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Significance of Snowpack for Root-zone Water and Temperature Cycles in Subarctic Lapland

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Abstract

Snowmelt timing is a critical factor for tree growth in high latitudes, but threshold conditions with respect to soil moisture availability and soil temperature for the root-zone processes are not well known. We monitored snowpack thickness, air and soil temperature, and water content in the soil, sapwood, and roots of downy birch (*Betula pubescens* Roth.) in Finnish Lapland through 1999–2003. An extreme cold event in January 1999 ($T_{AIR} = -49°C$) resulted in soil freezing (at 10-cm depth) down to $T_{10} = -26°C$ at a snow-free site, but beneath the 50-cm-thick snowpack the soil temperature was $T_{10} = -0.5°C$. Snowmelt water was able to infiltrate partially frozen soil sequences, such that an increase in water content of the soil and birch roots occurred two to six weeks before soil temperatures rose notably above 0°C. The soil T_{10} reached +0°C a week after the disappearance of snow. The increase in water content of birch trunks was coincidental with the air temperature rises notably above 0°C. The systematic interseasonal pattern of water content in the birch root-trunk system, i.e. high peaks in late winter–early spring and fall, suggests sap flow in downy birch.

Introduction

Soil water content (θ_{SOIL}), temperature (T_{SOIL}), and nutrient cycling are attributed to interannual and intraseasonal climatic events, such as incident solar radiation, freeze-thaw cycles, snow interaction, and precipitation. Snowpack governs the length of the growing season and impacts on carbon and nitrogen budgets, and meltwater runoff, but it also acts as a good insulator that determines the root-zone soil temperature in winter (Harding et al., 2001; Venäläinen et al., 2001; Lindström et al., 2002; Weich and Karlsson, 2002; Callesen et al., 2007; Mellander et al., 2007). Snowmelt timing is critical for tree growth in high latitudes and the unfrozen soil water is a prerequisite factor for the initiation of springtime root-zone processes and recovery of photosynthetic capacity of ground vegetation and trees (Myneni et al., 1997; Vaganov et al., 1999; Jarvis and Linder, 2000).

Water stored in sapwood provides reserves to meet late-winter transpiration needs (Waring et al., 1979; Boyce and Lucero, 1999). Sapwood water content is generally low during freezing conditions, e.g., in trunks of Scots pine (*Pinus sylvestris* L.; Waring et al., 1979), but episodic high trunk water content values, e.g., in trunks of lodgepole pine (*Pinus contorta* Dougl.), in winter is concomitant with thaw periods (Sparks et al., 2001). The seasonal variation in water content in conifer trunks may be small, as observed for Douglas-fir (*Pseudotsuga menziesii* (Mirbal) Franco) by Beedlow et al. (2007). Moreover, pine species, such as Scots (Irvine and Grace, 1997), pinyon (*Pinus monophylla* Torr. & Frém.), and ponderosa (*Pinus ponderosa* Dougl.) pines (Constantz and Murphy, 1990) tend to have fairly small changes in water content during the growing season. However, the seasonal pattern of water content in birch species may be different from that in conifers.

There are not many reports on fluctuations of trunk water content of deciduous trees in winter. The study by Clark and Gibbs (1957) on yellow birch (*Betula lutea* Michx.) indicated minor variation in trunk water content due to precipitation, evapotranspiration, and winter insolation. Seasonal variation in water content of temperate deciduous hardwoods is small among different tree species (Wullschleger et al., 1996). In contrast to conifers, broadleaved species such as aspen (*Populus tremuloides* Michx.) and cottonwood (*Populus fremontii* S.Wats.), exhibit high annual variation in the trunk water content (Constantz and Murphy, 1990). To date there are no reports on trials to record interannual variations in soil-root-trunk water content in harsh climatic conditions. We focused on monitoring water content at sites of downy birch for five consecutive years (1999–2003) in Finnish Lapland.

The major part of the water considered to be available for transpiration is in the stem sapwood (Waring et al., 1979), but when the air temperature continually exceeds 0°C in spring, soil water availability becomes a crucial factor for recovery of root-zone processes. Low soil temperature is known to reduce water uptake and photosynthesis, such that soil water is considered to be unavailable to plants when soil temperature falls below −1°C (Tranquillini, 1979). Some studies, however, have concluded that water uptake may occur during late winter and early spring, as particularly evidenced for subalpine Engelmann spruce (*Picea engelmannii* Parry) by Boyce and Lucero (1999) and for subarctic Siberian larch (*Larix sibirica* Ledeb.) by Sugimoto et al. (2002). In addition, photosynthesis is possible in shoots and twigs of downy birch in their chlorenchyma in the leafless period in early spring (Kauppi 1991; Pfanz et al. 2002). In late winter, soil is supplied by snowmelt water that is able to percolate through organic and

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mineral soil sequences, even in subzero conditions (Leenders and Woo, 2002; Sutinen et al., 2008).

Time-domain reflectometry (TDR) is a versatile technique to determine water content in soils (Topp et al., 1980; Sutinen, 1992; Hänninen, 1997), and has also been used to monitor water content in wood tissues (Constantz and Murphy, 1990; Wullschleger et al., 1996; Irvine and Grace, 1997; Sparks et al., 2001; Nadler et al., 2003). TDR measurement of soil water content usually employs 15- to 30-cm-long transmission lines buried horizontally in soil sequences. TDR estimation of sapwood water content in trunks for a variety of tree species has been carried out with probes varying in length from 7 to 15 cm (Wullschleger et al., 1996; Nadler et al., 2003). Irvine and Grace (1997) applied short probes, 5 cm and 2 cm in length, to determine trunk water content of Scots pine (*Pinus sylvestris* L.). In order to estimate water content in trunk sapwood and in roots of downy birch we used 3.5-cm-long probes. Our long-term (this study, 1999–2003) measurements of temperature and water content of soil, roots, and trunks of downy birch provided us with a basis to assess the timing of root-zone water availability in spring and seasonal soil water patterns in the harsh climatic conditions in Finnish Lapland. The objectives of the present study were to see (i) if snowpack is able to alleviate climatic extremes in winter, (ii) if snowmelt contributes to soil water content contemporaneously with the air temperature rise notably above 0°C, and (iii) if this will trigger the spring recovery of downy birch (*Betula pubescens* Roth.).

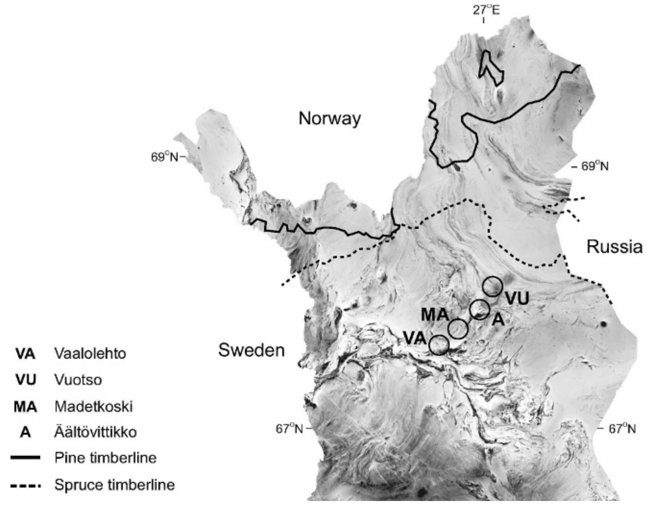


FIGURE 1. Study sites and conifer timberlines in Finnish Lapland plotted on an airborne magnetic total intensity map, adopted from Sutinen et al. (2005). High total intensity variations at Vaalolehto, Madetkoski, and Äältövittikko sites are due to mafic rocks of the Lapland Greenstone Belt. The Vuotso site lies between two roundish granite blocks. The distance between Vaalolehto and Vuotso sites is 35 km. See site descriptions in Table 1.

Materials and Methods

CLIMATE IN FINNISH LAPLAND

The climate in central Finnish Lapland is cold and humid with a long-term (1971–2000) annual mean temperature between −1 and −2°C, the average temperature of the coldest month (January) varying between −12 and −14°C, while that of the warmest month (July) between 14 and 16°C. The length of the frost-free period is 60–70 days, and the growing season is about 75 days. The annual mean precipitation varies between 500 and 550 mm with the maximum seasonal sum in summer and precipitation above 0.1 mm on approximately 200 days a year (Vajda and Venäläinen, 2003).

Two permanent weather stations (by the Finnish Meteorological Institute): Vuotso (68°05′N, 27°11′E) and Madetkoski (67°53′N, 26°45′E) (see locations in Fig. 1), provided measurements of the climatic variables: air temperature, precipitation, and thickness of snowpack for this study. Snow depth was recorded twice a day, at 06:00 and 18:00 UTC, and in the present study we have used the morning measurement. The daily precipitation amount was measured with a rain gauge at 06:00 UTC, and we used daily mean T_{AIR} that was calculated as a mean of eight measurements made at three-hour intervals.

DIELECTRIC MIXTURES

Soils and wood tissues can be considered as dielectric mixtures (water, rock particles/wood, and air). TDR-probes and -sensors (e.g. CS615 water content probes; Campbell Scientific, 1996) measure propagation velocities of electromagnetic waves through the soil or sapwood (Constantz and Murphy, 1990), with the velocity being a function of the soil/wood physical properties, such as density, dielectric (ε) properties and water content (Topp et al., 1980; Skaar, 1988; Hänninen, 1997). In the soil dielectric mixture, free water $\varepsilon_{WATER} = 81$ outweighs the impact of the other soil dielectric constituents, such as rock particles (ε_{ROCK} = 4–7) (Hänninen and Sutinen, 1994), air ($\varepsilon_{AIR} = 1$), and that of ice (ε_{ICE} = 3.2–3.8) (Bogorodsky et al., 1983); hence, unfrozen water content governs the wave propagation velocity in a soil. Since the dielectric value of dry wood is around 2 and that of dry cell walls are around 4 to 5 (Skaar, 1988), the increase in the seasonal ε_{ROOT} and ε_{TRUNK} of downy birch is due to free water.

EXPERIMENTAL SETUP

The Geological Survey of Finland has a field station in Vuotso (68°05′N, 27°11′E; see locations in Fig. 1) with year-round occupation, and including snow plowing in winter. In addition, the parent material at the Vuotso site is porous sandy till (Table 1), hence the absence of snow was expected to bring much lower winter soil temperatures as compared to those of the silty till at the Vaalolehto (67°51′N, 26°37′E) site which had the normal snow cover. Since the Vuotso site hosts stands of Scots pine, and Vaalolehto immature stands of Norway spruce and downy birch, the Äältövittikko site (67°56′N, 26°52′E), hosting a mature stand of downy birch and Norway spruce, was selected as a site for measurements of water content and temperature in soil and in the roots and trunks of downy birch.

Next to the Vuotso weather station (Fig. 1; Table 1), an experimental instrumentation was set up in fall 1998 for measurements of soil dielectric permittivity (ε) (i.e. water content; Topp et al., 1980) and soil temperature down to the bedrock surface at 250-cm depth. The parent material is composed of sandy till with a 40% fine fraction content (i.e. silt and clay), and is derived from granite gneisses (GIS database of the Geological Survey of Finland; see Salmela et al., 2001). The instrumentation measured soil temperature (T107 temperature sensors) and soil water content (CS615 Water content reflectometers; Campbell, 1996), which were automatically logged with CR10X data loggers (Campbell Scientific, Logan, Utah). Soil depths of 10, 40, 70, 80, 90, 100, 110, 120, 130, 150, and 245 cm were instrumented, and the timing of daily measurements was 04:00, 10:00, 16:00, and 22:00 UTC. The Vuotso site was intentionally kept snow-free with tractor plowing through the winter of 1998–1999.

TABLE 1

Site descriptions of the Vuotso and Madetkoski weather stations (by Finnish Meteorological Institute), and the Vuotso, Vaalolehto, and Äältövittikko study sites in Finnish Lapland.

	Vuotso weather	Vuotso soil	Vaalolehto soil	Madetkoski weather	Äältövittikko soil/wood
Location	68°05′N	68°05′N	67°51′N	67°53′N	67°65′N
	27°11′E	27°11′E	26°37′E	26°45′E	26°52′E
Elevation (m a.s.l.)	250	250	235	225	250
Temperature sum (day degrees)	681	681	700	710	689
Parent material	(Sandy till)	Sandy till	Silty till	(Outwash sand)	Silty till
Temperature	Air autom.	Soil autom.	Soil autom.	Air autom.	Soil manual
Precipitation	Autom.	—	—	Autom.	—
Snow	Autom.	—	—	Autom.	Manual
Dielectric	—	Soil autom.	Soil autom.	—	Soil/wood manual

The Vaalolehto site (Fig. 1; Table 1) was instrumented for automatic monitoring of θ_{SOIL} and T_{SOIL} in a similar way to the Vuotso site, except the depth of the sensors was 10 and 40 cm. The parent sediment is silty till (silt and clay fraction 52%) overlying the bedrock composed of chlorite-amphibole schists (GIS database by the Geological Survey of Finland) as a <4-m-thick veneer. The site was classified, according to Cajanderian forest classification, as HMT (*Hylocomium-Myrtillus* type). The Vaalolehto site, with a mixed Norway spruce (*Picea abies* L. Karst)–downy birch stand (50 years of age), received normal snow cover.

INSTRUMENTATION OF THE DOWNY BIRCH SITE

The Äältövittikko site (Fig. 1; Table 1), located on gently undulating (slope less than 1.5%) glacial terrain and reaching an elevation of 250 m (a.s.l.) (see site description in Sutinen et al., 2007), was targeted for once-a-week (winter and summer) or twice-a-week (spring and fall) monitoring of the ε_{SOIL} of silty till as well as ε_{ROOT} and ε_{TRUNK} of downy birch. According to the Geological Survey of Finland's GIS database, the underlying bedrock consists of intermediate volcanites and, in general, till covers the site as a 4-m-thick veneer. Podzol (Spodosol) soil was classified as a Typic Haplocryod and the site was classified, according to Cajanderian forest classification, as HMT (*Hylocomium-Myrtillus* type). The site hosts a mature (>150-year-old) forest stand dominated by downy birch with Norway spruce as a principal associate, and is characterized by understory vegetation containing *Hylocomium*, *Polytrichum*, and *Sphagnum* mosses (forest management yearbooks by the Finnish Forest and Park Service, Sodankylä; Salmela et al., 2001).

In September 1995, the root-zone soil, roots, and trunks (at breast height of 1.3 m) of downy birch were instrumented for water content and temperature measurements at the Äältövittikko study site. While automatic sonar assessments were made of snowpack depth at the Vuotso and Madetkoski weather stations, snow depth, as a reference, was recorded manually at the Äältövittikko site (Fig. 4). Water content and temperature were monitored manually on a weekly basis, except during the snowmelt period and fall, when twice-a-week measurements were performed. Water content was determined via soil dielectric permittivity (ε) with TDR (Tektronix 1502B, Beaverton, Oregon), and temperature was assessed with Pt-100 temperature probes (Sensycon, Germany) and with a Beamex TC 305 temperature calibrator (Beamex, Pietarsaari, Finland). We used 15-cm-long parallel transmission lines (two steel rods) with 6-cm spacing to record the ε of the till with 55% fine fraction content (silt and clay fractions; see Sutinen et al., 2007). In order to obtain the soil θ_v we applied the ε/θ_v calibration presented by Topp et al. (1980) as follows: $\theta_v = -0.053 + 0.029\varepsilon - 0.00055\varepsilon^2 + 0.0000043\varepsilon^3$. For wood tissue, we applied triple 3.5-cm-long probes (injection needles) to monitor ε_{ROOT} and ε_{TRUNK} of downy birch through 1999–2003. Since the instrumentation was set up in 1995, we expected that the variations in ε_{WOOD} were due to sap transfer rather than wounds attributed to mechanical disturbances, i.e. boring of 1.5 mm pilot holes for the needles. The equation $\theta = -0.2349 + (0.0541\varepsilon) - (1.295 \times 10^{-3}\ \varepsilon^2) + (1.174 \times 10^{-5}\ \varepsilon^3)$ presented by Irvine and Grace (1997) was applied for the ε/θ-conversion of sapwood and roots of downy birch.

Results

CLIMATE 1999–2003

The climate conditions, including the air temperature and precipitation values during the period 1999–2003, approximated the long-term averages (Figs. 2, 3). The annual mean temperature measured at the Vuotso weather station was −1.0°C, with the lowest monthly mean value equal to −15.4°C (in January) and the highest value equal to 14.7°C (in July). Based on the monthly averages, the coldest month was recorded in January 2003, with a monthly mean temperature of −20.9°C and the minimum temperature of −36.9°C. However, the lowest daily average and minimum temperature were registered at the end of January 1999, with five consecutive days with average temperatures below −30.0°C and three consecutive days with daily minimum temperatures below −45.0°C, the lowest minimum temperature being −49.0°C on 28 January (Fig. 2). The registered low temperatures of this period were generated by an arctic air mass stationed over northern Scandinavia, setting a new record low temperature for Finland (−51.5°C in Kittilä, Lapland, data not shown).

The summer (June-July-August) mean temperatures measured at Vuotso during 1999–2003 were as much as 1–1.5°C higher than the long-term average (Fig. 2). The amount and temporal variation of precipitation during the period studied was similar to the long-term average values, except in the year 2000, which proved to be an exceptionally wet year, with the annual amount of precipitation exceeding the average (510 mm) by about 100 mm (Fig. 3). In the beginning of the year (January–April) as well as in July the recorded precipitation was higher by 40–250% than the usual monthly values. Both in April and June, the monthly precipitation amounts were close to or above 100 mm (96.2 mm at Madetkoski station and 102.4 mm at Vuotso for April, respectively, and 111.0 mm and 109.9 mm in June) due to the increased number of days with precipitation, 18 (in April, long-term average 14) and 23 (in June, long-term average 15) and also due to 3–4 days of heavy rain (above 10.0 mm). The years

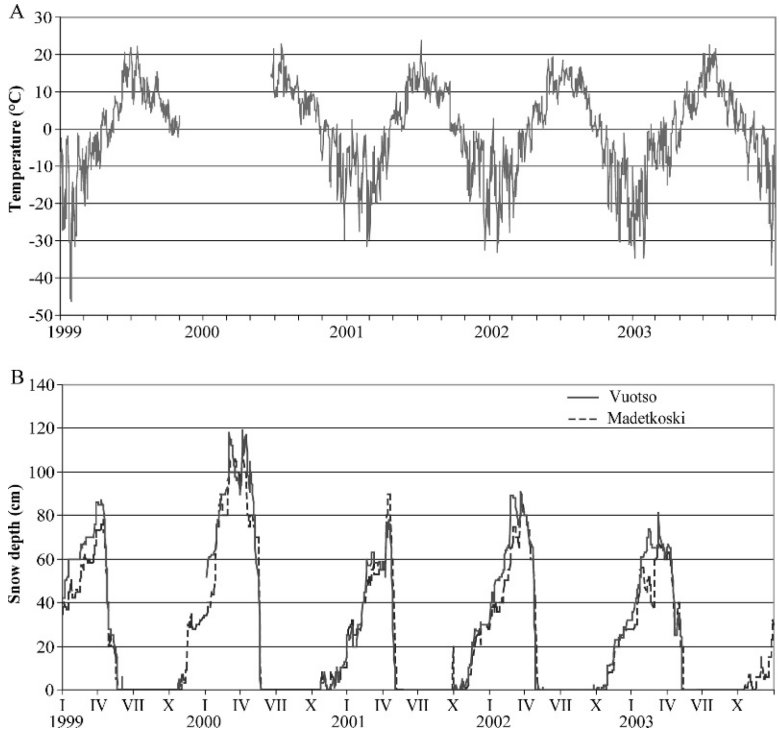


FIGURE 2. (A) Air temperature at Vuotso (68°05′N, 27°11′E), and (B) snowpack thickness at Vuotso and Madetkoski (67°53′N, 26°45′E) weather stations through 1999–2003 in Finnish Lapland.

2002 and 2003 seemed to be drier, with precipitation amounts below the averages and long rain-free periods (15–18 days), especially at Madetkoski.

The accumulated snow cover during the measurement years varied between 80 and 120 cm at Vuotso and between 65 and 105 cm at Madetkoski, and the continuous snow cover lasted, in general, from 14–25 October until 1–24 May (Fig. 2). Unusually deep snow conditions occurred during winter 2000 due to the high precipitation amounts recorded during this period, with snow cover of 120 cm at Vuotso and 115 cm at Madetkoski. Snow thicknesses above 90 cm lasted for 82 (Vuotso) and 50 days (Madetkoski), and the snow cover disappeared on 24 May (lasting for 7 months).

INTERSEASONAL SOIL CONDITIONS

The temporal pattern of soil water regime was rather consistent at the virgin forest site (Äältövittikko) throughout the interseasonal (1999–2003) monitoring period (Fig. 4) such that snowmelt contributed to soil saturation (i.e. soil $\varepsilon > 30$, $\theta_v > 0.44\ cm^3\ cm^{-3}$), according to the dielectric mixing model as presented by Hänninen (1997), during the second half of May. Interseasonally, the dielectric values of till exhibited a consistent pattern, with high peaks during snowmelt followed by a drying period until midsummer, and then a wetting phase in fall (Fig. 4). The time span of the soil saturation in spring was proportional to the thickness of the snowpack (Figs. 2, 4) such that a 105-cm-thick

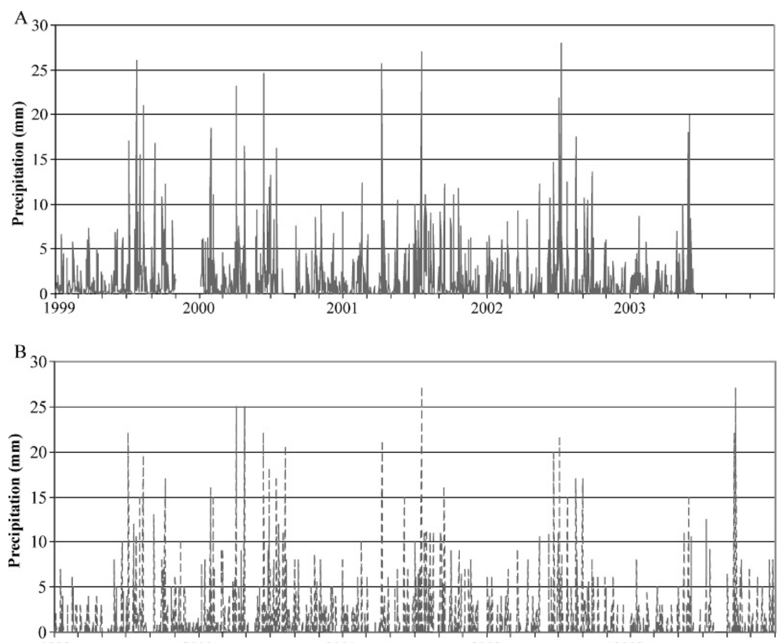
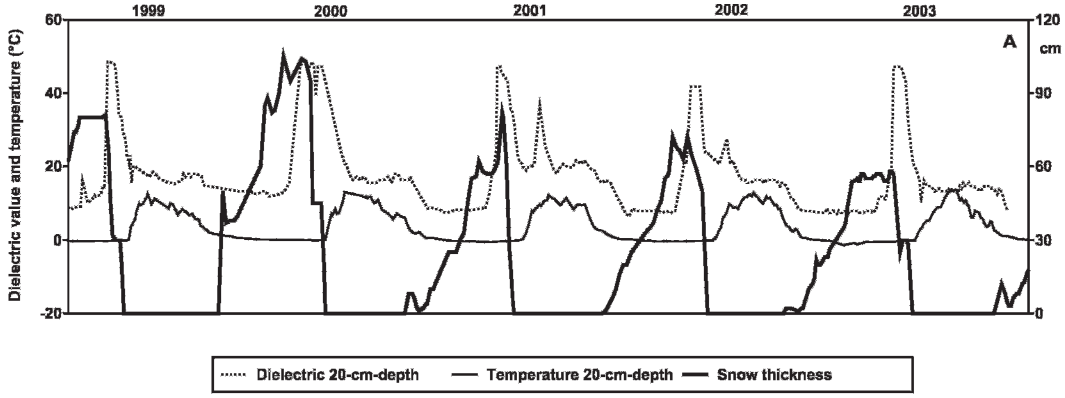


FIGURE 3. Precipitation at (A) Vuotso (68°05′N, 27°11′E) and (B) Madetkoski (67°53′N, 26°45′E) weather stations through 1999–2003 in Finnish Lapland.



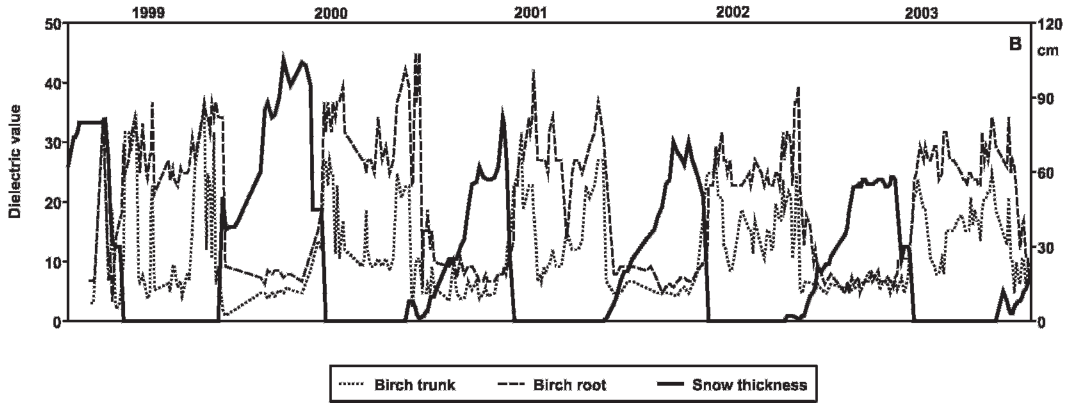


FIGURE 4. Interseasonal (1999–2003) variation in (A) dielectric values and temperature of silty till at 20-cm-depth and snowpack thickness, and (B) variation in dielectric values of trunk and root of downy birch and snowpack thickness at Äältövittikko (67°65′N, 26°52′E) study site in Finnish Lapland.

snowpack contributed to nine weeks of soil saturation in 2000, but the melting of a 57-cm-thick snowpack in 2003 resulted in only four weeks of saturation (Fig. 4). The snowmelt percolation of liquid water through soil columns with a variety of textures occurred at zero or subzero soil temperatures.

A notable increase in the soil ε occurred before final snowmelt for all years 1999–2003 (Fig. 4). The soil T_{20} rise above 0°C occurred 3.5–2 weeks after the rise in the ε_{SOIL} at 20-cm depth, such that the delay in the rise of soil T_{20} was as follows: 13 days in 1999, 25 days in 2000, 19 days in 2001, 16 days in 2002, and 18 days in 2003. The maximum ε_{SOIL} occurred quite closely (−5 days/ +8 days) to the disappearance of snow. At the monitored site in Lapland, snow disappeared on 18, 22, 9, 2, and 16 May during the period 1999–2003, respectively.

WATER CONTENT IN WOOD TISSUES

The TDR-dielectric measurements of water content in trunk sapwood and roots of downy birch demonstrated a rather regular interseasonal pattern (Fig. 4). A notable increase in the ε_{ROOT} occurred from several days up to two weeks before the final snow melt: 3 May in 1999 (15 days), 11 May in 2000 (13 days), 25 April in 2001 (16 days), 29 April in 2002 (3 days), and 13 May in 2003 (3 days). The annual ε_{ROOT}-pattern showed high values ($30 < \varepsilon_{ROOT} < 40$, corresponding to $0.54 \text{ cm}^3 \text{ cm}^{-3} < \theta_{ROOT} < 0.61 \text{ cm}^3 \text{ cm}^{-3}$) from the disappearance of snow to mid- to late July, and again another group of peaks roughly from mid-September to mid-October (Fig. 4). During the mid-season period the ε_{ROOT} values varied from 20 to 25 ($0.42 \text{ cm}^3 \text{ cm}^{-3} < \theta_{ROOT} < 0.49 \text{ cm}^3 \text{ cm}^{-3}$). During the winter dormancy the $\varepsilon_{ROOT} < 10$ was obtained.

Simultaneously with root tissue, trunk sapwood exhibited an interseasonal pattern with a significant increase in the ε_{TRUNK} values in late spring. The maximum ε_{TRUNK} values reached those of the roots in 1999, but in 2000–2003 the ε_{TRUNK} values were systematically lower (Fig. 4). At the beginning and in late summer, the ε_{TRUNK} values varied from 23.7 to 31.7 ($0.48 \text{ cm}^3 \text{ cm}^{-3} < \theta_{ROOT} < 0.55 \text{ cm}^3 \text{ cm}^{-3}$). The mid-season ε_{TRUNK} values ($8 < \varepsilon_{TRUNK} < 18$; $0.19 \text{ cm}^3 \text{ cm}^{-3} < \theta_{ROOT} < 0.39 \text{ cm}^3 \text{ cm}^{-3}$) were also quite small in comparison to those of roots. In the fall, the abrupt decrease in the ε_{TRUNK} values occurred much earlier than it did in the root values (13 days in 1999, 12 days in 2000, 6 days in 2001, 4 days in 2002, and 14 days in 2003). In the dormancy periods the ε_{TRUNK} values were smaller than ε_{ROOT} values (Fig. 4).

SNOW AND EXTREME COLD EVENT

A cold winter event was recorded in January 1999 (Fig. 2), with the lowest daily average and minimum temperature at the end of January 1999, and with five consecutive days with average temperatures below −30.0°C. This period also included three consecutive days with daily minimum temperature below −45.0°C, and with the lowest minimum temperature of −49.0°C obtained on 28 January (Fig. 2). The registered low temperatures of this period were generated by an arctic air mass stationed over northern Scandinavia, setting a new record low temperature for Finland (−51.5°C in Kittilä, Lapland, data not shown).

The soil temperature response to cold air was almost linear at the site intentionally kept snow-free during the winter. Due to the porous matrix of the sandy till in Vuotso, T_{10} reached −26.1°C on 29 January, T_{40} −17.5°C on 30 January, and T_{80} −11°C on 1

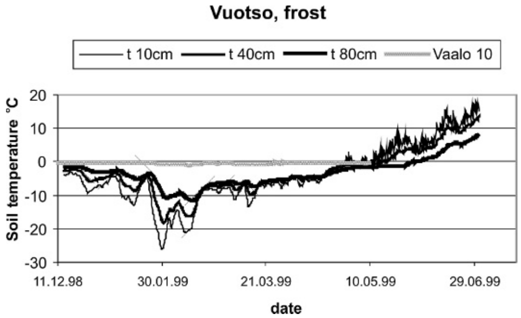


FIGURE 5. Soil temperature at the snow-covered site (Vaalolehto T_{10}; 67°51′N, 26°37′E) and snow-free site (Vuotso T_{10}, T_{40}, T_{80}; 68°05′N, 27°11′E) during the extreme cold event in 1999 in Finnish Lapland. See air temperature in Figure 2A.

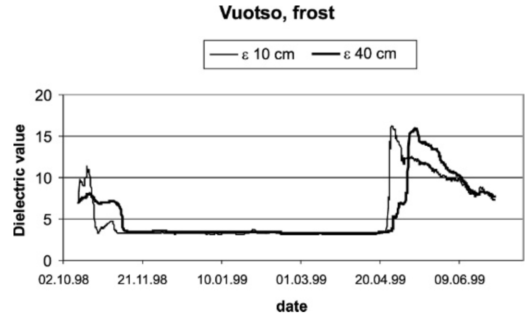


FIGURE 6. Dielectric values of sandy till at snow-free site (Vuotso; 68°05′N, 27°11′E) through winter 1998–1999 in Finnish Lapland.

February (Fig. 5). The site froze down to bedrock at 250-cm depth, such that the minimum $T_{150} = -11$°C was obtained on 18 March and $T_{245} = -1.13$°C on 28 May (data not shown). The deepest soil sequences were frozen (subzero temperatures) during the rest of the season in 1999. As to the dielectric response to subzero soil temperatures, the soil ε_{10} fell below 4 on 3 November 1998, and exceeded 4 on 23 April 1999 (Fig. 6). The corresponding dates for ε_{40} were 11 November 1998 and 27 April 1999, respectively. The constant $\varepsilon_{10} \approx 3.2$ and $\varepsilon_{40} \approx 3.4$ were obtained for the sandy till during the cold event.

In contrast to frozen sandy till ($\varepsilon_{10} \approx 3.2$; Fig. 6) at the snow-free site in Vuotso, silty till at the Vaalolehto site was partially unfrozen ($6.1 < \varepsilon_{10} < 11.5$; data not shown) beneath the snowpack throughout the winter period 1998–1999. The thickness of the snowpack was 40 cm at the beginning of January and 75 cm at its maximum in mid-April 1999 (Fig. 2). Consistently mild soil temperatures were recorded at the Vaalolehto site: $T_{10} = -0.57$°C on 29 January, $T_{10} = -0.8$°C on 12 February, and $T_{10} = -0.21$°C at the end of April 1999 (Fig. 5). Notably, rise in soil temperature above 0°C occurred on 12 May in Vuotso and on 26 May in Vaalolehto.

Discussion

TDR-ACQUISITION OF WATER CONTENT

Even though the formula $\theta = -0.2349 + 0.0541\varepsilon - (1.295 \times 10^{-3}\,\varepsilon^2) + (1.174 \times 10^{-5}\,\varepsilon^3)$ presented by Irvine and Grace (1997) applies to Scots pine, it was regarded as being feasible for the ε/θ-conversion of sapwood and roots of downy birch because their probe length (50 mm) was close to that applied here (35 mm). Using 13-cm-long probes, Wullschleger et al. (1996) obtained the second order quadratic equation: $\theta = -0.251 + (4.66 \times 10^{-2}\,\varepsilon) - (4.93 \times 10^{-4}\,\varepsilon^2)$ for different tree species (red maple, white oak, chestnut oak, and black gum). The equation is in good agreement with the calibration data of Constantz and Murphy (1990), but tends to overestimate the water content of sapwood and roots of downy birch measured here. This is due to the frequency dependency associated with probe length (see Irvine and Grace, 1997; Penttinen et al., 1999). As to the high peaks in root tissue ($30 < \varepsilon_{ROOT} < 40$) measured here, the calibration of Wullschleger et al. (1996) gives about 0.20 $cm^3\,cm^{-3}$ higher values as compared to the calibration of Irvine and Grace (1997). It is known that tree density affects the dielectric properties of wood (Skaar, 1988), hence dielectric values of sapwood vary among tree species and applied probe lengths (see Constantz and Murphy, 1990; Wullschleger et al., 1996; Irvine and Grace, 1997; Sparks et al., 2001). In our study, the birch trees were ca. 20 cm in diameter, hence the 3.5-cm-long probes installed perpendicularly into the trunk were appropriate for sapwood measurements.

SOIL FROST

The presence (Vaalolehto and Äältövittikko sites) or absence (Vuotso experimental site) of snowpack contributed to major differences in soil temperatures under the extreme winter conditions in Finnish Lapland (Figs. 2, 4, and 5). It is well established that the thermal and soil moisture properties are highly dependent on the soil texture and structure (Motovilov, 1979; Hänninen, 1997; Sutinen et al., 1997, 2008), hence the fine grained glacial till under snow cover did not experience frozen conditions (Figs. 4, 5), but in contrast, due to low air temperatures (down to −49°C), deep soil frost was observed for porous sandy till at the snow-free site (Fig. 5). This is similar to previous observations made on glacial tills, ranging from a sandy to a silty matrix, showing that $T_{20\text{–}50}$ is above or close to 0°C under snow cover in the subarctic climate of northern Finland (Hänninen, 1997; Sutinen et al., 1997). According to Hänninen (1997) soil surface duff may experience $T_{DUFF} = -4.5$°C due to fluctuations 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 from December to June. However, stratified sandy materials, owing to their higher porosities, tend to follow changes in the T_{SNOW}, and T_{40} may reach −1.5°C beneath snow cover from March to May during the winter in northern Finland (Koivusalo et al., 2001).

Apart from winter conditions in forest sites, the consistently low $\varepsilon_{10} \approx 3.2$ and $\varepsilon_{40} \approx 3.4$ of sandy till at the Vuotso experimental site (Fig. 6) indicates that soil was frozen for almost six months in winter 1998–1999. In addition, subzero soil temperatures at the sediment-rock-interface of the Vuotso snow-free site lasted the whole season, e.g., at the beginning of July, $T_{245} = -1$°C was recorded (data not shown). Our data are similar to those observed and modeled for snow-free sites in northern Finland showing the maximum depth of soil frost to be 100–300 cm (Venäläinen et al., 2001).

The minimum root-zone temperature, i.e. $T_{10} = -26.1$°C of the sandy till at the Vuotso site on 29 January (Fig. 5) is below those temperatures capable of damaging frost-hardened root tissues, e.g., those of Scots pine that reach their maximum cold hardiness of −20°C in the winter months (Sutinen et al., 1999). However, due to low wind speeds in the closed forest canopies (Vajda et al., 2006), the long-term (1971–2000) depth of snow cover on the studied sites is around 80 cm. Winter soil temperature is known to be associated with the development of snow cover (Sutinen et al., 1999; Lindström et al., 2002; Weich and Karlsson, 2002; Sutinen et al., 2008). Due to winter precipitation and wind climate in the northern boreal zone (Vajda et al., 2006) cases similar to that in Vuotso (i.e. intentionally kept snow-free) are not likely in the forest sites.

SNOWMELT

The present study showed that a notable increase in the soil ε (i.e. water content) occurred before final snowmelt for all years 1999–2003 (Fig 4), thereby supporting previous studies that demonstrated meltwater released from snowpack can infiltrate through organic soil horizons (Leenders and Woo, 2002) and mineral soils (Baker and Spaans, 1997; Sutinen et al., 1997), even in cases where the soil is frozen (Sutinen et al., 2008). Snowmelt water, even though in subzero temperatures, seems to provide critical reserves for roots of downy birch in late winter and early spring in a similar way as observed for Engelmann spruce and Siberian larch (Boyce and Lucero, 1999; Sugimoto et al., 2002).

The time-span of the soil saturation (i.e. soil $\varepsilon > 30$, $\theta_v > 0.44$ cm^3 cm^{-3}) in spring was shown to be proportional to the thickness of snowpack. A 105-cm-thick snowpack contributed to a nine-week-long soil saturation period in 2000, but the melting of a 57-cm-thick snowpack in 2003 resulted in only four weeks of soil saturation (Figs. 2, 4; see Sutinen et al., 2007). This is similar to previous reports showing a 2- to 8-week-long snowmelt saturation period in fine-grained tills of Norway spruce stands (Hänninen, 1997; Sutinen et al., 1997). Unlike in fine-grained tills, snowmelt saturation is absent and seasonal soil θ_v is low in sandy tills of Scots pine stands (Hänninen, 1997), and the effect of snowmelt decreases at deeper horizons; hence, the most vigorous changes in the soil ε occur in the root zone of the northern boreal forests (Sutinen et al., 2006).

While the soil saturation in spring is proportional to the thickness of snowpack (Fig. 4; Hänninen, 1997; Sutinen et al., 1997), T_{SOIL} does not exhibit similar behavior. When applying $T_{SOIL} = +3^\circ$C threshold value (see Mellander et al., 2007), the length of the growing season was 152 days in 2000 (105 cm of snow), while it was 134 days in 2003 (57 cm of snow; Fig. 4). During 2006 (data not shown), the snowpack thickness was 50 cm and the length of the growing season was 147 days at the Äältövittikko site. At the Vaalolehto site, and with $T_{SOIL} = +3^\circ$C threshold, the length of the growing season was as follows: 133 days in 2000 (115 cm of snow; see Fig. 2), 128 days in 2003 (66 cm of snow), and 142 days in 2006 (42 cm of snow, data not shown). Even though the spatial variability of snow cover and the T_{SOIL} depends on the wind climate, incoming radiation, forest canopy, and understory vegetation cover (Harding et al., 2001; Vajda et al., 2006), the climatic scenarios suggest an increase in the air temperature, and consequently T_{SOIL}. The model estimates suggest that the period of persistent snowpack will shorten by 73–93 days and an increase of T_{SOIL} by 0.9–1.5°C (10-cm-depth) within a century, e.g. in northern Sweden (Mellander et al., 2007).

WATER CONTENT IN DOWNY BIRCH

Significant variations were observed in water content of roots and trunks of downy birch through the period 1999–2003 in Finnish Lapland (Fig. 4). A bimodal pattern with high ε_{ROOT} and ε_{TRUNK} peaks in late winter–early spring as well as in the fall resembles that observed for yellow birch (Clark and Gibbs, 1957; see also for oak in Constantz and Murphy, 1990). The study on yellow birch showed maximum water content of trunks (47%) in late April, followed by decreasing water content (33%) until September, and again an increase in October–November. In comparison to water content in trunks of yellow birch (Clark and Gibbs, 1957), the differences between the highs in spring and fall and lows in summer were higher for downy birch here: 33–50% in the root and 67–85% in the trunk, respectively (Fig. 4). Summer rainfalls (see Fig. 3) appear to have contributed to the increase in water content in the trunks of downy birch (Fig. 4) in a similar way as demonstrated with a flood irrigation experiment for English walnut by Constantz and Murphy (1990).

The seasonal pattern in the ε_{TRUNK} of downy birch differed from those of conifers, showing minor seasonal changes in trunk water content (Irvine and Grace, 1997; Beedlow et al., 2007). Irvine and Grace (1997) found the highest water content (50 cm^3 cm^{-3}) in Scots pine in July, but the seasonal fluctuation of water content was of the order of 12%. It is well established that water stored in trunk sapwood provides reserves to meet late-winter transpiration needs (Waring et al., 1979; Boyce and Lucero, 1999), but episodic high trunk water content values in winter is concomitant with thaw periods (Sparks et al., 2001).

The similarity of the interseasonal pattern of water content in birch, i.e. high peaks of ε_{ROOT} and ε_{TRUNK} in late winter–early spring as well as in the fall, suggests sap flow in the wood tissues of downy birch. The exact mechanism for the initiation of water uptake is not fully understood, yet photosynthesis is possible in the chlorophyll-containing tissues (chlorenchyma) of the twigs and branches (Pfanz et al., 2002). Particularly, shoots and twigs of downy birch possess a capacity for photosynthesis in their chlorenchyma in the leafless period in early spring and late fall (Kauppi 1991). In early spring, the twigs of downy birch transmit the photosynthetically active radiation, and notable rise in the bark temperature is concomitant with the rise in air temperature (Kauppi, 1991; Pfanz et al., 2002). Since soil water is available in the root zone through the snowmelt percolation (Leenders and Woo, 2002; Sutinen et al., 2008; Fig. 4), simultaneous timing of these factors trigger the sap flow in downy birch. However, precise sap flow measurements are needed to fully understand these processes. Future climatic warming will eventually result in a longer growing season (Mellander et al., 2007), yet the snowmelt is important for the spring recovery and water uptake by downy birch.

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