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Soil freezing–thawing characteristics and snowmelt infiltration in Cryalfs of Alberta, Canada

Hailong He [a,b], Miles F. Dyck [b,*], Bing C. Si [c,d], Tingjun Zhang [e,f], Jialong Lv [g], Jinxing Wang [g,*]

[a] College of Natural Resources and Environment (Institute of Soil and Water Conservation, CAS&MWR), Northwest A&F University, Yangling, Shaanxi 712100, China
[b] Department of Renewable Resources, University of AB, Edmonton T6G2H1, Canada
[c] College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China
[d] Department of Soil Science, University of Saskatchewan, Saskatoon SK S7N5A8, Canada
[e] College of Natural Resources and Environment, Lanzhou University, Lanzhou 730000, China
[f] National Snow and Ice Data Center, University of Colorado, Boulder, CO 80309, USA
[g] College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi 712100, China

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ABSTRACT

Soil freeze–thaw processes and snowmelt infiltration significantly influence the hydrological cycle and ecosystem productivity in cold, semi-arid areas. In this study, 5 years (2008–2013) of soil moisture, temperature (0–100-cm depth) and meteorological data monitored at the Breton Plots, University of Alberta was used to understand the soil freezing–thawing phenomena and snowmelt infiltration under natural boundary conditions. The field data demonstrated that the timing of snowpack accumulation and soil wetness prior to freezing govern the winter soil thermal regime. Deep frost (≥50 cm) was found in years of late snow accumulation and dry fall soil conditions while shallow frost occurred in years of early snow accumulation and wet fall soil conditions. In addition, air-filled porosity of the top 10 cm and the soil water storage of the top 30 cm measured in the fall are the main factors governing soil water storage change following spring snowmelt. Furthermore, soil freezing and thawing curves (SFTCs, expressed in the form of TDR-measured relative permittivity/water content vs temperature) were introduced to facilitate the understanding of the freeze–thaw processes under field conditions. The field measured SFTC is different from soil freezing characteristic (SFC, TDR-measured relative permittivity/water content vs temperature) measured in lab conditions (e.g., constant total soil water content and near-thermal equilibrium) because of changing total soil water content under field conditions from snowmelt infiltration or frost-induced water redistribution and transient temperature conditions. The mechanisms for SFTC/SFC are explained and the differences between lab and the field SFTC/SFC are compared and discussed. This study and the use of SFTC could improve our understanding of the frozen soil processes and snowmelt infiltration in field conditions.

1. Introduction

In cold, semi-arid areas, snowmelt may recharge soil water and groundwater reservoirs that are closely linked to agricultural and ecosystem productivity (Hayashi and van der Kamp, 2005; Hayashi, 2013) and snowmelt may also somewhat affect the soil development processes (e.g., podzolization, Schaetzl and Isard, 1991, 1996; Schaetzl et al., 2015). Snowmelt on the other hand may become runoff if soil infiltration capacity is inhibited by ice lenses, ice-filled pores or basal ice layers on the soil surface (Cary et al., 1978; Kane, 1980; Miller, 1980; Stahli, 2005). Snowmelt runoff significantly increases erosion of fertile surface soils (Zuzel et al., 1982), migration of pesticides and other agricultural chemicals and pollution of soil and surface waters (Rascher et al., 1987; Williams and Melack, 1991; Groffman et al., 2001; Cade-Menun et al., 2013; Likens, 2013), and it may trigger spring flooding (Shanley and Chalmers, 1999; Janowicz et al., 2002; Hall et al., 2012). Therefore, the partitioning of snowmelt infiltration and runoff has important implications for water resource management and the development of mitigation strategies to reduce environmental risks. This is especially important for the Canadian Prairie region where climate change is predicted to reduce depth of soil frost and frost duration (Cutforth et al., 2004), and to increase the number of freezing and thawing cycles during winter, and significantly change the amount, timing and phase (snow or rainfall) of winter precipitation (IPCC, 2007).

Snowmelt infiltration into frozen soils is more complicated than water infiltration into unfrozen soils because it involves coupled water and heat transport with phase changes. The factors affecting snowmelt infiltration include: (1) soil and air temperature regimes (Iwata et al., 2008, 2010, 2011); (2) soil hydraulic, thermal and physical properties

* Corresponding authors.
E-mail addresses: hailong.he@nwsuaf.edu.cn (H. He), miles.dyck@ualberta.ca (M.F. Dyck), Bing.Si@usask.ca (B.C. Si), tjzhang@lzu.edu.cn (T. Zhang), ljll@nwsuaf.edu.cn (J. Lv), jwang118@126.com (J. Wang).

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(Kane, 1980; Hayashi et al., 2003); (3) soil water content at the onset of freezing (Kane and Stein, 1983a,b, 1984; Granger et al., 1984; Zhao and Gray, 1999; Stadler et al., 2000; Gray et al., 2001; Watanabe et al., 2013); (4) soil depth (Christensen et al., 2013); (5) freeze–thaw cycles (Fouli et al., 2013); (6) characteristics of the overlying snowpack and its melt rate (Shanley and Chalmers, 1999; Decker et al., 2003; Iwata et al., 2010); (7) the thermal regime of the infiltrating water and soil (Zhao et al., 1999); and (8) meteorological conditions (e.g., wind speed, precipitation, radiation and albedo) and their interactions (Granger et al., 1984; Eigenbrod, 1996; Stahli, 2005). Many lab simulations or manipulated field studies have been conducted in the past to find out the dominant factor(s) that influence soil freeze–thaw processes and snowmelt infiltration; this work has greatly advanced our understanding of frozen soil dynamics. But the lab simulations and the manipulated field studies are generally associated with boundary conditions different from the real field environment. For example, lab simulations do not account for the effects of snowpack insulations and the possible basal ice; different degrees of complete freeze–thaw cycles were imposed but few complete freeze–thaw cycles take place in field conditions. Similarly, the manipulated field investigations could not reflect the processes affected by many interacted factors. Therefore, field studies without manipulation may facilitate our understanding of the complicated frozen soil processes.

However, few such field studies (Granger et al., 1984; Iwata et al., 2008; Sutinen et al., 2008) that have quantitatively examined the relationship between freezing–thawing processes, snowmelt infiltration and the governing factors were found. This may be attributed to the logistical and technical difficulties of performing long-term and comprehensive field work in cold environments (Kane, 1980; Iwata et al., 2010). In the absence of field observations, numerical models (Flerchinger and Saxton, 1989; Zhao and Gray, 1997; Jansson, 1998) may be employed and sensitivity analysis was used to examine the influence of different factors. These methods are useful for the purpose of understanding these processes, but the results are largely dependent on the detailed input data (e.g., soil water and temperature, air temperature, precipitation and snowpack dynamics) that may only be available at well evaluated site and the choice of parameters and algorithms. An alternative to process models are empirical relationships such as those describing snowmelt infiltration developed by Granger et al. (1984) and Zhao and Gray (1997). These models may have practical site-specific applications to water management problems and only require a few variables, but they are difficult to be applied across landscapes of large area (Henry, 2007; Iwata et al., 2008).

To better understand the freeze–thaw processes and snowmelt infiltration in field conditions and to overcome the difficulties of conducting long term and comprehensive field studies, the establishment of automated monitoring stations for comprehensive measurement of soil (e.g., water and temperature) and weather variables are one of the best approach. The automated monitoring stations enable continuous observations over the winter seasons across different years, various boundary scenarios may be included and analyzed. In Alberta, Canada, 48 such stations were established beginning in 2005 to form a Drought Monitoring Network for long term monitoring of soil conditions (Walker, 2006). In this study, the University of Alberta Breton Plots station, near Breton, AB was chosen as an example. Because of its relatively long monitoring history and comprehensive datasets, it provides a unique opportunity to investigate snowmelt infiltration into frozen soils with different scenarios of initial soil moisture content, snow cover, and thawing–refreezing cycles.

Recent development in calibration models (i.e., dielectric mixing models) for unfrozen water estimation with electromagnetic methods (e.g., time/frequency domain reflectometry, TDR/FDR), which account for the effects of dielectric permittivity of ice, particle surface area, particle shape and interactions between soil components etc. (e.g., Bittelli et al., 2004; Watanabe and Wake, 2009; He and Dyck, 2013), has greatly improved the measurement of unfrozen water in frozen soil. The improved unfrozen water measurement then can be used to better reflect the soil freezing characteristics (SFC) or soil freezing–thawing curves (SFTC) in lab and field conditions, respectively. SFC and SFTC describe the relationship between freezing soil temperature and unfrozen water content, they are similar to the soil moisture characteristic for unfrozen soils (i.e., water content versus matric potential, Koopmans and Miller, 1966; Spaans and Baker, 1996; Flerchinger et al., 2006). SFC and SFTC are critical for modeling soil freeze–thaw processes, water and solute transport but are not well studied (Parkin et al., 2013). Many of the available studies capturing only a short period of the winter season (e.g., spring thawing period) may not well represent the winter processes. More studies are based on lab simulations but the lab simulated SFC is different from that measured in field conditions (Kelleners and Norto, 2012). A complete overwinter SFC/SFTC, therefore, is required to fully understand water and heat dynamics in frozen soils (Parkin et al., 2013) and to show the differences from lab-mimic SFC.

The objectives of this study are to use the soil and weather station data at the Breton Plots in concert with the dielectric mixing models for unfrozen water content measurement and the complete soil freezing–thawing curves to investigate the processes of soil freezing and thawing and snowmelt infiltration into partially frozen soils. The mechanisms for SFTC/SFC will be investigated and the differences between lab and field SFTC/SFC will be compared and discussed.

2. Material and methods

2.1. Site description

The Breton Plots (lat. 53° 05′N, long. 114° 26′W, 850 m above the sea level) were established southwest of Breton, Alberta, in 1930 by the University of Alberta to conduct agricultural and soil fertility research in the gray soil zone of Alberta. The area is described as cold and semi-arid to sub-humid having a mean annual temperature of 3.70 °C, the average temperature from December through February is −8.24 °C, and −4.40 °C from November through April and 15.25 °C from June through August (calculated from 1974 to 2007 data downloaded from Environment Canada http://climate.weather.gc.ca/index_e.html#access, hereafter Environment Canada). The mean annual precipitation is 564 mm, with 413 mm in the form of rainfall mainly occurring between May and August and 151 mm as snow.

Soil at the site is classified as a loam-textured, Gleyed Dark Gray Luvisol (Cryalfs in USDA Soil Taxonomy or Albic/Gleyed Luvisol in FAO World Reference Base for Soil), developed on medium-textured glacial till parent material under boreal forest vegetation. The soil profile consists of 5 horizons with increasing bulk density, details can be found in Table 1.

2.2. Instrumentation

The soil and meteorological instrumentation is contained in a grass-covered area with approximate dimensions of 15 m × 28 m that is not disturbed by the agricultural activities at the site. ThetaProbes (type ML2x sensors, Delta-T Devices Ltd, Cambridge, England) were installed at 5, 20, 50, and 100 cm from the mineral surface in a hand-excavated pit (~80 cm length × 25 cm width × 25 cm depth) for soil moisture measurement. Four 107BAM thermistors (Campbell Scientific (Canada) Corp., Edmonton, Canada) were installed close to the Thetaprobe for temperature measurement. ThetaProbe and temperature data were automatically logged on an hourly basis (CR10x, Campbell Scientific (Canada) Corp., Edmonton, Canada). More details about the instrument installation procedure are described by Walker (2003). Instruments for record of meteorological variables follow the standard weather stations. The daily data of precipitation, snowfall, average air temperature and daily data of snow depth from October 2008 to October 2013 were used in this study. In addition, the daily water level data between