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Does the removal of snowpack and the consequent changes in soil frost affect the physiology of Norway spruce needles?

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ABSTRACT

Climate change may cause a decrease in snow cover in northern latitudes. This, on the other hand, may result in more severe soil frost even in areas where it is not common at present, and may lead to increased stress on the tree canopy. We studied the effects of snow removal and consequent changes in soil frost and water content on the physiology of Norway spruce (*Picea abies* [L.] Karst.) needles and implications on root biomass. The study was conducted at a 47-year-old Norway spruce stand in eastern Finland during the two winters of 2005/06 and 2006/07. The treatments in three replicates were: (i) natural snow accumulation and melting (CTRL), (ii) artificial snow removal during the winter (OPEN), and (iii) the same as OPEN, but the ground was insulated in early spring to delay soil thawing (FROST). In spite of the deeper soil frost in the OPEN than in the CTRL treatment, soil warming in spring occurred at the same time, whereas soil warming in the FROST was delayed by 2 and 1.5 months in 2006 and 2007, respectively. The soil water content was affected by snow manipulations, being at a lower level in the OPEN and FROST than CTRL in spring and early summer. The physiological measurements of the needles (e.g. starch, carbon and nitrogen content and apoplastic electrical resistance) showed differences between soil frost treatments. The differences were mostly seen between the CTRL and FROST, but also in the case of the starch content in early spring 2007 between the CTRL and OPEN. The needle responses in the FROST were more evident after the colder winter of 2006. The physiological changes seemed to be related to the soil temperature and water content in the early growing season rather than to the wintertime soil temperature. No difference was found in the fine root (diameter < 2 mm) biomass between the treatments assessed in 2007. In the future, conditions similar to the OPEN treatment may be more common than at present in areas experiencing a thick snow cover. The present experiment took place over the course of two years. It is possible that whenever thin snow cover occurs yearly, the reduced starch content during the early spring may be reflected in the tree growth itself as a result of reduced energy reserves.

1. Introduction

In the northern hemisphere approximately 55% of the land surface is covered by seasonal frozen soil that may last from a few weeks to several months (Zhang et al., 2003). The depth and duration of soil frost varies between years and location, depending on vegetation, soil texture, soil moisture content and snow depth, the last inevitably being the most important source of variation (Ling and Zhang, 2003; Zhang, 2005; Hollister et al., 2005; Isard et al., 2007; Sutinen et al., 2008). In areas with shallow snow cover, the soil may freeze deeply, whereas in areas with deep snow cover the soil may stay unfrozen throughout the winter (e.g. Soveri and Varjo, 1977; Isard and Schaetzl, 1998; Zhang, 2005). According to the recent IPCC report, the area covered by snow in March–April is declining in the Northern Hemisphere (IPCC, 2007).

Wintertime precipitation is predicted to increase with climate change in the boreal zone (Ruosteenoja et al., 2005; IPCC, 2007), but there are considerable uncertainties concerning the proportion of the precipitation that occurs as rain and snow, and hence the accuracy of predictions for soil frost remains uncertain (Poutou et al., 2004; Räisänen, 2008). It is possible that areas with a deep snow cover in the present climate will have either no, or only a thin, insulating snow cover in the future, leading to deeper soil frost than at present (Isard and Schaetzl, 1998; Venäläinen et al., 2001). A tendency towards decreased soil temperatures has been observed in the Michigan region (USA) in spite of a slight increase in winter air temperatures (Isard et al., 2007). In Canada, annual soil freezing days have declined despite decreases in snow depth but soil freeze–thaw cycles have increased with the increase in the mean winter air temperatures (Henry, 2008). According to model simulations for Finland, the depth of soil frost may be reduced in the

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southern part of the country towards the end of this century, but could increase in the northern part of Finland, especially towards the middle of the century (Kellomäki et al., 2010). This would also be due to a reduced snow cover and the occurrence of cold winters in the future.

The term soil frost covers the physical attributes of temperature and water content. The equilibrium between the water and ice in the soil and, accordingly, the water vapor pressure over ice, is defined by temperature. Previous studies have demonstrated the effects of soil frost on the forest soil processes and the shoot and root responses of trees. In the same experimental plots as in this study, nitrous oxide (N_2O) emissions and the carbon dioxide (CO_2) production rate increased in the soils with delayed thawing (Maljanen et al., 2010). Soil NO_3^- concentrations and the leaching of carbon, nitrogen and phosphorus increased as a result of soil freezing (Fitzhugh et al., 2001; Groffman et al., 2001; Hardy et al., 2001). Delayed thawing in spring has been reported to cause a delay in the onset of trunk sap flow, a reduction in CO_2 assimilation, transpiration, and the potential efficiency of PSII by dark-adapted chlorophyll fluorescence (F_v/F_m) in Scots pine (*Pinus sylvestris* L.) and Norway spruce (Bergh and Linder, 1999; Strand et al., 2002; Mellander et al., 2004, 2006, 2008; Repo et al., 2007). In addition, laboratory studies showed that delayed soil thawing has reduced the short root growth and root tip formation in Scots pine saplings (Repo et al., 2005, 2008). It has caused a reduction in the F_v/F_m, in the water potential and in the chlorophyll a/b ratio, and an increase in the apoplastic electrical resistance of the needles, in addition to reduced trunk sap flow. Stronger soil freezing has also increased the root mortality in sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Brit.) and Norway spruce (Groffman et al., 2001; Tierney et al., 2001; Gaul et al., 2008). Based on a modeling approach, the timing of soil frost thawing affects the net primary production of Scots pine (Mellander et al., 2008), and the soil frost depth explains the spatial variance in the productive capacity of forests in the southern and central part of Finland (Solantie, 2003).

Because of the wide distribution of soil frost in the boreal zone and its importance for the growth and carbon sequestration of forest trees, especially in the face of climate change, we arranged a snow manipulation study on a stand of Norway spruce. Our aim was to investigate the physiological responses of Norway spruce needles to different soil frost conditions, i.e. temperature and water content, set up by removing the snow cover throughout two consecutive winters and by insulation of the soil surface from late winter until early summer. We hypothesize that soil frost, its delayed thawing and a consequent restricted water uptake would affect the physiological activity of needles.

2. Materials and methods

2.1. Experimental set-up

A snow manipulation experiment was carried out at a 47-year-old (in 2005) Norway spruce stand on flat level ground in the boreal coniferous zone near the city of Joensuu, Finland (62°36′N, 29°43′E, 84 m a.s.l.) between 2005 and 2007. The habitat of the site is classified as mesic heath forest and the forest type as *Myrtillus* (MT), according to the Finnish classification system (Cajander, 1949). The stand characteristics were assessed by means of the normal methods of forest inventory used in Finland (Koivuniemi and Korhonen, 2006). The average height of the trees was 17 m, the stand density 864 trees per hectare, the stand volume 211 $m^3\ ha^{-1}$ and the basal area 25.4 $m^2\ ha^{-1}$. The soil was glacial till and the pedological soil type ferric podzol. The organic matter content in the organic horizon was 70.8%, and in the uppermost mineral soil layer (3–10 cm) 9.0% (for soil texture, see Guitart Xarpell et al., 2010). The mineral soil nutrient content by layers at the study site was determined by means of analysis of ammonium-acetate extracts (Table 1).

Table 1
Mean soil extractable nutrients (NH_4-acetat extract), pH and nitrogen content by layers at the study site (n = 9).

	Soil layer		
	Organic	Eluvial	Illuvial
P, mg/kg	65.6	2.7	2.4
Ca, mg/kg	1170	36.6	21.6
Mg, mg/kg	265	9.5	8.4
K, mg/kg	428	47.3	17.1
Fe, mg/kg	27.6	173.5	62.9
Cu, mg/kg	0.021	0.020	0.117
Zn, mg/kg	7.94	0.85	0.32
Mn, mg/kg	100.9	28.4	21.1
Al, mg/kg	59.3	238.0	635.3
pH	3.9	4.2	4.7
N, %	1.71	0.22	0.12

The experiment was set up in 2005 with three treatments and three replicate plots. Spatially, the plots (size 12 m × 12 m for each) with different treatments in each replicate were arranged side by side, with a transition zone of 5 m between the plots. The replicate plots were located rectangularly around the data logger in the middle of the study area. Different soil frost conditions were obtained by snow manipulations in the two winters 2005/06 and 2006/07. The treatments were: (1) snow accumulated and thawed according to the natural rhythm (CTRL). (2) Snow was removed by shoveling (OPEN). (3) The same as OPEN, but the ground was insulated with a layer of hay (ca. 15 cm) between plastic sheeting in late March (week 13) to delay soil thawing (FROST). The OPEN treatment currently falls within the natural variation in some locations, especially in the western part of Finland, but the FROST treatment, with soil temperature close to 0 °C until mid-July, is beyond the natural variation (Solantie, 2000). Snow removal to the transition zone between the plots was undertaken within two days of each snow fall. A thin layer of snowpack was left on the ground surface to facilitate shoveling. From the transition zone, part of the melting water was expected to infiltrate to the experimental plots. In heavy rainfalls some water percolated at the edges of the plastic sheets into the soil. When the soil temperature in FROST rose permanently above 0 °C, the insulation was removed on July 21 and July 4 in 2006 and 2007, respectively. For each plot a log was kept of air temperature at a height of 2 m, soil temperature at depths of 5, 15 and 50 cm (105T thermocouple, Campbell Scientific, Shepshed, U.K.), and volumetric soil moisture content at a depth of 15 cm (CS615, Campbell Scientific, Shepshed, U.K.). A measuring rod was set in the middle of the CTRL plots to facilitate monitoring of the snow depth. The snow water equivalent was assessed on the CTRL plots in winter 2006/07. Daily precipitation in the experimental area was obtained from the climate data of the Finnish Meteorological Institute as interpolated onto a 10 km × 10 km grid (Venäläinen et al., 2005).

Three trees per plot were selected randomly from the middle of each plot to avoid the border effects. One shoot from each tree was sampled at a distance of 1–3 m from the top of the canopy in 2006 and 2007 at approximately one-month intervals between April and October. The calendar weeks for sampling were 14, 18, 22, 26, 31, 35 and 39 in 2006 and 14, 19–20, 23, 26-27, 32, 36–37, and 41–42 in 2007.

2.2. Chlorophyll content of needles

The dark-adapted (20 min) chlorophyll fluorescence was measured for previous-year (C+1) and current-year (C) needles in three replicates (MINI-PAM, Heinz Walz Gmbh, Effeltrich, Germany). The