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Measuring soil frost depth in forest ecosystems with ground penetrating radar

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ABSTRACT

Soil frost depth in forest ecosystems can be variable and depends largely on early winter air temperatures and the amount and timing of snowfall. A thorough evaluation of ecological responses to seasonally frozen ground is hampered by our inability to adequately characterize the frequency, depth, duration and intensity of soil frost events. We evaluated the use of ground penetrating radar to nondestructively delineate soil frost under field conditions in three forest ecosystems. Soil frost depth was monitored periodically using a 900 MHz antenna in South Burlington, Vermont (SB), Sleepers River Watershed, North Danville, Vermont (SR) and Hubbard Brook Experimental Forest, New Hampshire (HBEF) during winter 2011–2012 on plots with snow and cleared of snow. GPR-based estimates were compared to data from thermistors and frost tubes, which estimate soil frost depth with a color indicating solution. In the absence of snow, frost was initially detected at a depth of 8–10 cm. Dry snow up to 35 cm deep, enhanced near-surface frost detection, raising the minimum frost detection depth to 4–5 cm. The most favorable surface conditions for GPR detection were bare soil or shallow dry snow where frost had penetrated to the minimum detectable depth. Unfavorable conditions included: standing water on frozen soil, wet snow, thawed surface soils and deep snow pack. Both SB and SR were suitable for frost detection most of the winter, while HBEF was not. Tree roots were detected as point reflections and were readily discriminated from continuous frost reflections. The bias of GPR frost depth measurements relative to thermistors was site dependent averaging 0.1 cm at SB and 1.1 cm at SR, and was not significantly different than zero. When separated by snow manipulation treatment at SR, overestimation of soil frost depth (5.5 cm) occurred on plots cleared of snow and underestimation (−1.5 cm) occurred on plots with snow. Despite some limitations posed by site and surface suitability, GPR could be useful for adding a spatial component to pre-installed soil frost monitoring networks.

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1. Introduction

Seasonal soil freezing is an important natural perturbation that is common in cold regions around the world. Soil frost depth can be highly variable and depends largely on early winter air temperatures and the amount and timing of snowfall. Recent interest in understanding soil freezing effects on ecological systems has stemmed from the expectation that future changes in climate will alter the temporal patterns and spatial extent of seasonally frozen ground (Brown and DeGaetano, 2011; Campbell et al., 2010; Henry, 2008). Changes in soil freezing regimes could have important implications for forest ecosystems, since freezing influences physical, chemical, and biological processes in soil (e.g., Groffman et al., 2001; Haei et al., 2011; Hentschel et al., 2009; Iwata et al., 2010). A number of studies over the last decade have shown that soil frost events influence soil carbon and nitrogen leaching from forested watersheds (e.g., Christopher et al., 2008; Fitzhugh et al., 2003; Groffman et al., 2011; Kaste et al., 2008; Matzner and Borken, 2008). However, a thorough evaluation of ecological responses to seasonally frozen ground is hampered by our inability to adequately characterize the frequency, depth, duration and intensity of soil frost events.

Soil frost is often considered problematic, and the heaving associated with it can have adverse effects, such as uplifting planted seedlings and compromising the integrity of roads and structures (Saarenketo and Scullion, 2000). In forest ecosystems, long-term observations and short-term experiments have shown that soil

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freezing can affect ecosystem processes by damaging fine roots (Tierney et al., 2001), and altering litter decomposition, trace gas fluxes, and nutrient leaching (Fitzhugh et al., 2003; Groffman et al., 1999, 2001, 2011). Soil frost can also alter hydrologic flow paths, particularly in agricultural areas where hard, impenetrable "concrete" frost forms (Shanley and Chalmers, 1999). There are some operational benefits of frost; frozen soil can improve accessibility and minimize disturbance during logging operations and loosen compacted agricultural soil.

Despite the importance of soil frost in ecological studies, the methods for measuring its depth are rudimentary and need improvement. One of the oldest methods is a direct measure that involves digging pits and visually detecting ice crystals or using tactile methods to determine whether the ground "feels" frozen (e.g., Campbell et al., 2010). This approach is subjective and destroys or impairs the experimental area and has largely been replaced by more favorable indirect methods such as frost tubes (Ricard et al., 1976), temperature probes and electrical methods. Frost tubes are a useful indicator of soil frost depth; but, they only provide data for specific points across the landscape and may exhibit lag effects during rapid changes in temperature (McCool and Molnau, 1984). Another common method uses temperature probes installed at fixed depths in the soil profile, and the interpolated 0 °C isotherm is considered the frost line. This method provides measurements over time when connected to a data logger; however, it requires pre-installation and is not well suited for measuring soil frost over broad areas. Additionally, it is possible that solutes may depress the freezing point of soils, especially in areas with environmental contaminants (e.g., road salt) and the gradient between temperature probes in the profile is assumed to be linear, which may be incorrect. Other, more technologically advanced methods of soil frost measurement such as time domain reflectometry and electrical conductance have similar limitations (Baker et al., 1982; Hayhoe and Balchin, 1986). Ground penetrating radar (GPR) is also becoming recognized as a useful tool for quantifying soil frost (Steelman and Endres, 2009; Steelman et al., 2010) and has advantages over conventional methods. It may be rapidly deployed and provides spatially contiguous frost depth detection; series of parallel transects may be arranged to collect frost depth data over broad areas.

GPR antennas propagate short pulses of electromagnetic energy into the ground and receive reflected signals on the soil surface. Whenever a pulse contacts an interface separating layers with different electrical conductance, a portion of the energy is reflected back to a receiver on the surface. The material property that creates the electromagnetic contrast and causes reflections is relative dielectric permittivity (ε_r), which is a dimensionless quantity relating to a material's behavior when subjected to an electric field. The larger the difference between the dielectrics of two adjacent materials, the stronger the radar wave reflection. For example, ε_r of frozen soil varies from 2 to 8, while moist soils range from 10 to 30 (Cassidy, 2009). When freshwater freezes, ε_r drops from 81 to 4 (air = 1); a phenomenon that makes it possible to detect frozen layers with GPR (Daniels, 2004). If GPR emerges as a reliable tool for quantifying soil frost quickly and accurately over plots or broader areas, it could be an integral part of focused ecological response studies, or used in conjunction with established frost networks to aid in the interpretation of long-term biogeochemical patterns.

The purpose of this study was to evaluate the suitability of GPR for characterizing soil frost in forest ecosystems in northern New England. While it is possible to detect frost depth with GPR, there are a number of uncertainties that need to be resolved to use the tool effectively in forest ecosystem research applications and routine monitoring. Earlier studies were limited to agricultural lands where snow cover was removed immediately before scanning to improve contact with the soil (Steelman and Endres, 2009; Steelman et al., 2010). However, snow removal is not ideal for monitoring protocols because it is labor intensive, causes disturbance, and enhances soil frost penetration. To date, GPR has not been deployed to assess soil frost depth in forests under native snow/surface conditions and there is no guidance as to productive approaches or suitability to enhance current monitoring protocols. The objectives of this study are to: (1) Determine if GPR can provide soil frost depth estimates comparable to those collected with thermistors and frost tubes, under varied site conditions common to New England forests (e.g., variable soils, topography, presence of rocks and tree roots), (2) Determine how the presence of snow cover affects frost depth detection, (3) Provide guidance on future applications of GPR to estimate soil frost depth in forests.

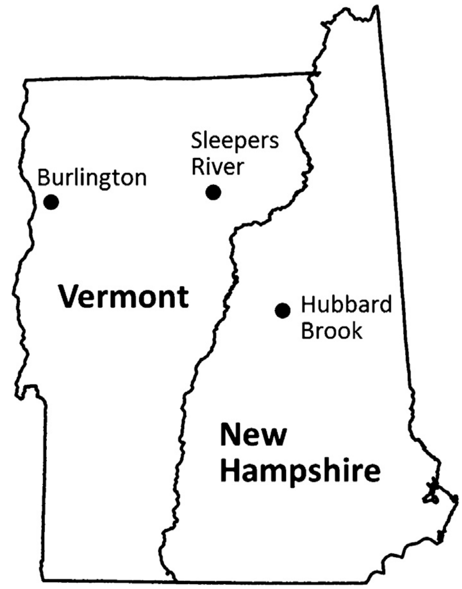

Fig. 1. Location of study sites in Vermont and New Hampshire, USA.

2. Materials and methods

2.1. Study sites

The study was conducted across an elevation gradient at three sites in northern Vermont and New Hampshire (Fig. 1). The South Burlington, Vermont (SB) site is a 25 year-old balsam fir (*Abies balsamea*) planation adjacent to the USDA Forest Service, Northern Research Station Laboratory, 95 m a.s.l., 44.45338° N–73.19088° E. The moderately well drained soil is loamy sand with few pebbles in the upper 0.5 m. The Hubbard Brook Experimental Forest (HBEF) site in Thornton, New Hampshire, is a mature northern hardwood stand, 290 m a.s.l., 43.94648° N–71.70153° E. The soil is loamy sand with some rocks in the upper 0.5 m and is well-drained. The Sleepers River Watershed (SR), North Danville, VT, site is a naturally regenerated balsam fir stand with trees >40 years old, 590 m a.s.l., 44.4854° N–72.16669° E. The soil is sandy loam with numerous rocks in the upper 0.5 m and somewhat poorly drained. Soil texture and organic matter (OM) content for each site is presented in Table 1.

2.2. Experimental design and snow depth manipulation

A randomized complete block design where snow manipulation (snow removed, snow intact) was replicated three times was used to implement the study and analyze data at each site (SB, HBEF, SR). Within a replicate, one plot (2 m × 10 m) was shoveled free of snow each week and snow cover was left intact on the other (2 m × 10 m) for a total of 6 plots per site. The snow removal treatment had two