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Frost heaving of planted tree seedlings in the boreal forest of Northern Sweden

France Goulet

Institutionen för skogsskötsel
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Licentiatavhandling som för vinnande av skoglig licentiatexamen kommer att offentligen försvaras i hörsal Björken, SLU, Umeå, onsdagen den 7 juni 2000, kl. 10.00.

Abstract

Frost heaving can be a leading cause of tree seedling mortality in many places in the boreal forest of Northern Sweden. The aim of this investigation was to improve our understanding of frost heaving of planted tree seedlings as related to snow cover, scarification, planting methods and soil types. The thesis is based on a review paper, three field experiments and one laboratory experiment. The experiments focus on different methods to control frost heaving of forest tree seedlings and on a number of factors affecting the extent of frost heaving.

The review paper identifies the many aspects of frost heaving of forest tree seedlings and agricultural crops based on an intensive review of the research contributions made during the last century. Even if many investigations have been carried out with the aim to decrease the extent of frost heaving, very little quantitative results are available for tree seedlings.

In a field experiment , the choice of planting positions was effective in decreasing frost heaving of planted seedlings following mounding or disc-trenching. Seedlings planted in the depressions were largely affected by frost heaving with a maximal vertical displacement of 5.4 cm while frost heaving did not occur on the top of the mound. On the other hand, the planting time and planting depth had no influence on the extent of frost heaving. In another field experiment the size of the scarified patches was strongly correlated to frost heaving which reached between 7.6 and 11.5 cm in 4 and 8-dm patches compared to between 4.4 and 5.3 in non-scarified soil and in a 1-dm patch. Ground vegetation probably decreases the diurnal temperature variation and the number of freezing-thawing cycles. The duration and magnitude of frost temperatures, the frost hour sum, increased with patch size. The difference between the 8-dm and 1-dm patch increased to 2064 hour-degrees at the end of the winter. In larger patches, the planting depth seemed to be effective in reducing the maximum frost heaving of the seedlings. In the third field experiment snow cover also showed to be an important factor in regard to frost heaving of tree seedlings. In a snow-free treatment combined with soil scarification, an uplift of 14.6 cm was measured during a winter season. In contrast no vertical displacement was observed under a simulated snow cover. The strong influence of snow on the extent of frost heaving indicates that further investigation should be focused on the interaction between maximum frost heaving and snow depth. In the laboratory freezing chamber experiment it was demonstrated that soil from spodic B horizon is less susceptible to frost heaving than soil from E horizon. Needle ice did not grow at all on soil samples from E horizon during a 3-day test, neither on fresh, nor on oven dried samples. On fresh samples of soil from Bs horizon, needle ices reached a maximum height of 9,7 cm in average.

The use of theodolite and wooden dowels to estimate the extent of frost heaving in this study allowed to follow the process during the frost heaving period. A vertical uplift in millimetres could be recorded. A development of reliable measuring methods which allow a continuous estimation of the extent of frost heaving damage during the whole process, would undoubtedly represent an important step towards a better understanding of frost heaving of tree seedlings.

Keywords: frost heaving, plant injuries, planting, seedlings, regeneration, site preparation, snow cover

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The use of theodolite and wooden dowels to estimate the extent of frost heaving in this study allowed to follow the process during the frost heaving period. A vertical uplift in millimetres could be recorded. A development of reliable measuring methods which allow a continuous estimation of the extent of frost heaving damage during the whole process, would undoubtedly represent an important step towards a better understanding of frost heaving of tree seedlings.

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Contents

List of papers

This licentiate thesis is a summary and discussion of the following four papers, which will be referred to by their respective Roman numerals.

I. Goulet F. (1995). Frost heaving of forest tree seedlings: a review. New Forests 9: 67-94.

II. Sahlén K. and Goulet F. Reduction of frost heaving of Norway spruce and Scots pine seedlings by different planting methods. (Submitted manuscript)

III. Bergsten U., Goulet F., Lundmark T. And Ottosson Löfvenius M. Frost heaving in a boreal forest soil in relation to scarified soil area and snow cover. (Manuscript)

IV. Goulet F., Bergsten U. and Grip H. Is soil from the spodic B horizon more susceptible to frost heaving than soil from E horizon? (Manuscript)

Introduction

Frost heaving can be a leading cause of tree seedling mortality in areas with below-freezing air temperatures, high soil moisture and frost susceptible soils. Such conditions are predominant in many places in the boreal forest of Northern Sweden. Regeneration areas with Norway spruce and Scots pine are sometimes highly damaged by frost heaving resulting in reduced growth and survival. The economical consequences can locally be significant.

Theory and mechanism of frost heaving

Considerable studies have been made with the aim of understanding the mechanism of frost heaving (Miller 1972, Penner 1977, Saarelainen 1992). Taber (1929, 1930) suggested that heaving was caused by a migration of water through the soil to a freezing zone where ice lenses were formed. Such principles were confirmed afterwards by many researchers and a capillary theory for ice lens growth was developed. This theory required that a film of water exist between the ice and soil particles at all times to serve as a path for water to the ice phase. The capillary theory was later on termed "primary frost heaving" to make a difference with "secondary frost heaving", involving the growth of the ice into some of the pores formed by stationary soil particles below the ice lens itself (Miller 1972). In the case of frost heaving of seedlings, the capillary or primary frost heaving theory has most relevance. Frost heaving of seedlings has indeed been early recognized to be a surface phenomenon (Schramm 1958).

Frost heaving of forest tree seedlings

The essential mechanism of frost heaving of plants have been described as early as 1907 by Hesselman. Rob Scagel (1994), like a great number of specialists, has also attempted to develop a clear description of the process. *"Soil water in the surface layer expands as it forms ice. The expanding soil surface firmly grips the seedling. The freezing layer draws moisture to it from unfrozen soil layers, causing the ice lens to expand. Further, as the ice lens expands, the surface soil and the seedling are lifted. Upon thawing, the soil collapses, leaving the seedling plug extruded. During fall and early spring, exposed soils can freeze nightly, thawing again the following day. If the seedling is not firmly anchored into the ground by its root system, each freeze-thaw cycle can contribute to the lifting."*

Many studies were carried out to observe the effect of heaving on spruce and pine seedlings such as loss of growth (Low 1969, 1975), high mortality (Söderström 1973, Rietveld and Heidmann 1976) and physical damages (Shaw et al. 1987). The two chief ways in which heaving injures plants are mechanical breakage or tearing of roots, and a lifting of roots from the soil, exposing them to dessication by wind, sun and low temperatures. Roots are sensitive to low temperatures which can impair their growth capacity and survival (Lindström and Nyström 1987, Lindström and Stattin 1994).

Various factors such as soil type, amount of shade and amount of ground cover, have been investigated and correlated to frost heaving. A number of studies concluded that the risk of frost heaving may be increased on fine-textured soils (von der Gonna and Lavender 1989; McMinn and Hedin 1990). The presence of ground cover is another factor that is essential to decrease the effects of frost heaving on pine seedlings (Ledgard 1976, 1978, 1979, Woods et al. 1978, 1979)

Measuring frost heaving of forest tree seedlings

Most studies of frost heaving in which plants have been considered have been based upon field observation made several weeks after the frost action has occurred, in some cases being made in the spring on plants heaved the previous autumn and winter. Heidmann and Thorud (1976), for example, measured the height of ponderosa pine seedlings in the fall to get a reference point. These measurements were subtracted from later measurements to determine the amount of heaving.

Many investigators have been interested in relating soil frost heaving in field plots to vegetation cover, snow cover, air and soil temperatures, and have constructed various soil frost apparatus such as heavometers and besteads for this purpose. Such apparatus measures at daily or weekly intervals the upward movement of pointed wooden dowels or of a rod projecting above a framework. Automated frost heaving recording devices are used to measure the small diurnal cycles.

Statistical methods have also been used based on meteorological records. In a study made by Penner (1970), the progress of heaving of rod projected above the surface was followed by levelling survey.

Controlling frost heaving of forest tree seedlings

There are several ways to reduce frost heaving of soils as described by Heidmann (1976). Few methods have shown to be especially effective in reducing the extent of frost heaving of forest tree seedlings. Such methods include mulching, shading, use of chemicals, choice of container stock, planting positions, planting time, planting depth, sowing, soil preparation.

In a recent guide by Sutherland and Foreman (1995), the planting position following specific soil preparation is recommended to reduce the frost heaving potential of planted pine and spruce seedlings. The extent of frost heaving after mounding is however not clear. Frost heaving can be more serious in mounds than in patches and unscarified spots (Söderström 1977, Örlander 1987). It increased on mounds of fine-textured soil (Thorsen 1978, Örlander and Adelsköld 1989). Bäcke et al. (1986) predicted a decrease in frost heaving of planted seedlings for mounding in general while Örlander et al. (1990) recommended inverted humus mounds to reduce the extent of frost heaving. McMinn and Hedin (1990) did not observe in their study any frost heaving following site preparation by inversion. Furthermore heaved seedlings can be sensitive to soil temperatures which vary greatly in mounds (Lindström and Troeng 1995). Seedling emergence and increased hydraulic conductivity are also negatively correlated in moist soil but positively correlated in dry soil (Oleskog et al. 1999). The soil composition of the planting/seeding spot is therefore an important factor.

Planting with large seedlings early in the spring and planting with the root collar 5-10 cm under the soil surface can be used as control methods to reduce or prevent frost heaving of tree seedlings (Örlander and Gemmel 1989).

Small seedlings are most sensitive to mechanical disturbance and the negative effects of frost heaving are especially pronounced when direct seeding is used (Winsa and Bergsten 1994).

Objectives

The main goal of this licentiate work was to improve our understanding of frost heaving of planted tree seedlings as related to different factors such as snow cover, scarification, planting methods and soil types.

The first paper (I) identifies through a literature review the many aspects of frost heaving of forest tree seedlings and agricultural crops which have been investigated over the past century. The paper examines the theory and mechanism of frost heaving, the effects of frost heaving on plants and the factors affecting frost heaving of plants. The experimental methods used either in laboratory or in the field to measure frost heaving are described. Methods used to reduce frost heaving of forest tree seedlings are also presented and discussed.

The aim of the second paper (II) was to determine the effect of planting spot, planting depth and planting time on the extent of frost heaving of Norway spruce and Scots pine seedlings on a frost heaving susceptible soil in northern Sweden.

The aim of the third paper (III) was to quantify the effects of the size of the scarified area (patches) and the influence of snow cover on the surface and soil temperature and thereby on the extent of frost heaving on a frost heaving susceptible soil in northern Sweden.

The aim of the fourth paper (IV) was to experimentally test the hypothesis that soil from Bs horizon is more susceptible to frost heaving than soil from E horizon.

Materials and methods

This licentiate work was performed through the completion of a literature review, the realisation of three field experiments in the boreal forest of Northern Sweden and a laboratory experiment. A summary of the methods used are presented below. For more details about the measurement procedures and techniques see papers I-IV.

Review paper (Paper I)

In the review paper, most of the article published during the last century which pertain to the theory of frost heaving in general and to the frost heaving of plants in particular were reviewed. The research contributions were examined and discussed in the light of an increasing need to understand and control frost heaving of forest tree seedlings.

Field experiment (Paper II)

Norway spruce seedlings (*Picea abies* (L.) Karst.) and Scots pine seedlings (*Pinus sylvestris* L.) were planted in 1989 in northern Sweden on two dates: during the spring (early planting) and during the fall (late planting). In each case, two planting depths (normal and deep planting) and four planting sites (in the depression, in the scalp/trench area, on the top of the mound and in the untreated humus layer) were used. The height of seedlings from the soil surface to the terminal buds were measured in the fall prior to the first frost period to the nearest millimetre as a reference point. These measurements were subtracted from later measurements, in late spring before the growing season, to determine the amount of heaving. Measurements were made during two years. Precipitation and temperature data were collected from nearby meteorological stations. The effects of treatment factors on the size of frost heaving were determined by analysis of variance.

Field experiment (Paper III)

The effects of scarified soil area and snow cover on frost heaving of soil and tree seedlings in a frost heaving susceptible soil was quantified in two adjacent field experiments in the boreal forest of northern Sweden. In one experiment five soil treatments was compared: without scarification, and humus-layer and soil removed down to the mineral soil in square-patches with the side of 1, 2, 4 or 8 dm. In the centre of each treatment a Scots pine seedling was planted. Wooden dowels (ø 15 mm, 40 cm high), i.e., indicators on frost heaving, were placed at each centre, one on soil surface (Heave Surface) and one at a soil depth of 5 cm (Heave Soil). In the other experiment, the treatments natural snow cover, simulated snow cover, and snow-free were compared by using wooden boxes. Styrofoam insulation was used to simulate snow cover and a protecting cloth-cover was used in the snow-free treatment. In the centre row of each treatment/box four 1-year old Scots pine seedling were planted. Two seedlings were planted in patches of 4x4 dm where the humus layer had been removed and two seedlings were planted directly in the humus layer. Also, wooden dowels (ø 15 mm, 120 cm high) were placed on soil surface near the seedlings.

A wooden frame was used to allow each wooden dowel to move, through holes, in a vertical direction and made it possible to measure height movements of dowels with a theodolite. Movements of the wooden dowels were recorded one season from October to November, i.e., until snow cover made the measurements difficult to perform, and from April to June. Heaving of the seedlings was recorded by measuring the height of the seedlings to the terminal buds in the late fall prior to the period of snow covering, to the nearest millimetre as a reference point. These measurements were subtracted from later measurements, after thawing in late spring. Frost heaving of four trees was also measured to have a reference for movements of trees due to frost heaving. Data from a nearby climate station were used for standard climate description of the site.

Laboratory experiment (Paper IV)

Soil samples were collected from an area frequently exposed to frost heaving in northern Sweden. A laboratory-freezing test, simulating an open system, was performed with each soil type (fresh and oven-dried soil from E horizon and from Bs horizon). Each frost heaving experiment was performed during three days and height of needle ice (maximum and area- weighted) and frozen area of soil surface were measured as indicators of frost heaving and frost.

Major results

Frost heaving of forest tree seedlings: a review

The review paper confirmed that the mechanism of frost heaving of plants are well described and documented. In considerable studies, the effect of frost heaving on the plants and the different factors affecting frost heaving of plants are observed. Different controlling methods are tested either in the field or in the laboratory to reduce or prevent frost heaving. It has however been difficult to quantify the extent of the damages and to show the efficiency of the methods.

Reduction of frost heaving of Norway spruce and Scots pine seedlings by different planting methods

The choice of planting positions shows to be effective in decreasing frost heaving of planted seedlings following mounding or disc-trenching. The amount of heaving was considerable higher in the depressions with a maximum vertical displacement of 5.4 cm. On the tops of the mounds and in the humus layer, it was almost insignificant. Seedlings planted in the depressions had therefore higher risk to have portion of the root system exposed or completely thrown out and lying on the ground. The degree of heaving injury was related to the planting depth only for Scots pine planted in the depressions and apparently not at all related to the planting time.

Frost heaving in a boreal forest soil in relation to scarified soil area and snow cover

The diurnal variation of soil surface temperature increased with the size of the patches, particularly during the period before the ground was covered by snow, but also with shallow snow cover. Also the duration and magnitude of frost temperatures, the frost hour sum, increased with patch size with a difference of 2064 hour-degrees between the 1-dm and the 8-dm patches at the end of the winter. The simulated snow cover completely removed the diurnal temperature variation and effectively reduced the cooling of the soil as compared to the treatment with no snow and natural snow cover. The development of frost hour sum in the snow free treatment and natural snow was almost similar until the natural snow cover was established, thereafter the snow-free plot continued to cool off and the frost sum dropped to lower values.

There were no indications during late autumn of frost heaving for treatments with intact humus layer while scarified patches greater than 2 dm showed significant frost heaving for all three indicators, Heave Seedling, Heave Surface and Heave Soil. The vertical displacement ranged between 1.0 to 6.1 cm. Maximum up lift in scarified patches because of frost heaving, nearly 11.5 cm, was observed in late winter, i.e., in April and early May. Frost heaving increased with the size of the patches for both the wooden dowels at the surface of and in the soil and for the seedlings in the same way as the increase observed for the diurnal variation of soil surface temperature. The extent of frost heaving was higher for Heave Surface than for Heave Soil. The maximum vertical displacement of trees in late winter was on average 4.4 cm, i.e., similar to the values observed for seedlings and dowels with an intact humus layer and a natural snow cover. The treatment that was kept free from snow during the winter in combination with soil scarification showed the highest values of frost heaving, 14.6 cm. In contrast, no obvious vertical displacement were observed in the treatments with a simulated snow cover comparable to extreme snow depth.

Is soil from the spodic B horizon more susceptible to frost heaving than soil from E horizon

Needle ice did not grow at all on soil samples from E horizon, neither on fresh, nor on oven dried samples. With this soil, the area was frozen almost 100%. On fresh samples of soil from the spodic B horizon needle ices reached a maximum height of 9.7 cm. Needle ices were not uniform on a given surface since their appearance varied in the time. The oven dried samples of soil from the spodic B horizon showed similar results as the soil sample from E horizon. The soil texture was similar for both types of soil and cannot explain therefore the difference in the appearance of needle ices. Further investigation should be done to compare the unsaturated hydraulic conductivity of the soil samples.

Conclusions

Forest tree seedlings growing on exposed mineral soil can be susceptible to heavy mortality or decreased growth due to frost heaving. A number of experiments have earlier been conducted to control the extent of frost heaving of planted seedlings. It has however been difficult to quantify the efficiency of the different methods and understand the mechanism involved.

A lot of the work performed so far with tree seedlings has been of a descriptive nature.

Choice of planting positions has been shown in the present study to be effective in controlling frost heaving of planted seedlings following mounding or disc-trenching. Seedlings planted in the depressions were largely affected by frost heaving. On the top of the mound, frost heaving was prevented as in the untreated humus layer. However frost heaving related to soil temperature patterns in mounds should be further investigated. The water-holding properties, such as moisture characteristic and saturated/unsaturated conductivities, of different soil mixtures at the planting spot should also be considered. The planting time and the planting depth have shown no correlation in this study with the extent of frost heaving.

In an area where the humus layer has been removed, the extent of frost heaving is largely influenced by the size of the scarified patches as shown in the second study. Ground vegetation decreases the diurnal temperature variation and the number of freezing-thawing cycles. On frost heaving susceptible soil, the humus layer should not be removed at all, or only in a very small area, as in this case not bigger than ca 1 dm in diameter. In larger patches, increased planting depth might reduce the maximum frost heaving due to improved root anchorage.

Both laboratory and field experiments need to be conducted to test the hypotheses concerning the control of frost heaving of forest tree seedlings. The soil composition and the soil/site preparation at the planting spot are factors which should be investigated further in the attempt to develop more effective controlling methods. The extent of frost heaving on organic soil compared to mineral soil is especially a factor of interest. The strong influence of snow on the extent of frost heaving independent of site preparation, indicates that further investigation could be focused on the interaction between maximum frost heaving and snow depth. Partial or complete overstories of dominant vegetation affect the snow depth and soil temperature. This praxis should be studied in relation to frost heaving.

Such investigations cannot be done without the development of reliable measuring methods which allow a continuous estimation of the extent of frost heaving damage during the whole process, in contrast with single measurements at a given time. The use of theodolite and wooden dowels to estimate the extent of frost heaving in this study allowed to follow the process during the frost heaving period.

Differences in vertical displacement was recorded with a resolution of one millimetre. However, it is still difficult to extend this methodology to the heaving of seedlings which have no fixed points and which often disappear behind surrounding vegetation, soil formations and snow. A development of the methodology in this direction would undoubtedly also represent an important step towards a better understanding of the process of frost heaving of tree seedlings.

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