cutting rings were measured using a vernier caliper (0.001 mm) and used for H_0, whereas to measure H_f, the cutting ring samples were sealed and refrigerated at -10°C for 48 h, after which the lengths of the soil columns were immediately measured (Fig 1).

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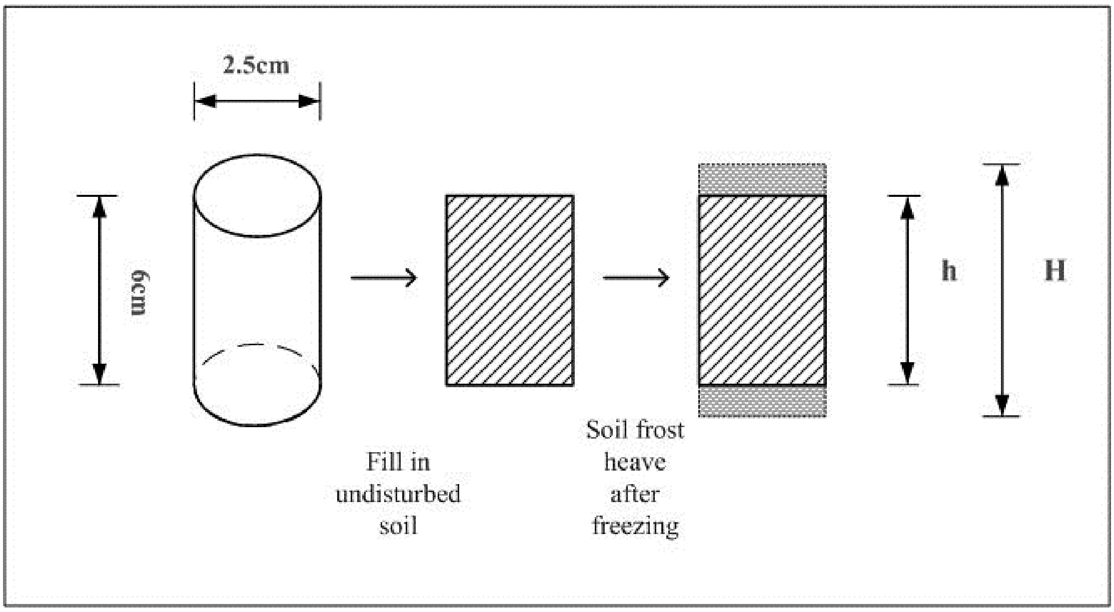

Fig 1. Schematic diagram of our lab-based frost heave simulation.
Cutting ring cylinders were filled with undisturbed soil from various depths of soil profiles from a broad-leaved Korean pine forest, and soil expansion was measured by comparing the lengths of each soil column before (H_0) and after (H_f) freezing.

Because the diameters of the samples were constrained by the cutting ring cylinders, changes in the volume of the soil columns could be assessed by measuring changes in length alone. Therefore, the frost heave rate could be calculated as:

$$f = 1 - \frac{V_0}{V_f} = 1 - \frac{H_0}{H_f}, \quad (1)$$

where f is frost heave rate (%), V_0 (cm^3) and H_0 (cm) are the soil column volume and length before freezing, respectively, and V_f (cm^3) and H_f (cm) are the soil column volume and length after freezing, respectively.

In situ measurement of frost heave

We arranged nine frozen soil swell-shrink measuring scales (Fig 2) in a 3 × 3 pattern in the same broad-leaved Korean pine forest, with 20 m between adjacent scales. The nine measuring scales were divided into 3 groups, and vernier baseboards (2 in Fig 2) were installed at different depths in each group (0, 15, and 30 from ground level). Changes in elevation were observed every 4 d, in order to measure changes in the soil volume at the three different depths, and we also measured the soil moisture content of each soil layer before and after freezing.

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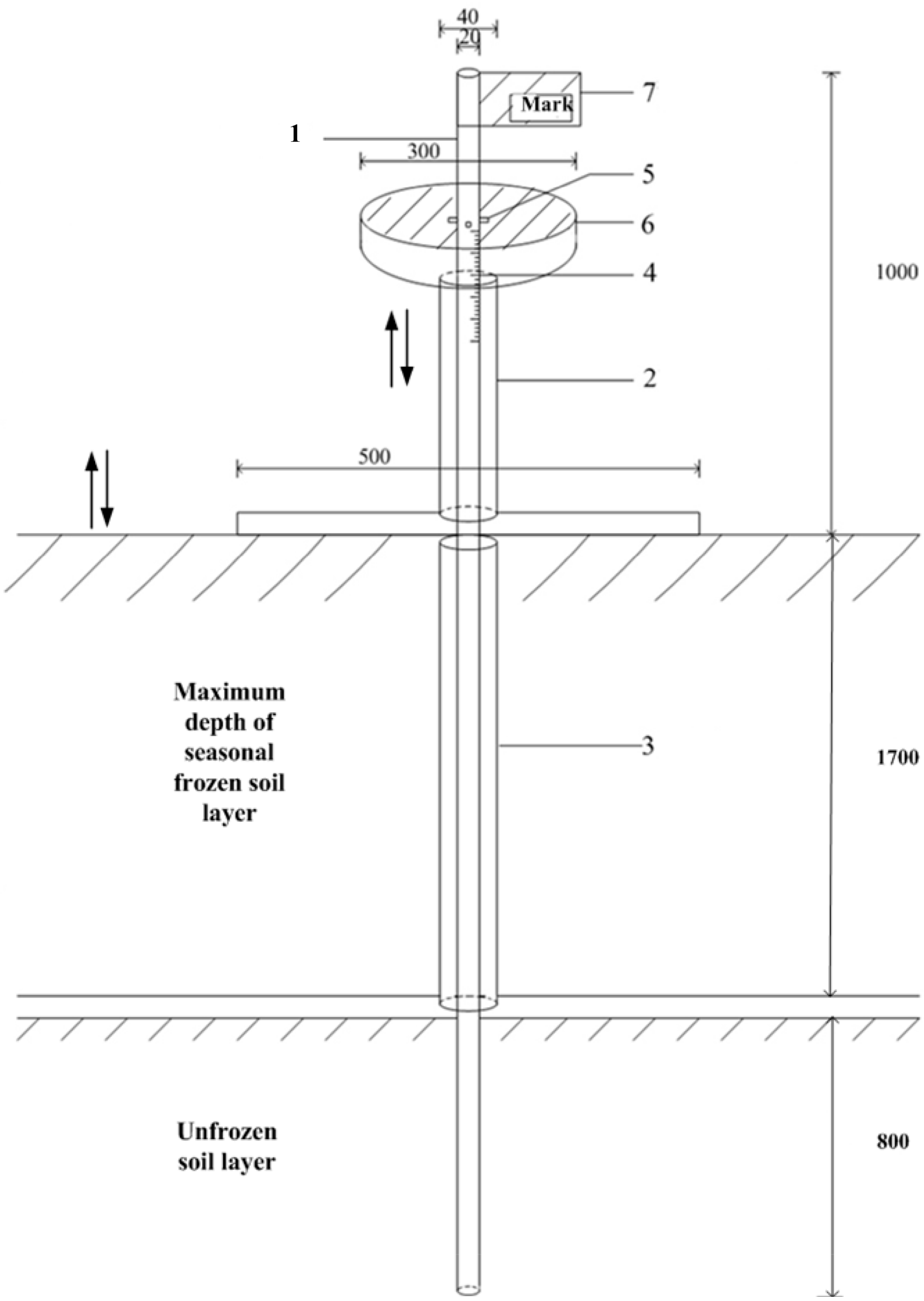

Fig 2. Schematic diagram of a frozen soil swell-shrink measuring scale.
1, fiducial pillar (steel, fixed in the ice-free soil layer); 2, vernier (polymethyl methacrylate, included baseboard and vernier); 3, protective casing (polyvinyl chloride, prevented displacement of the fiducial pillar); 4, graduated scale (mm); 5, support bracket (steel, supported the snow cover); 6, snow cover; 7, marker flag (plastic).

Results

Lab-based simulation of frost heave

The lab-based simulation demonstrated that frost heave rate differs between soils from different sampling depths, regardless of soil moisture content (Fig 3), and the differences in the frost heave rates of shallow soils (0, 15, 30 cm in depth) were greater than those of the underlying layers. In addition, the frost heave rates of shallow soils (0, 15, and 30 cm in depth) with soil moisture contents of 20, 30, 40, and 50% accounted for larger percentages

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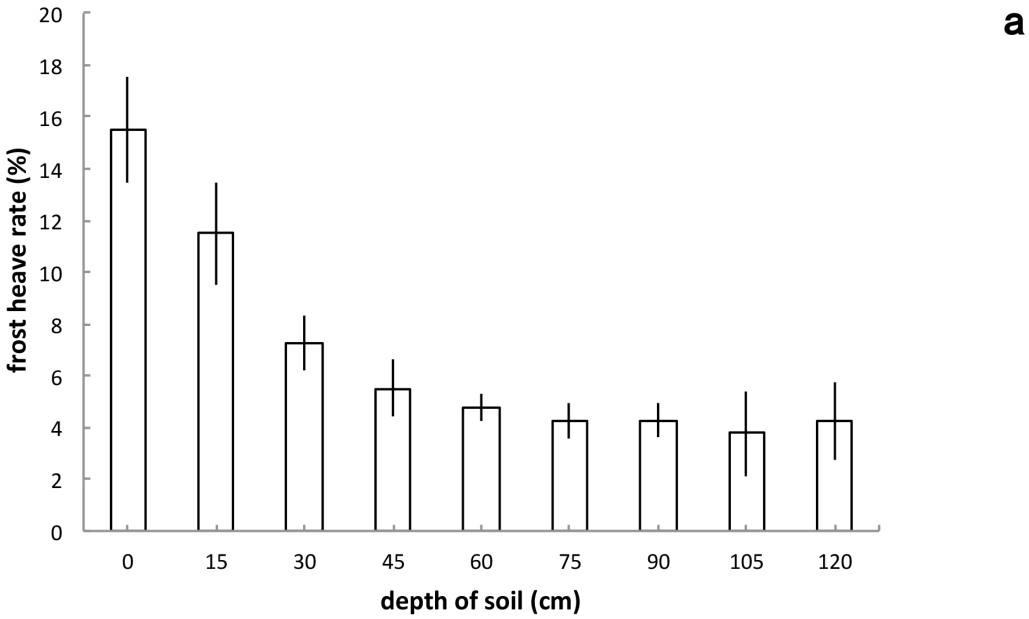
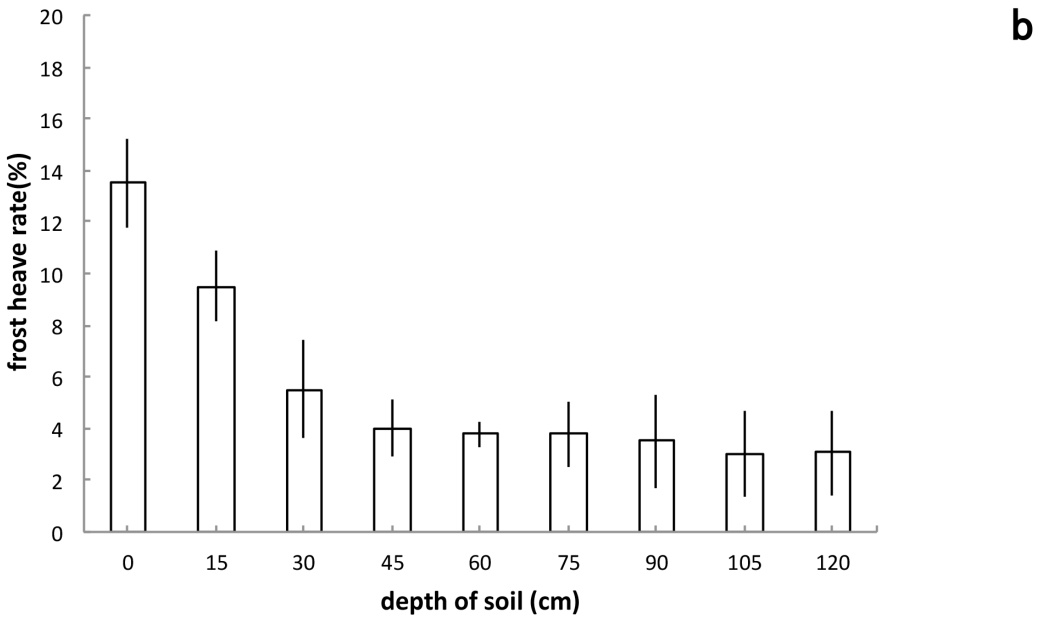
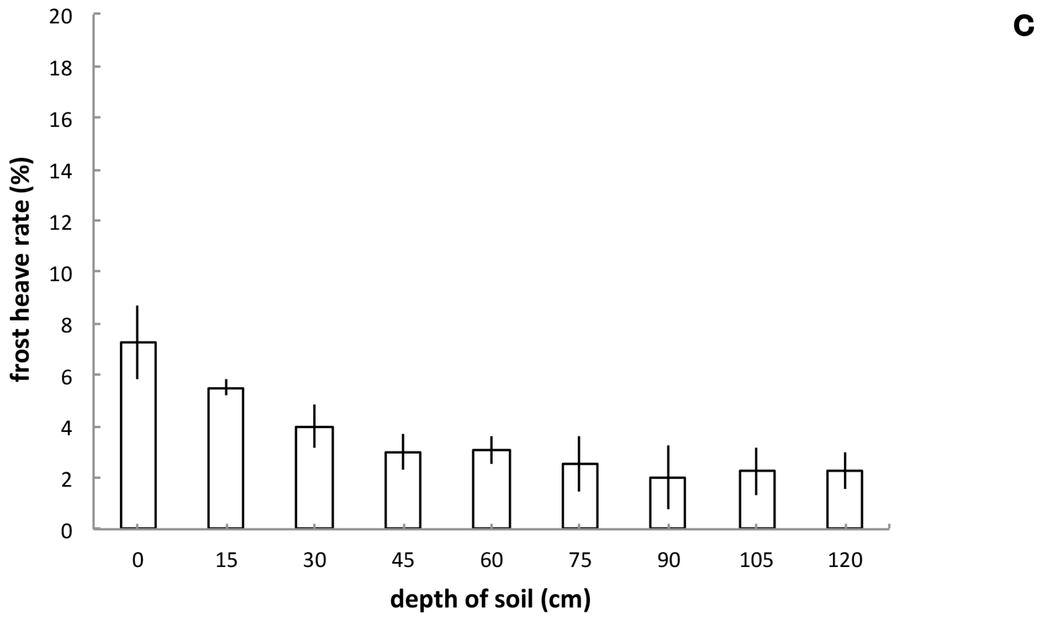
(54, 52, 57, and 56%, respectively) of the total frost heave than did the rates of soils from >30 cm deep; the frost heave rates of the shallow soils were 2.13, 2.45, 1.81, and 1.75 times greater than the rate of soil from 30 cm depth.







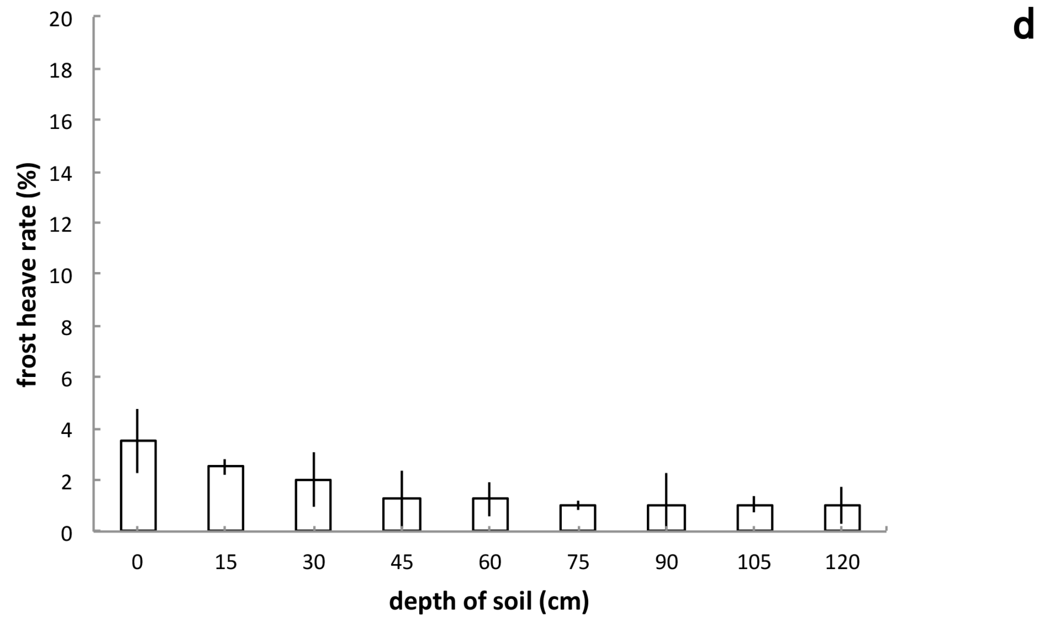


Fig 3. Simulated frost heave of undisturbed soils from different depths of broad-leaved Korean pine forest.

The soil was frozen by refrigeration under soil moisture contents of 50% (A), 40% (B), 30% (C), and 20% (D). Values indicate means ± SE (n = 3).

Frost heave rate was also associated with soil type, with the highest frost heave rate in loam and the lowest in loess, as well as soil moisture content, with the highest frost heave rate in soils with 50% soil moisture content and the lowest rate in soils with 20% soil moisture content (Fig 4). Furthermore, frost heave rate and soil moisture content were linearly correlated in each soil type ($R^2 > 0.96$; Fig 4), with higher frost heave rates in soils with higher moisture contents, and rate of increase for frost heave rate in response to soil moisture content (i.e., regression slope) was greater in loam (0.422) than in either albic soil (0.241) or loess (0.111). The linear regression equations of frost heave rate in response to soil moisture content were:

$$f_1 = 0.422x - 4.850 \qquad R^2 = 0.967 \tag{2}$$

$$f_2 = 0.241x - 2.470 \qquad R^2 = 0.990 \tag{3}$$

$$f_3 = 0.111x - 0.993 \qquad R^2 = 0.990 \tag{4}$$

where f_1, f_2, and f_3 are the simulation soil frost heave rates in loam, albic soil, and loess, respectively, and x is the soil moisture content.

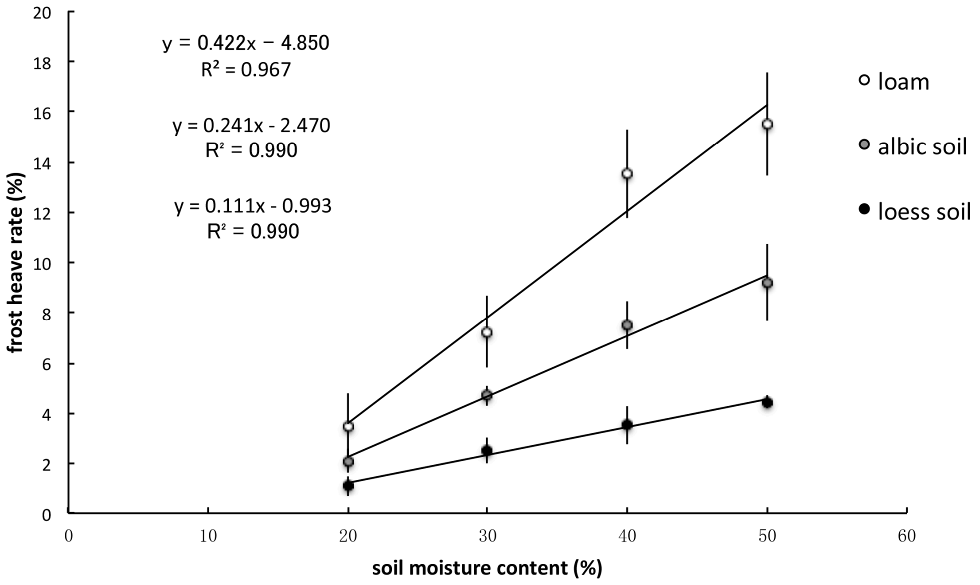


Fig 4. Simulated frost heave of three soil types in response to soil moisture content. Values indicate means ± SE (n = 3).

In situ measurement of frost heave

Our *in situ* measurement (Fig 5) demonstrated that the initiation of frost heave occurred first in loam, followed by albic soil and loess. Therefore, in order to obtain accurate measurements, the mean frost heave of each layer was calculated from measurements that coincided with the occurrence of maximum freezing depth, and the resulting mean frost heave values were 2.96, 1.86, and 0.57 cm for the loam, albic soil, and loess, respectively, with soil moisture contents of 55.6, 44.8, and 26.8%. Moreover, the *in situ* frost heave rates of loam, albic soil, and loess were 1.11, 0.76, and 0.45 times those observed in our lab-based simulation, respectively, which suggested that the frost heave of deeper soil was reduced by the stress of overlying soil.

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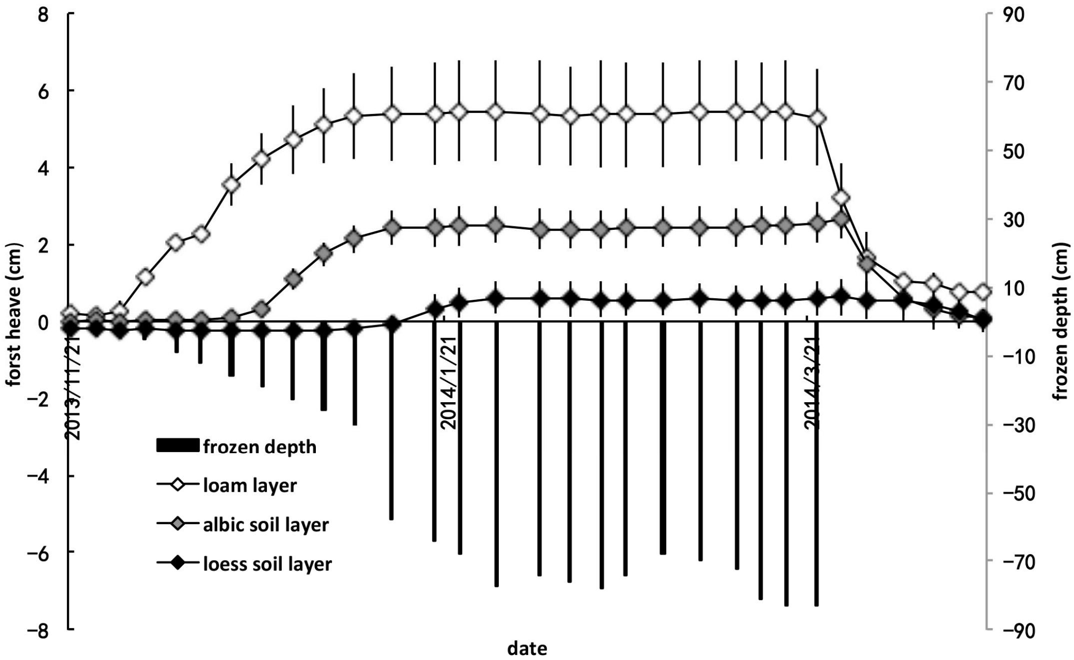

Fig 5. *In situ* frost heave in three soil types of a broad-leaved Korean pine forest.
The symbols and error bars indicate mean ± SE (n = 9) frost heave, and the black lines indicate the mean freezing depth (n = 9).

Correction of simulation frost heave rates

To correct the linear correlations of frost heave rate and soil moisture content from our lab-based simulation, we estimated the effect of gravitational pressure from overlying soil by assessing the relationship between the simulated and *in situ* frost heave rates (Fig 6). The *in situ* frost heave rates under specific soil moisture contents were calculated from the changes of elevation recorded by the verniers and freezing depth of each soil layer (the maximum freezing depth was 83 cm in 2014), and corresponding estimates of simulated frost heave rates could be calculated for the *in situ* soil moisture contents by using the previously determined relationships (see equations in Fig 4). The relationships between *in situ* frost heave rate (*F*) and the simulation frost heave rate (*f*) were:

$$F_1 = 0.984 f_1 + 1.999 \qquad R^2 = 0.613 \qquad (5)$$

$$F_2 = 0.714 f_2 + 0.601 \qquad R^2 = 0.579 \qquad (6)$$

$$F_3 = 0.409 f_3 - 0.129 \qquad R^2 = 0.376 \quad , \qquad (7)$$

where F_1, F_2, and F_3 and f_1, f_2, and f_3 are the *in situ* and simulation frost heave rates of the loam, albic soil, and loess, respectively.

The differences between the simulation and *in situ* frost heave rates were greatest in the loess, followed by albic soil and loam, and we found that the gravitational pressure from overlying soil affected *in situ* frost heave rates by changing the stable soil moisture content. Therefore, the estimated simulation frost heave rates corresponded to a range of *in situ* rates (Fig 6), the range of which expanded with soil depth and resulted in a better fitting model for the relationship between *in situ* and simulation frost heave rates in the loam than in the albic soil or loess.

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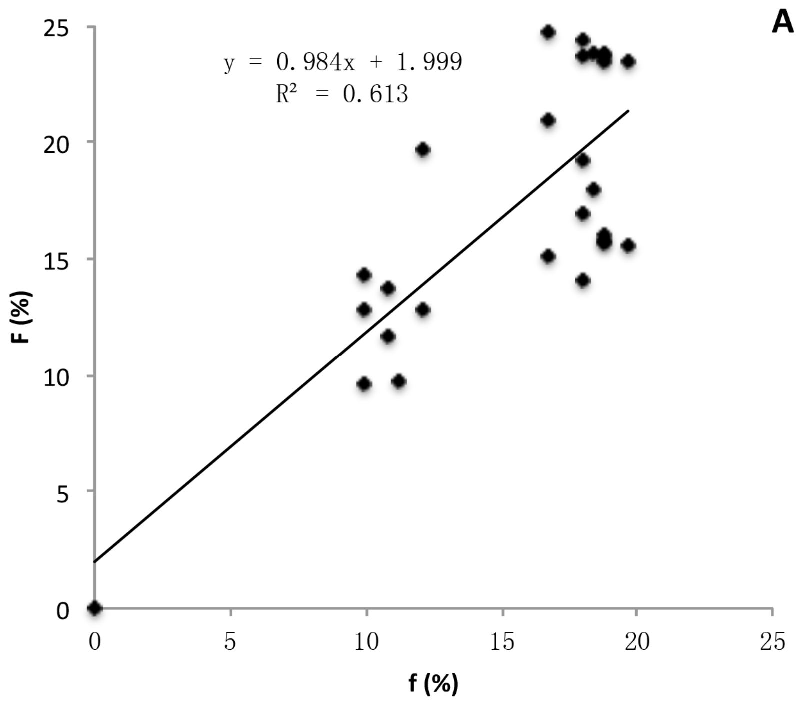

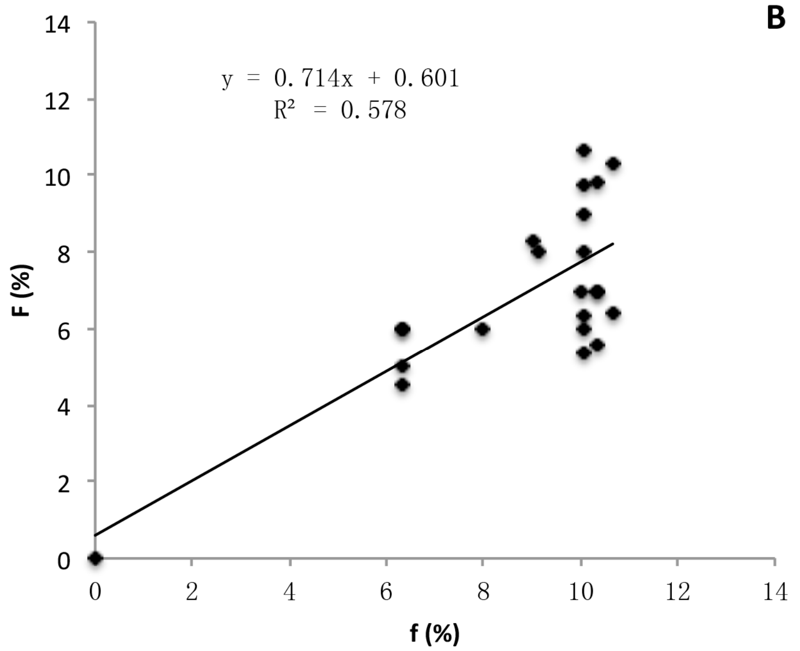

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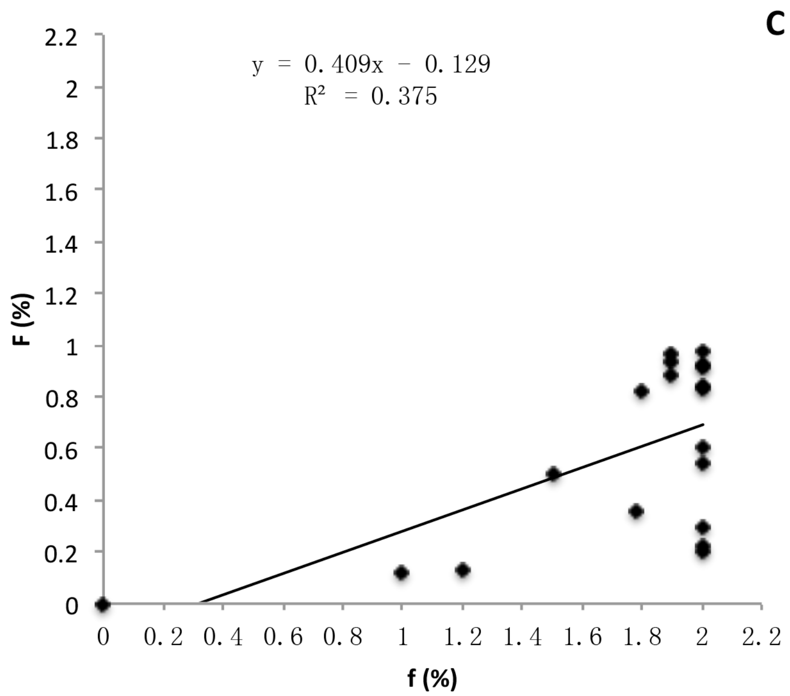

Fig 6. *In situ* and simulated frost heave in loam (A), albic soil (B), and loess (C).
F, *in situ* frost heave rate; *f*, simulation frost heave rate.

In situ frost heave rates

By combining equations 2, 3, and 4 with equations 5, 6, and 7, the linear regression equations of *in situ* frost heave rate in response to soil moisture content were established as follows:

$$F_1 = 0.416x_1 - 2.773 \quad (8)$$
$$F_2 = 0.172x_2 - 1.166 \quad (9)$$
$$F_3 = 0.046x_3 - 0.537 , \quad (10)$$

where F_1, F_2, and F_3 and x_1, x_2, and x_3 are the *in situ* frost heave rates and soil moisture contents of the loam, albic soil, and loess, respectively. The equations demonstrated that for each 100% increase of soil moisture content, the *in situ* frost heave rates increase by 41.6, 17.2, and 4.6% in the loam, albic soil, and loess, respectively.

Therefore, the empirical relationship between frost heave and freezing depth can be summarized as:

$$H = \begin{cases} F_1 h & (h \le h_1) \\ F_1 h_1 + F_2(h - h_1) & (h_1 < h \le h_2) \\ F_1 h_1 + F_2(h_2 - h_1) + F_3(h - h_1 - h_2) & (h \ge h_2) \end{cases} , \quad (11)$$

where, H is the extent of frost heave, F_1, F_2, and F_3 are the *in situ* frost heave rates of the loam, albic soil, and loess, respectively, h is the freezing depth, and h_1 and h_2 are the depth of the lower bounds of the loam and albic soil, respectively.

Discussion

Influence of soil type, soil moisture content, and gravitational pressure

Frost heave is affected by both internal factors, which include mainly include water content, soil type, particle composition, permeability, and salt content (Norikazu, 2003), and external factors, which include the gravitational pressure, pore water pressure, freezing rate, and environmental temperature (Wang, 2000). However, the most significant impact factors are soil moisture content, soil type, and the gravitational pressure of overlying soil.

Soil moisture is required for soil frost heave to occur, and without water, freezing soil would exhibit thermal expansion and contraction. However, not all soil moisture is capable of producing frost heave, and frost heave is generally only thought to occur when the soil moisture content is more than the moisture content of initial frost heave (7–18%, related with the soil) (Wang, 2000). In closed systems, like our lab-based simulation, frost heave forms a fixed value in the stability phases of freezing at specific soil moisture contents, whereas in open systems, like the forest soils examined in the present study, frost heave is affected by the soil moisture content before freezing, as well as the replenishment of water from outside (Zhao, 1999; Wang, 2000). Therefore, even in frozen soil, soil moisture content is dynamic, which is why we measured the soil moisture content of each layer at the same time we observed changes in elevation, and an understanding of the dynamics of soil moisture content is necessary to calculate frost heave rate based on empirical relationships (equations 8, 9, and 10).

Soil characteristics, especially density, are also related to frost heave, and soils that are more compact exhibit less-exaggerated frost heave (Zhao, 1999; Wang, 2000). In the present study, the compactness of loess was higher than that of both albic soil and loam, and, accordingly, exhibited lower frost heave rate.

In addition, gravitational pressure is an important impact factor of frost heave, as well, especially in deeper soils. This occurs because (1) the gravitational pressure changes with increasing depth and (2) the stresses from the overlying soil lead to a small vertical settlement effect of nether soil, which made the F value decreasing slowly in a small range during the stable period of freezing depth. In the present study, the frost heave rates observed in our lab-based simulation were larger than those observed *in situ,* owing to the lack of gravitational pressure from overlying soil. Therefore, in order to confirm and improve the empirical relationships between frost heave rate and soil moisture content, the influence of gravitational pressure should be taken into consideration.

Ecological significance of frost heave in forest soils

Frost heave imparts a variety of ecological and environmental benefits to seasonally frozen soils, especially in forest ecosystems. For instance, frost heave creates spaces for water conservation, and the subsidence that occurs as the soil thaws can significantly affect the diversity and biomass of soil microbial communities (Groffman, 2001; Herrmann, 2002; Oztas, 2003; Sulkava, 2003); promote community regeneration (Schimel, 1996; Withingtin, 2007; Tan, 2010), which affects the activity of soil enzymes (Lipson, 1999); and accelerate litter decomposition (Coxson, 1987), which affects the global circulation of carbon and nitrogen (Fitzhugh, 2001; Maximov, 2008). Therefore, the effects of frost heave are important to investigate, and from an ecological engineering point-of-view, the effects of frost heave could potentially be used to manage and develop forest resources, by promoting the activity of forest soil and for protecting the capacity of forests to conserve water.

Among the benefits of frost heave, water conservation is the most fundamental and valuable, since it is important for the germination and growth of plants at the beginning of the growing season. Frost heave is able to improve the water conservation capacity of soils by 1) moving a small portion of soil moisture from lower soil layers to upper soil layers and 2) by increasing soil porosity and snowmelt storage space (Zhao, 1997; Sugimoto, 2002).

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Conclusions

The results of the present study demonstrate that the frost heave rates of seasonally frozen forest soils are mainly related to soil type, soil moisture content, and the stress of overlying soil. We found linear correlations between frost heave rate and soil moisture content, with frost heave rates increasing with the soil moisture content, and frost heave rate was highest in loam and lowest in loess. Our observation of *in situ* frost heave not only confirmed the influence of soil type, but was also used to correct the empirical relationship between frost heave rate and soil moisture content.

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