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Effect of mild winter events on soil water content beneath snowpack

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Abstract

The cold climate of Fennoscandia allows soils to experience ephemeral freezing and snow cover. Snowmelt impacts on runoff and solute transport, but is also one of the most important contributors to recharge of ground water reserves. The presence of a snowpack governs the length of a growing season, but limited information is available on the response of partially frozen soil to mild climatic events in winter. We studied time series of soil temperature and unfrozen soil water content during freezing cycles and mild climatic events during two climatically contrasting winters (2001–2002, 2002–2003) at five sites differing in texture and hydraulic features in Finland. Frost penetration was found to be attributable to snowpack thickness, such that soil temperatures seldom fell below −1.5 °C, when a snow cover of more than 30 cm was present. Soil surface temperatures can fall below 0 °C and soil water freezes to 10-cm depth, but soil water is predominantly unfrozen during winter in deeper soil horizons, 30- to 90-cm depths. Water released by snowmelt during mild climatic events in winter was observed to infiltrate through partially frozen soil, hence contributing significant recharge to ground water resources.

Keywords: Soil; Frozen; Snowmelt; Water; Infiltration; Boreal; Finland

1. Introduction

In the southern and mid-boreal climatic zones of Fennoscandia soils experience freeze–thaw cycles and snow cover. A snowpack ultimately governs the length of the growing season and the overall carbon budget and 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). Soil water content (θ_v), nutrients in soil solution and soil temperature (T) are three of the most important causative factors that control soil chemical processes and nutrient uptake, tree growth, species composition and diversity (Williams and Smith, 1989; Vaganov et al., 1999; Stottlemyer, 2001; Sutinen et al., 2002). The soil θ_v, soil T and nutrient cycling 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,b). 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), limited

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information is available on the changes in unfrozen soil water content during wintertime.

Meltwater infiltration into frozen soil may by impeded by soil surface conditions, e.g. by the ice lenses formed during the soil freezing processes, but 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 (Boike et al., 1988; 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 (Boike et al., 1988; 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. Several studies have focused on the final snowmelt in spring, early summer, but limited information is available on wintertime infiltration into frozen soils. Stähli et al. (1999) demonstrated with neutron probe measurements that winter infiltration increase total of soil water content (ice and liquid) for sandy soils. 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 moisture (θ_v) and soil temperature (T) in glacial drift materials derived from a variety of lithologies in Finnish Lapland (Hänninen, 1997; Sutinen et al., 1997). These observations have confirmed that the unfrozen soil moisture of a site primarily depends on soil physical properties, and the magnitude of intra- and inter-seasonal variation in θ_v is site-specific. Soil water may freeze down to 50-cm depth, depending on the thickness of the snowpack. However, fine-grained tills beneath a snowpack may be frozen only on the top of the soil sequence, but once frozen, till (to 30-cm depth) may experience melting as a result of insulation of snowpack and upward heat transfer occurring through conduction and convection (Hänninen, 1997). Hydrologic and thermal processes in frozen soil are strongly impacted by soil texture (Motovilov, 1979; Stein and Kane, 1983; Boike et al., 1988). Organic soils also play an important role in the snowmelt runoff dynamics of forest ecosystems (Leenders and Woo, 2002; Nyberg et al., 2002).

In order to study wintertime changes in the unfrozen soil moisture (θ_v) and soil temperature (T) within the snowpack–soil interface, five soil-monitoring stations were established next to long-term and on-going climatic monitoring facilities operated by the Finnish Meteorological Institute (FMI). The sites covered a variety of sediment types and textures as well as a range of climatic regions in Finland. These stations, acquiring coupled data on climate and soil variables, will provide a basis for further studies and modelling of frost penetration. The present study focused on the changes in unfrozen soil θ_v and soil T during two winter periods with contrasting climatic conditions such that winter 2001–2002 was warmer than winter 2002–2003 (see Fig. 3). We aimed to see if water released by snowmelt during mild winter events can contribute to the increase in unfrozen soil θ_v in partially frozen soil.

2. Materials and methods

2.1. Study sites

On the basis of the permanent weather stations network operated by the FMI, five study sites (Fig. 1; Hänninen et al. 2005) were selected. These represent a wide variety of parent sediment types and textures (GIS database by GSF), and thereby soil types, ground vegetation and forest stand structures common in Finland. The selected sites also cover a range of long-term snow thickness patterns measured along the southern-mid-boreal climatic gradient in Finland (Solantie, 2000).

The mid-boreal Ylistaro site that lies along the coastline of Gulf of Bothnia (26 m a.s.l) is underlain by marine clayey sediments of the former Litorina Sea (~8000 years BP), and is a former agricultural field. The mid-boreal Haapavesi site (112 m a.s.l.) is located on a fine-grained glacial till plain, and is planted with Norway spruce (*Picea abies* L. Karst.). The mid-boreal Multia site (181 m a.s.l.) is on a drumlin and is forested with Norway spruce. The southern boreal Nurmijärvi site lies on ice-marginal end-moraine (110 m a.s.l.) composing of glaciofluvial sand deposits and is