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Snowmelt Infiltration Through Partially Frozen Soil in Finnish Lapland

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Abstract

Snowmelt timing is critical for tree growth in high latitudes, but threshold conditions with respect to root-zone soil water availability in spring is not well understood. In spring 2008 we measured snowpack thickness, apparent snow water (ASW), air and soil temperature, as well as soil water content (SWC) in Mustavaara fell (67°59'N, 24°06'E), Finnish Lapland. Three monitoring stations were established on a fell (mountain shaped by Pleistocene glaciations) gradient: forest at 394 m.; forest line at 447 m and tree line at 480 m a.s.l. Forest hosts stands Norway spruce (Picea abies) and are underlain by Haplic Podzol developed on glacial tills. Before the onset of the snowmelt (on 16th of April) the snowpack was at the thickest, 104 cm, in the forest line as compared to those of 85 cm in forest, and in 45 cm in treeline. Soil temperature (20-cm-depth) remained below 0°C until the 1st of June. Due to air temperature rise notably above 0°C on 27th of April, the onset of snowmelt occurred throughout the elevation gradient. At all stations (treeline, forest line, and forest) the effect of snowmelt was seen as the rise of ASW (29th of April) two days later and the rise of SWC (30th of April) three days later, hence suggesting that snowmelt water infiltrate rather unimpeded through the soil. The maximum SWC was observed to be rather simultaneous with snow disappearance in the treeline, whereas in the forest and forest line snow disappeared almost a month later than maximum SWC. We contend that snowmelt infiltration through partially frozen soil significantly contributes to ground water reserves and soil water availability, rather than soil temperature, is pivotal for the start of height increment of trees in northern boreal conditions.

Key words: soil, frozen, snowmelt, water, infiltration, treeline, Lapland, Finland

1. Introduction

In high latitudes and elevations, the length of the growing season and variations in the soil water availability are controlled by the thickness of the snowpack and the timing of snowmelt (*Vaganov et al.,* 1999; *Groisman and Davies,* 2001; *Euskirchen et al.,* 2006; *Sutinen et al.,* 2007a; *MacDonald et al.,* 2008). In addition to being a crucial factor with regard to winter soil temperature (*Vajda et al.,* 2006; *Sutinen et al.,* 2008), snowpack shelter is also important to decomposition of organic matter and soil nutrient cycling. Snowmelt contributes to the major part of the seasonal soil water in the northern hemisphere (*Groisman and Davies,* 2001) and snowmelt provides necessary

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soil water reserves for the initiation of root water uptake in late winter and early spring (*Sutinen et al.,* 2009). Hence variability in snowpack thickness, and thereby soil chemistry, may be a critical driver for plant communities and the tree species-specific spreading in the forest-tundra ecotone. With respect to climate change, the models of *Euskirchen et al.* (2006) suggest an earlier snowmelt until 2100, yet these trends are spatially variable on a continental scale. According to the observations and future climatic scenarios, the snowpack thickness will be reduced in the northern hemisphere (*Groisman and Davies,* 2001). This feature significantly affects the ecology in forest-tundra, particularly on the Fennoscandian fell regions, where the winter wind climate is the major factor for snow drifting and winter soil temperature (*Vajda et al.,* 2006).

A snowpack impacts on meltwater runoff and recharge of ground water reserves (*Stein and Kane,* 1983; *Stadler et al.,* 1997; *Vaganov et al.,* 1999; *Solantie,* 2000; *Lindström et al.,* 2002; *Bayard et al.,* 2005). The soil water content (SWC) and soil temperature (T) are profoundly attributed to inter-annual and intra-seasonal climatic events, such as incident solar radiation, freeze-thaw cycles, snow interaction, and precipitation (*Solantie,* 2000; *Venäläinen et al.,* 2001a; 2001b). Even though snowmelt timing and unfrozen soil water are prerequisite factors to the springtime acceleration of water uptake and recovery of photosynthetic capacity of trees and ground vegetation (*Vaganov et al.,* 1999; *Sutinen et al.* 2009), limited information is available on the changes in unfrozen soil water content during springtime snowmelt along alpine forest-treeline gradient.

Meltwater infiltration into frozen soil may be impeded by soil surface conditions, e.g. by the ice lenses formed during the soil freezing processes, yet the rate of water entry into frozen soils is attributed to spatial variability of the soil physical properties (*Motovilov* 1979; *Gray et al.* 2001). The studies in permafrost regions in Alaska and Siberia have indicated that meltwater released from snowpack is able to infiltrate into frozen soil (*Hinkel et al.,* 2001). Also, snowmelt water has been found to infiltrate unimpeded into organic soil horizons in the subalpine treeline environment in Canada *(Leenders and Woo*, 2002). In agricultural soils of Minnesota, snowmelt water often forms ephemeral ponds, and infiltrates rapidly into soils despite the presence of a frozen layer in the soil below (*Baker and Spaans,* 1997). They conjectured, that water most likely infiltrates through air-filled macropores. There are also experimental evidence and models to indicate water infiltration into a frozen soil such that snowmelt water infiltrates into a frozen soil preferentially through contraction cracks and rotten root pathways (*Stadler et al.,* 2000; *Koivusalo,* 2003). In addition, *Stadler et al.,* (1997) demonstrated that the flow of snowmelt water through the frozen layers occurred not only in the liquid phase between soil particles and pore ice but also as microscopic bypass flow in the previously air-filled macropores. The development of precise TDR-sensors allows measurements of liquid water content during the winter from infiltration of snowmelt water in a variety of soil textures.

Since the 1990s, Geological Survey of Finland (GTK) has carried out inter-annual monitoring of the soil water content (SWC) and soil temperature (T) in glacial drift materials derived from variety of lithologies in Finnish Lapland (*Hänninen, 1997*;

Sutinen et al., 1997). These observations have confirmed by that the unfrozen SWC of a site primarily depends on soil physical properties, and the magnitude of intra- and inter-seasonal variation in SWC is site-specific (*Motovilov,* 1979; *Gray et al.,* 2001; *Sutinen et al.,* 2007b). The aim of this study was to see if notable rise in springtime air temperature will contribute to snowmelt infiltration into the soil sequences hence providing soil water reserves for the use of trees along forest-treeline gradient in Finnish Lapland.

2. *Materials and methods*

2.1 *Study sites*

The Mustavaara fell (mountain shaped by Pleistocene glaciations; 67°59'N, 24°06'E) is located 30 km south of the polar Norway spruce (*Picea abies* L. Karst) forest line and 55 km of the polar Scots pine (*Pinus sylvestris* L.) forest line (*Sutinen et al.,* 2007a). The fell is composed of mafic Mg-tholeitic metavolcanite rocks (bedrock database by Geological Survey of Finland), and is mantled by thin veneer of glacial till. The study area is a part of pristine forests of the Ounas-Pallastunturi National Park managed by the Finnish Forest and Park Service (Metsähallitus).

The presence of permanent snow cover lasts for 200–220 days of the year, and of the mean annual precipitation, 530 mm, more than 40% falls as snow, and precipitation June–September is 250 mm (Finnish Meteorological Institute (FMI); *Vajda et al.,* 2006). The soil types ranges from Typic Haplocryod to Skeletic Podzol. However, due to cryoturbation, creep and solifluction the soil profiles are, in many places, distorted and hence with no distinct horizons. With the aid of historical and modern aerial photos and the object oriented image analysis, we have found that the composition of the closed forest, dominated by downy birch in the 1940's, has significantly replaced by Norway spruce until 21st century (*Middleton et al.,* 2008).

2.2 *Instrumentation*

Three monitoring stations were established on a fell gradient: forest at 394 m., forest line at 447 m and tree line at 480 m a.s.l. Forest hosts stands Norway spruce. On September 2007 all three sites were instrumented for soil T and soil θ_v at 20-cm-depth increments as follows; 20, 40, 60 cm. In the text, T with numeric subscript indicates depth; e.g. T_{20} refers to soil temperature at 20 cm depth. The sensors were installed horizontally into the soil sequences of hand-excavated pits: 1 m in length, 0.5 m in width and 1 m in depth. The sensors were not placed one on the top of another, but positions shifted laterally ca. 30 cm. Soil water content (SWC) was recorded with CS615 TDR-probes and soil temperature with T107-sensors and were automatically logged with CR1000 data-loggers (Campbell Scientific, Logan, UT).

Climatic variables; air temperature (T_{AIR}), snow temperature (T_{SNOW}) and snow depth were also simultaneously recorded. Snow depth was measured with (SR50A) sonic range sensors (Campbell Scientific, Logan, UT, USA). Apparent snow water

(ASW) was measured with dielectric leaf wetness sensors (Decagon Devices Inc, Pullman WA, USA) placed on the ground surface and in snow 30 cm above ground. The leaf wetness sensors record voltage changes on the sensor surface, such that 900 mV corresponds to liquid water. Hence ASW is surrogate for snow water equivalent. All parameters were automatically logged with Campbell CR1000 data-logger in 3-h-intervals. The timing of daily measurements was set as follows; 03, 06, 09, 12, 15, 18 and 21 UTC, respectively. Snow depth was recorded twice a day, 06 and 18 UTC, and in the present study we have used the morning measurement. The daily precipitation amount was measured with a rain gauge at 06 UTC, and we used daily mean T_{AIR} that was calculated as a mean of eight measurements made with three hours interval.

2.3 *Sensor calibrations*

The CS615-sensors measure propagation velocity of the electromagnetic (EM) waves through the soil, the velocity as being a function of the soil physical properties, particularly dielectric (ε) properties and soil water content (*Topp et al.,* 1980; *Campbell Scientific,* 1996). In the soil dielectric mixture unfrozen free water ε=81 outweighs the impact of the other soil dielectric constituents, such as rock particles ε=4–7 (*Hänninen and Sutinen,* 1994), air ε=1, and that of ice ε=3.2–3.8 (*Bogorodsky et al.,* 1983), hence unfrozen water content governs the wave propagation velocity in a soil. As a result of the phase change from water into ice, the probes show water content, although significantly decreased, also for frozen soil (*Stein and Kane,* 1983).

Before field instrumentation, all sensors applied to this study were tested and calibrated in laboratory for air at -20ºC, for air, dry sand and water at +20ºC (see *Sutinen et al.,* 2008). We found sensor-specific noise to be low, such that the highest coefficient of variation (CV) as being 0.17%, but with an average CV<0.1%. The temperature dependence of the tested sensors was 0.001/ºC within a range from +20ºC to -20ºC. Hence we applied a temperature correction (t) for the primary data (τ) as follows,

$$\tau_c = \tau + 0.001\times(t-20) \qquad (1)$$

The dependence between the primary data and soil water content is a function of soil electrical conductivity (σ) (*Campbell Scientific,* 1996). The salinity of soils, can be due to the clay fraction content, its mineralogy and type of clay (marine or lacustrine) (*Peltoniemi,* 1982). Fertilization can also contribute to changes in probe response, particularly when the soil σ>50 mSm^{-1} (*Corwin and Lesh,* 2003; *Campbell Scientific,* 1996). Except marine sediments on the coastal Gulf of Bothnia (Siira 1985), salinity on the soils in Finland is low (i.e. σ<50 mS/m; *Peltoniemi,* 1982), hence we applied a single calibration formula to convert the primary measurement results to soil volumetric water content. At room temperature (~20ºC) the calibration sand was considered to be dry. However, the probe-specific correction term had to be applied such that $\Delta = 0.7-\tau_{\text{dry sand}}$. Hence the soil volumetric water content is obtained as follows:

$$\theta_v = -0.187 + 0.037\times(\tau_c - \Delta) + 0.335\times(\tau_c - \Delta)^2 \quad (2)$$

The volumetric soil water content (θ_v) and soil T were automatically measured from September 2007. In this paper we describe processes associated with melting of the snowpack in late spring, through 2nd of April to 22nd of May in 2008.

3. *Results*

3.1 *Treeline*

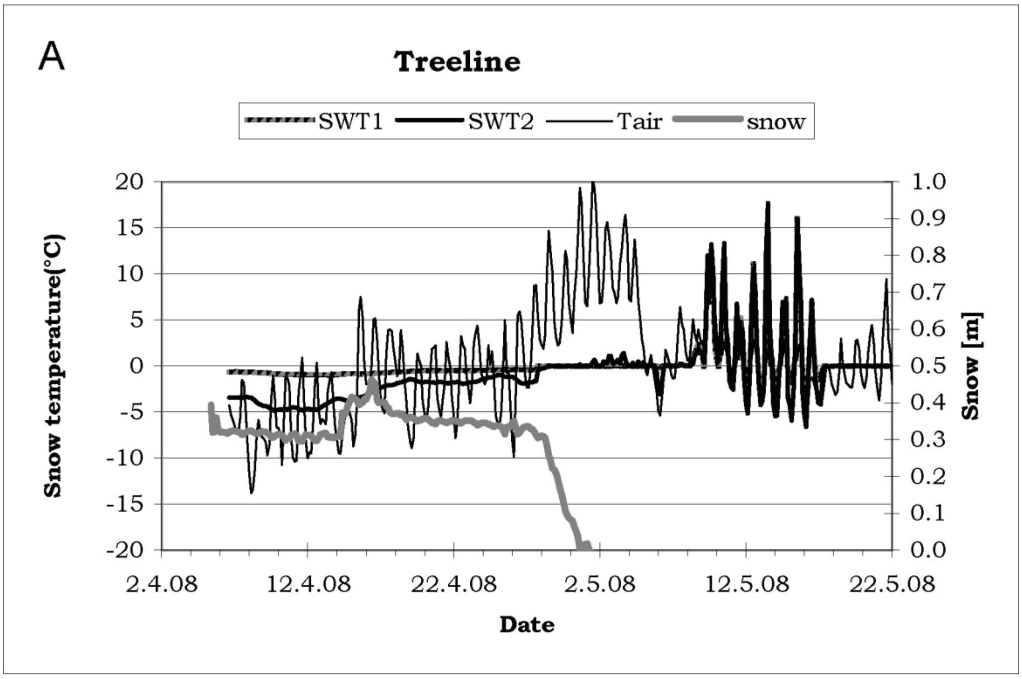
During the monitoring period (2nd of April through 22nd of May 2008) the maximum snowpack thickness of 45 cm was found at the treeline site (480 m a.s.l.). In the snowpack the minimum snow temperature of T_{SNOW}=–4.8°C was recorded, whereas snow on the ground surface maintained T_{SNOW}=<-1°C (Fig. 1a). Due to the increase in daytime air temperature above 0°C in the mid-April, snowpack started to melt, such that within 12 days the snow depth lowered by 12 cm. The onset of snowmelt was triggered by the air temperature constantly above 0°C on 27th of April with maximum of T_{AIR}=20.3°C on the 1st of May (Fig. 1a). Snow disappeared on the 3rd of May, hence it took only a week to melt snowpack of 34 cm.

At the treeline soil maintained subzero temperatures between 13th of November 2007 and 4th of May 2008. The minimum ST_{20}=-1.6°C was recorded on 30th of April 2007. ASW and SWC responded to the onset of snowmelt such that rapid increase was observed on the 28th of May (Fig. 1b). A six days long meltwater ponding was observed on the ground until the 5th of May. Simultaneously with the release of the ponded water the peak maximum of SWC_{20}=0.65 cm^3cm^3 was observed. Similar peak was not found in SWC_{40}, hence suggesting layered structure of the soil and dominance of surface runoff at the treeline site.

3.2 *Forest line*

At the forest line forest line (447 m a.s.l.) the maximum snowpack thickness of 104 cm was found in mid-April (Fig. 2a). In the snowpack the minimum snow temperature of T_{SNOW}=–2.4°C was recorded, whereas snow on the ground surface maintained T_{SNOW}=<–0.3°C (Fig. 1a). Due to the increase in daytime air temperature above 0°C in the mid-April, snowpack started to melt, such that less than two weeks the snow depth lowered by 14 cm. The onset of snowmelt was triggered on 27th of April with maximum of T_{AIR}=14.8°C on the 1st of May (Fig. 2a). Within a week snowpack melted by 50 cm, and contrast to treeline, snow disappeared as late as on the 3st of June.

At the forest line, soil temperature was below 0°C between 9th of March and 1st of June 2008. The minimum temperature was ST_{20}=-0.22°C. ASW and SWC responded to the onset of snowmelt such that rapid increase was observed on the 28th of May for ASW and on 30th for SWC (Fig. 2b). Meltwater ponding or high SWC peaks were not observed, and the maximum of SWC_{20}=0.26 cm^3cm^3 was observed.



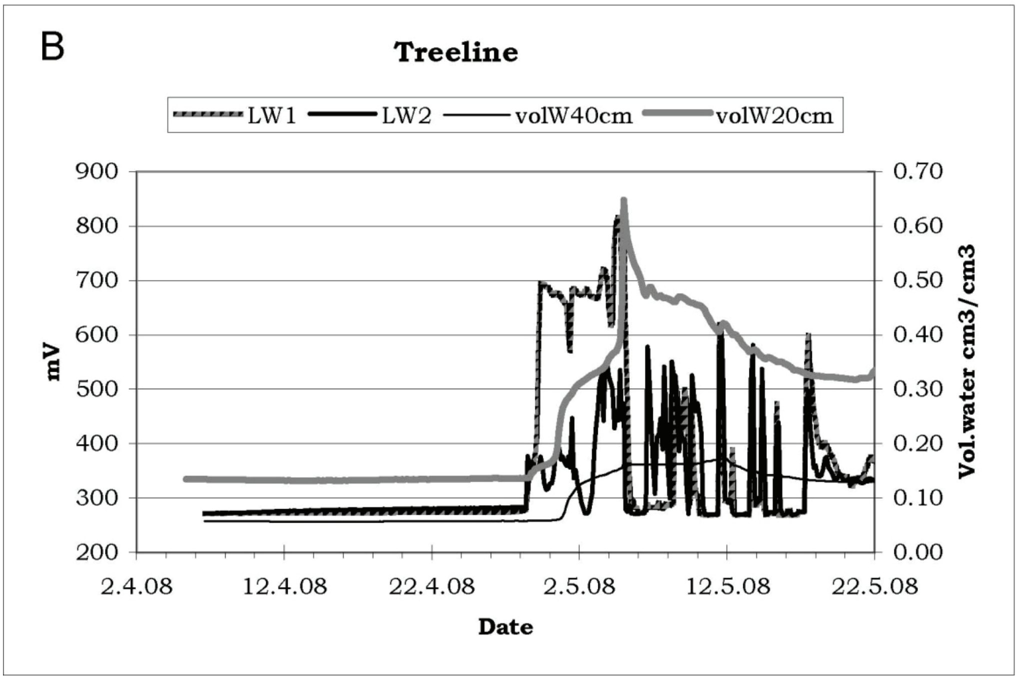


Fig. 1. Changes in climatic variables and soil properties at treeline site on a Mustavaara fell (480 m a.s.l.) during the late spring 2008. A. Snow temperature on ground surface (SWT1) and 30 cm above ground surface (SWT2), air temperature (T_{air}) as well as thickness of snowpack (snow). B. Apparent snow water on ground surface (LW1) and and 30 cm above ground surface (LW2) as well as soil water content at 20-cm-depth (volW20cm) and 40-cm-depth (volW40cm).

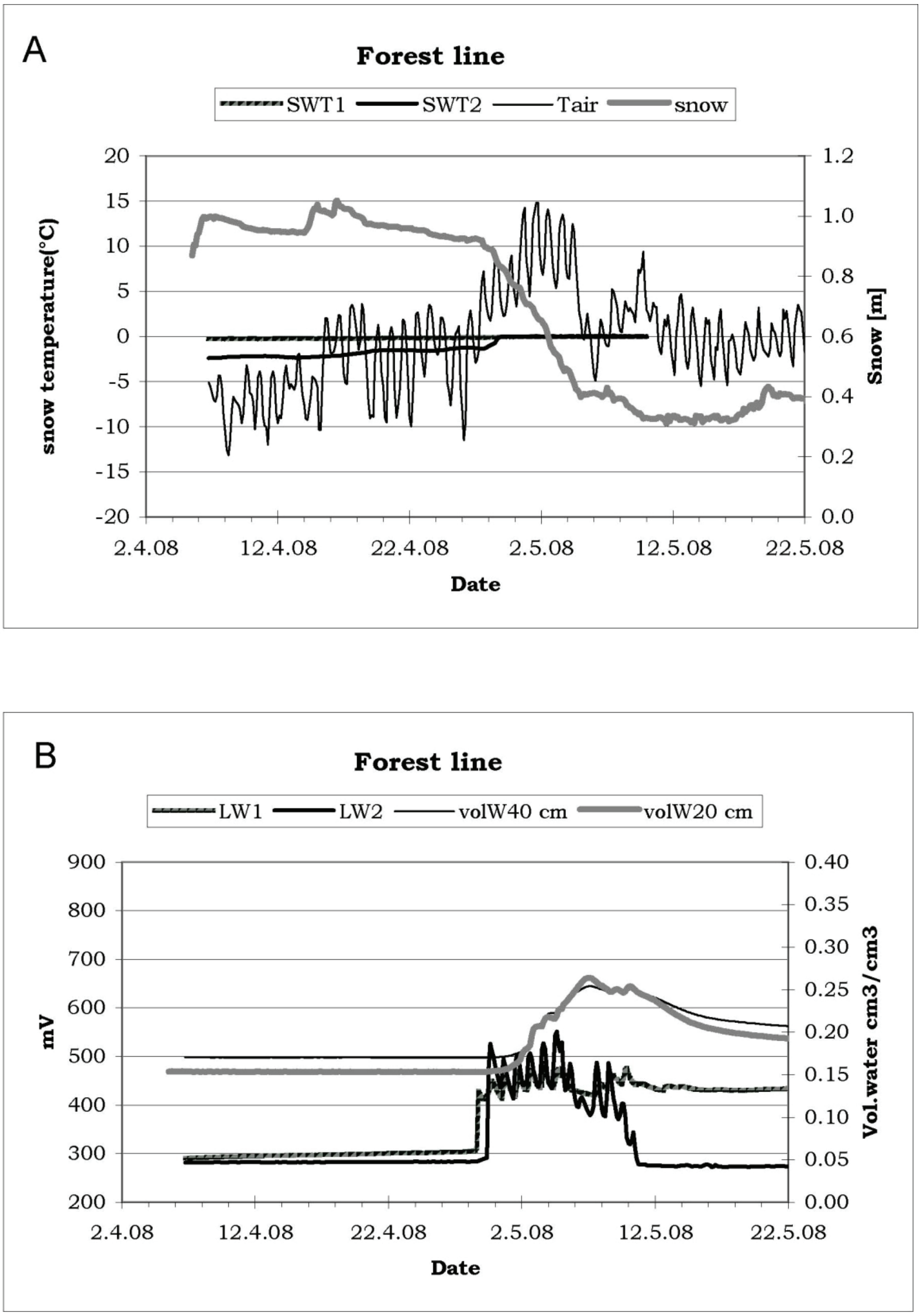


Fig. 2. Changes in climatic variables and soil properties at forest line site on a Mustavaara fell (447 m a.s.l.) during the late spring 2008. A. Snow temperature on ground surface (SWT1) and 30 cm above ground surface (SWT2), air temperature (T_{air}) as well as thickness of snowpack (snow). B. Apparent snow water on ground surface (LW1) and and 30 cm above ground surface (LW2) as well as soil water content at 20-cm-depth (volW20cm) and 40-cm-depth (volW40cm).

3.3 Forest

In forest (394 m a.s.l), soil temperature fell below 0°C on 7th of February and rose above on 1st of June 2008. The minimum temperature was ST_{20}=-0.23°C In the snowpack the minimum snow temperature of T_{SNOW}=–2.3°C was recorded, whereas snow on the ground surface maintained T_{SNOW}=<–0.6°C (Fig. 3a). Due to the increase in daytime air temperature above 0°C in the mid-April, 85-cm-thick snowpack started to melt, such that within 12 days the snow depth lowered by 17 cm. The onset of snowmelt was triggered by the air temperature constantly above 0°C on 27th of April with maximum of T_{AIR}=19.5°C on the 1st of May (Fig. 3a). Snow disappeared on the 3rd of June.

ASW and SWC responded to the onset of snowmelt such that rapid increase was observed on the 28th of May for ASW and on 30th for SWC (Fig. 3b). Moderate meltwater ponding and relatively low SWC_{20}=0.31 cm^3cm^3 peak on 5th of May was observed (Fig. 3b).

4. Discussion and conclusions

4.1 Soil freezing

Snowpack has a low thermal conductivity, hence making it a good insulator such that thick snowpack can even prevent the formation of soil frost (*Williams and Smith, 1989; Solantie, 2000; Bayard et al., 2005*). The present data suggest that soils in forest beneath snowpack seldom experience T_{20}<-0.5°C, whereas relatively thin snowpack in the treeline may result in T_{20}>-1.5°C in Finnish Lapland.

The study by *Sutinen et al.* (2008) demonstrated that soils deeper than 30 cm are unfrozen under the snow cover during winter in southern and mid-boreal climatic conditions of Finland. In a similar way, the long-term monitoring results by FMI indicate that mean annual frost depth in the forests in southern and middle boreal zones of Finland does not exceed 30 cm (*Solantie, 2000*). Similar to the present results, observations made on glacial tills with a range from sandy to silty matrix have indicated that $T_{20–50}$ is above or close to 0°C under snow cover in subarctic climate of northern Finland (*Hänninen,* 1997; *Sutinen et al*., 1997). According to *Hänninen* (1997) soil surface duff may experience soil T_{DUFF} down to T=-4.5°C due to fluctuations in at the snow-atmosphere interface, but T_{20} of silty till may only change from +0.8°C to +0°C and T_{50} from +1.5°C to +0.2°C for the period of December–June. However, stratified sandy materials, owing to higher porosity and tend to follow changes in the T_{SNOW}, and may reach T_{40}>-1.5°C beneath snow cower from March to May during winter in northern Finland (*Koivusalo et al.,* 2001). Apart from winter conditions in boreal forest, at snow-free sites the maximum depth of soil frost in southern and central Finland is ca. 100–150 cm, but that in northern Finland may reach 100–300 cm (*Venäläinen et al.,* 2001b).

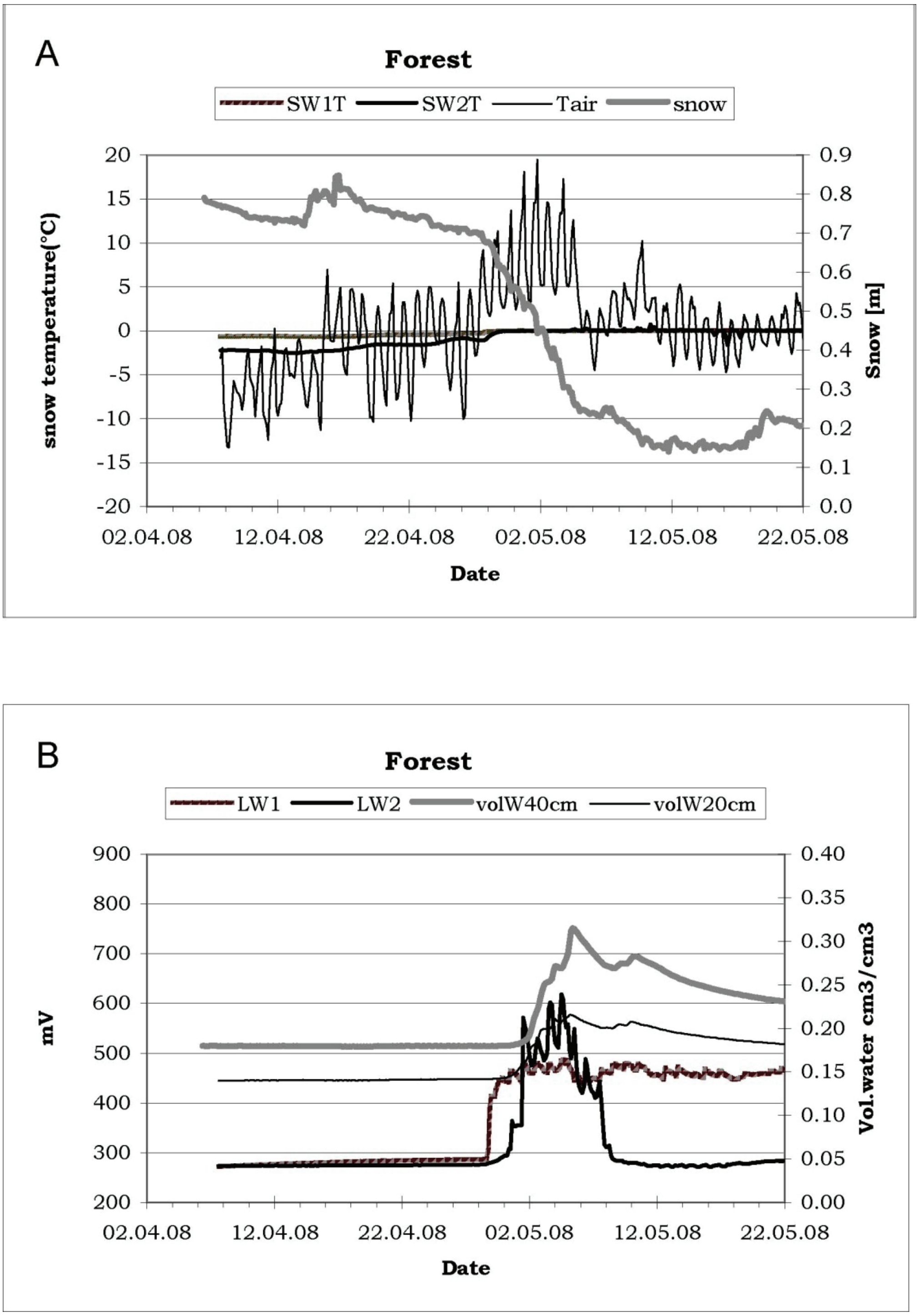


Fig. 3. Changes in climatic variables and soil properties at forest site on a Mustavaara fell (394 m a.s.l.) during the late spring 2008. A. Snow temperature on ground surface (SWT1) and 30 cm above ground surface (SWT2), air temperature (T_{air}) as well as thickness of snowpack (snow). B. Apparent snow water on ground surface (LW1) and and 30 cm above ground surface (LW2) as well as soil water content at 20-cm-depth (volW20cm) and 40-cm-depth (volW40cm).

4.2 Snowmelt infiltration

Notable increase in SWC occurred a month before final melting of snowpack at forest and forest line sites in Mustavaara fell in spring 2008 (Figs 2–3), whereas the peak-SWC was rather concomitant with disappearance of snow in treeline (Fig. 1). Hence soil water availability, a critical factor for initiation of growth of trees in high latitudes (*Vaganov et al.,* 1999; *Euskirchen et al.,* 2006) appears not to be a limiting factor on elevation gradient studied here. In addition, our recent results indicate that boreal soils rarely experience lower than -1.5°C temperatures beneath snowpack during winter, but more importantly, mild events are able to make unfrozen water available in the soil during winter-early spring (*Sutinen et al.,* 2008).

The fraction of the unfrozen soil SWC tended to increase pronouncedly after the onset of the snowmelt (Figs 1–3; see *Sutinen et al.,* 2008). Even though the onset dates and the rise in the soil SWC were rather concurrent here, the response of snowmelt to the early season soil SWC was site-specific. This implies that soil water availability would be a limiting factor only in the case with absence of snow, e.g. in the case of severe wind climate on the treeline (Fig. 1) and fell tundra (*Vajda et al.,* 2006). ASW data revealed that notable meltwater ponding occurred at the treeline site (Fig. 1b). This may resemble to agricultural soils of Minnesota, where snowmelt water often forms ephemeral ponds, and infiltrates rapidly into soils despite the presence of a frozen layer in the soil below (*Baker and Spaans* 1997). Water may infiltrate through air-filled macropores (*Baker and Spaans* 1997) or layered glacial till surface runoff may dominate.

The measurements and model (HBV) analysis from forested sites in northern Sweden demonstrated that soil has often thawed below the snowpack before the start of the spring flood events (*Lindström et al.,* 2002). Hence snow plays an important role not only by determining the length of the summer active season (*Vaganov et al.,* 1999; *Euskirchen et al.,* 2006), but also by the overriding influence on the runoff (*Lindström et al.,* 2002; *Nyberg et al.,* 2002). Meltwater released from snowpack can rapidly percolate down through soil pores, rotten root pathways, thermal contraction cracks or previously air-filled macropores (*Stein and Kane,* 1983; *Hinkel et al.,* 1997; *Stadler et al.,* 1997; *Stadler et al.,* 2000). Hence the fraction of the unfrozen soil SWC tends to increase pronouncedly after the onset of the snowmelt. Our observations showed that the increase in T_{AIR} markedly above 0°C resulted in infiltration of snow meltwater and significant rise in the soil SWC (Figs 1–3). This suggests that the acceleration of root-zone processes can occur concurrently with the rise in T_{AIR} in late winter-early spring (*Sutinen et al.,* 2009).

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References

Baker, J.M. and E.J.A. Spaans, 1997. Mechanics of meltwater above and within frozen soil. USA Cold Regions Research and Engineering Laboratory, *CRREL Spec. Rep.* **79**-10, 31–36.

Bayard, D., M. Stähli, A. Parriaux and H. Flühler, 2005. The influence of seasonally frozen soil on the snowmelt runoff at two Alpine sites in southern Switzerland. *J. Hydrol.* **309**, 66–84.

Bogorodsky, V., C. Bentley and P. Gudmansen, 1983. *Radio glaciology*. Glaciology and Quaternary Geology. D. Reidel Publishing Co.

Campbell Scientific, 1996. *Instruction Manual*. CS615 Water Content Reflectometer. Campbell Scientific, Logan, UT.

Corwin, D.L. and S.M. Lesch, 2003. Application of soil electrical conductivity to precision agriculture: Theory, principles and guidelines. *Agron. J.* **94**, 455–471.

Euskirchen, E.S., A.D., McGuire, D.W. Kicklighter, Q. Zhuang, J. Clein, R.J. Dargaville, D.G. Dye, J.S. Kimball, K.C. McDonald, J.M. Melillo, V.E. Romanovsky, N.V. Smith, 2006. Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems. *Global Change Biology*, **12**, 731–750.

Gray, D.M., B. Toth, L. Zhao, J.W. Pomeroy and R.J. Granger, 2001. Estimating areal snowmelt infiltration into frozen soils. *Hydrol. Process.* **15**, 3095–3111.

Groisman P.Y.A. and T.D. Davies, 2001. Snow cover and the climate system. In: (eds. Jones HG, Pomeroy JW, Walker DA, Hoham RW) pp. 1–44 Snow Ecology. An Interdisciplinary Examination of Snow-Covered Ecosystems. Cambridge University Press.

Hänninen, P. 1997. Dielectric coefficient surveying for overburden classification. *Geol. Surv. Finl. Bull.* 396, 72 p.

Hänninen, P. and R. Sutinen, 1994. Dielectric prediction of landslide susceptibility: A model applied to recent sediment flow deposits. In: Oliveira, R., Rodrigues, L.F., Coelho, A.G. and Punha, A.P. (Eds.) Proc. 7th International IAEG Congress, Balkema, Rotterdam, 137–144.

Hinkel, K.M., S.I. Outcalt and A.E. Taylor, 1997. Seasonal patterns of coupled flow in the active layer at three sites in northwest North America. *Can. J. Earth Sci.* **34**, 667–678.

Hinkel, K.M., F. Paetzold, F.E. Nelson and J.G. Bockheim, 2001. Patterns of soil temperature and moisture in the active layer and upper permafrost at Barrow, Alaska: 1993–1999. *Global Planet. Change* **29**, 293–309.

Koivusalo, H., 2003. Process-oriented investigation of snow accumulation, snowmelt and runoff generation in forested sites in Finland. PhD. Thesis, Helsinki University of Technology Water Resources Publication TKK-VTR-6. http://lib.hut.fi/Diss/2003/isbn9512262371/isbn9512262371.pdf.

Koivusalo, K., M. Heikinheimo and T. Karvonen, 2001. Test of a simple two-layer parametrisation to simulate the energy balance and temperature of a snow pack. *Theor. Appl. Climatol.* **70**, 65–79.

Leenders, E.E. and M-k. Woo, 2002. Modeling a two-layer flow system at the subarctic, subalpine tree line during snowmelt. *Water Resour. Res.* **38(**10), 201–208.

Lindström, G., K. Bishop and M. Ottoson Löfvenius 2002. Soil frost and runoff at Svartberget, northern Sweden-measurements and model abalysis. *Hydrol. Processes* **16**, 3379–3392.

MacDonald, G.M., K.V. Kremenetski and D.M. Beilman 2008. Climate change and the northern Russian treeline zone. *Phil. Trans. R. Soc.* B **363**, 2285–2299.

Middleton, M., P. Närhi, M.-L. Sutinen and R. Sutinen, 2008. Object based change detection of historical aerial photographs reveals altitudinal forest expansion [Electronic resource]. In: *GEOBIA 2008.* – Pixels, objects, intelligence: GEOgraphic Object Based Image Analysis for the 21st century, Calgary, Alberta, Canada, August 05–08, 2008. ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XXXVIII-4/C1. Calgary: University of Calgary. 6 p. Electronic publication.

Motovilov, Yu.G. 1979. Simulation of meltwater losses through infiltration into soil. *Soviet Hydrol.* **18**(3), 217–221.

Nyberg, L., M. Stähli, P.-E. Mellander and K.H. Bishop, 2002. Soil frost effects on soil water and runoff dynamics along a boreal forest transect: 1 Field investigations. *Hydrol. Process.* **15**, 909–926.

Peltoniemi, M. 1982. Characteristics and results of an airborne electromagnetic method of geophysical surveying. Bull. *Geol. Surv. Finl. Bull.* **321**, p. 229.

Siira, J. 1985. Saline soils and their vegetation an the coast of the Gulf of Bothnia, Finland. *Ann. Bot. Fennici* **22**, 63–90.

Solantie, R. 2000. Snow depth on January 15th and March 15th in Finland 1919–98, and its implications for soil frost and forest ecology. *Meteorological Publications* No. **42** FMI-MET-42, p. 176.

Stadler, D., H. Flühler and P.-E. Jansson, 1997. Modelling vertical and lateral water flow in frozen and sloped forest soil plots. *Cold Reg. Sci. Technol.*, **26**, 181–194.

Stadler, D., M. Stähli, P. Aeby and H. Flühler, 2000. Dye tracing and image analysis for quantifying water infiltration into frozen soils. *Soil Sci. Soc. Am. J.* **64**, 505–516.

Stähli, M., P.-E. Jansson and L.-C.Lundin, 1999. Soil moisture redistribution and infiltrationin frozen sandy soils. *Water Resour. Res.* **35**(1), 95–103.

Stein, J. and D.L. Kane, 1983. Monitoring the unfrozen water content of soil and snow using time domain reflectometry. *Water Resour. Res.* **19**(6), 1573–1584.

Sutinen, R., P. Hänninen, M. Mäkitalo, S. Penttinen and M.-L. Sutinen, 1997. Snowmelt saturation restricts Scots pine growth on fine-grained tills in Lapland. USA Cold Regions Research and Engineering Laboratory, *CRREL Spec. Rep.*, **79**–10, 507–512.

Sutinen, R., M. Kuoppamaa, E. Hyvönen, P. Hänninen, M. Middleton, M. Pänttäjä, A. Teirilä and M.-L. Sutinen, 2007a. Geological controls on conifer distributions and their implications for forest management in Finnish Lapland. *Scand. J. For. Res.,* **22**, 476–487.

Sutinen, R, M. Middleton, P. Hänninen, S. Vartiainen, A. Venäläinen, and M.-L.Sutinen 2007b. Dielectric constant time stability of glacial till at a clear-cut site. *Geoderma*, **141**, 311–319.

Sutinen, R., P. Hänninen and A. Venäläinen, 2008. Effect of mild winter events on soil water content beneath snowpack. *Cold Reg. Sci. Technol.,* **51**, 56–67.

Sutinen, R., A. Vajda, P. Hänninen and M.-L. Sutinen, 2009. Significance of snowpack for root-zone water and temperature cycles in subarctic Lapland. *Arctic, Antarctic, and Alpine Res*., **41**(3), 373–380.

Topp, G.C., J.L. Davis and A.K. Annan, 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resour. Res.* **16**(3), 574–582.

Vaganov, E.A., M.K. Hughes, A.V. Kirdyanov, F.H. Schweingruber and P.P. Silkin, 1999. Influence of snowfall and melt timing on tree growth in subarctic Eurasia. *Nature* **400**, 149–151.

Vajda, A., A. Venäläinen, P. Hänninen and R. Sutinen, 2006. Effect of vegetation on snow cover at the northern forest line: A case study in Finnish Lapland. *Silva Fennica*, **40**, 195–207.

Venäläinen, A., H. Tuomenvirta, M. Heikinheimo, S. Kellomäki, H. Peltola, H. Strandman and H. Väisänen, 2001a. Impact of climate on soil frost under snow cover in a forested landscape. *Clim. Res.* **17**, 63–72.

Venäläinen, A., H. Tuomenvirta, R. Lahtinen and M. Heikinheimo, 2001b. The influence of climate warming on soil frost on snow-free surfaces in Finland. *Clim. Change* **50**, 111–128.

Williams, P.J. and M.W. Smith, 1989. *The Frozen Earth: Fundamentals of Geocryology*. Cambridge Univ. Press, Cambridge, p. 306.