Using Ground Penetrating Radar to Characterize Soil Frost for Ecological Applications

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Ground penetrating radar can successfully estimate soil frost depth in forests on snow-free soil and through shallow snowpack. Site specific soil and surface conditions (i.e. wet snow, surface thaw or standing water) have the potential to interfere with frost delineation.

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Project Summary

Seasonal soil freezing is an important natural disturbance common in cold regions around the world. It is expected that future changes in climate will alter the temporal patterns and spatial extent of seasonally frozen ground influencing physical, chemical, and biological processes in soil. 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. Ground penetrating radar (GPR) may be used to detect objects or interfaces where there are abrupt changes in soil electrical properties. The electromagnetic waves generated by GPR transmitters move quickly in air and dry soil and attenuate in wet soils. When soil freezes, its dielectric value drops creating a detectable interface. GPR has the potential to nondestructively quantify seasonal soil freezing in forests, though it requires further evaluation before it can be put to use in ecological applications.

A series of test plots were established at sites in Vermont (2) and New Hampshire (1). Each site was fitted with soil temperature sensors (14 depths) and frost tubes (30) to make direct comparisons with GPR estimates of frost depth using a SIR-3000 GPR system (Geophysical Survey Systems, Salem, NH) during winter 2011-2012. Half of the experimental plots were shoveled free of snow every other week to alter snow depth and frost penetration.

Project Summary cont.

GPR was able to reliably detect frost and delineate depth beginning at depths of 10 cm. Favorable conditions for GPR include bare soil or shallow snow; while standing water, wet snow and surface thawing interfered with detection. The accuracy of frost depth estimation with GPR was good, but site specific corrections may be required. The New Hampshire site exhibited coarse, well-drained mineral soils at depth, which were not conducive to frost detection. Soil frost was detectable through snow <30 cm deep, but as snow depth increased the frost signal became more faint and interpretation subjective. Removal of snow provides the best detection, but significantly alters frost dynamics i.e. snow removal leads to deeper frost penetration.

These results show that GPR can be a valuable tool to quantify seasonal frost depth, though it is subject to soil and site conditions. It seems unlikely that GPR would give reliable results through deep snowpack i.e. >50cm. The best use of GPR would be intensive campaigns where capturing spatial variability is important. Though not the focus of this project; GPR could be readily used to map snow depth.

Background and Justification

- Recent interest in understanding soil freezing effects has stemmed from the expectation that future changes in climate will alter the temporal patterns and spatial extent of seasonally frozen ground[1] and affect physical, chemical, and biological processes in soil[2].

- Ecologists need a more robust method to quantify frost conditions as a starting point for understanding its effects. Past frost measurements have used coarse methods, such as:
  - subjective tactile observations (shovel and hack)
  - soil frost tubes.

[1] Campbell, J.L., Ollinger, S.V., Flerchinger, G.N., Wicklein, H., Hayhoe, K., Bailey, A.S. 2010. Past and projected future changes in snowpack and soil frost at the Hubbard Brook Experimental Forest, New Hampshire, USA. Hydrological Processes 24: 2465–2480.

[2] Groffman, P., C. Driscoll, T. Fahey, J. Hardy, R. Fitzhugh, and G. Tierney. 2001. Colder soils in a warmer world: A snow manipulation study in a northern hardwood forest ecosystem, *Biogeochemistry* 56(2), 135-150.

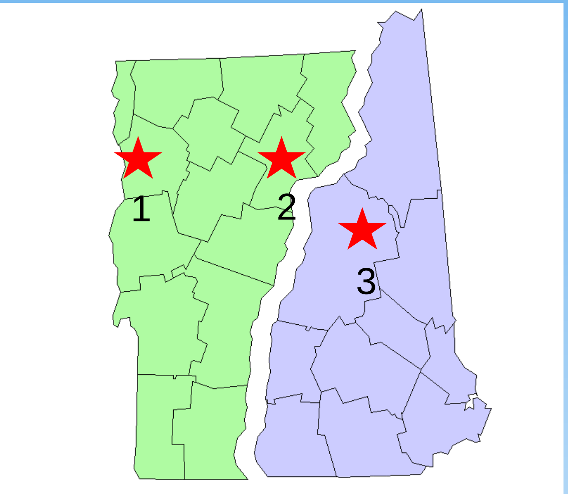
Background and Justification cont.

- Technologically advanced methods such as time domain reflectometry and electrical conductance produce data that are difficult to interpret.

- If GPR is found to be a reliable tool for quantifying ground 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.

Methods

Sites



We compared GPR with other methods for characterizing soil frost development at three forested sites: 1) U.S. Forest Service Laboratory, South Burlington (SB), VT, ele. 310’, 25 y.o. balsam fir plantation, 2) Sleepers River Watershed (SR), VT, ele. 1830’, 40+ y.o. balsam fir stand and 3) Hubbard Brook Experimental Forest (HB), NH, 950’, mature northern hardwood stand.

Snow Manipulation

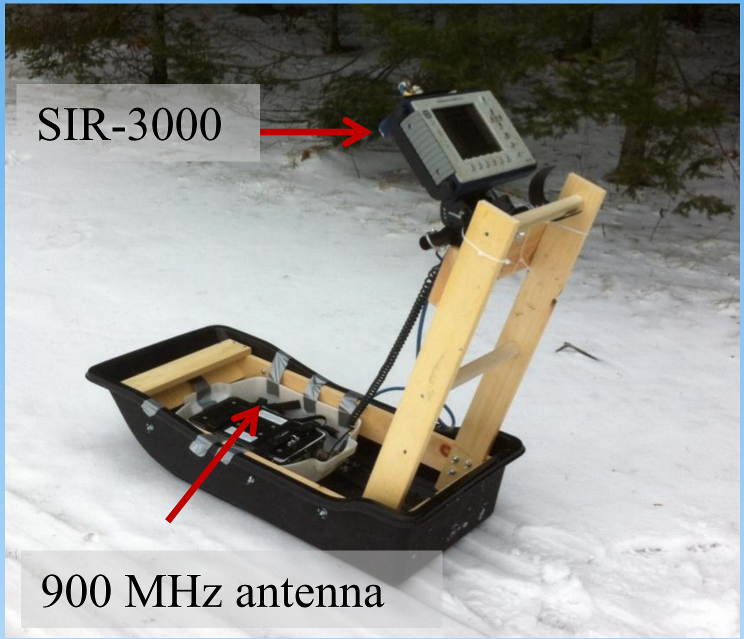
At each site, six measurement plots were established (2 by 10 m), half of the plots received biweekly snow removal, the others were left alone. The snow removal treatment has two purposes: to create areas of deeper soil frost penetration and to make comparative assessments of frost depth delineation through snowpack with the snow covered plots.

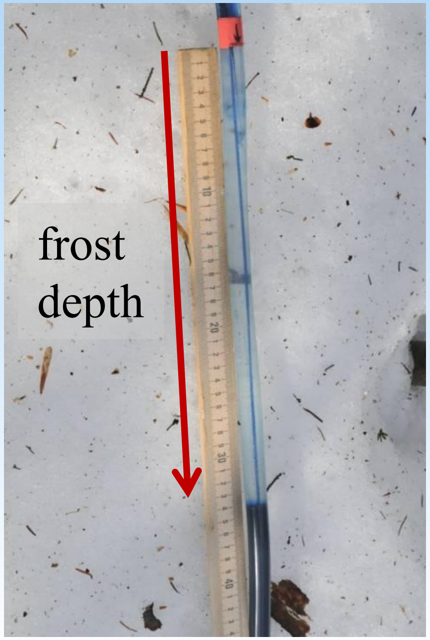
Sleepers River, snow removal

Monitoring Soil Frost

Soil frost was estimated with three techniques:

- SIR-3000 Ground Penetrating Radar unit (GSSI, Salem, NH), shown here with a 900 MHz antenna and fitted to a custom sled.
- Data logger (Onset Computer Corp., Onset, MA) equipped with high accuracy (+/- 0.2 C) thermistors.
- Frost tubes containing a blue dye that turns clear when frozen, inserted in PVC liners.





Sampling and Comparing Techniques

Along the centerline of each plot, frost tubes were placed every 2 m (5 total). At one location at each site, a soil temperature profile was created by inserting at depths of 1, 3, 5, 10, 15, 20, 25 cm in one snow removal plot and depths of 1, 3, 5, 10, 15, 20 cm in one snow plot.

During the 2011-12 winter, the SB site was scanned 15 times with GPR, while the SR and HB sites where scanned 5 times.

Hubbard Brook plot showing frost tube layout.

GPR sled at Sleepers River

The plots were scanned by pushing the GPR sled along the centerline and electronically marking the location of the frost tubes. As the antenna moves along it generates electromagnetic pulses into the soil and receives reflections back. Frost tubes (30 per site) were measured for direct comparison with GPR and the soil temperature thermistors.

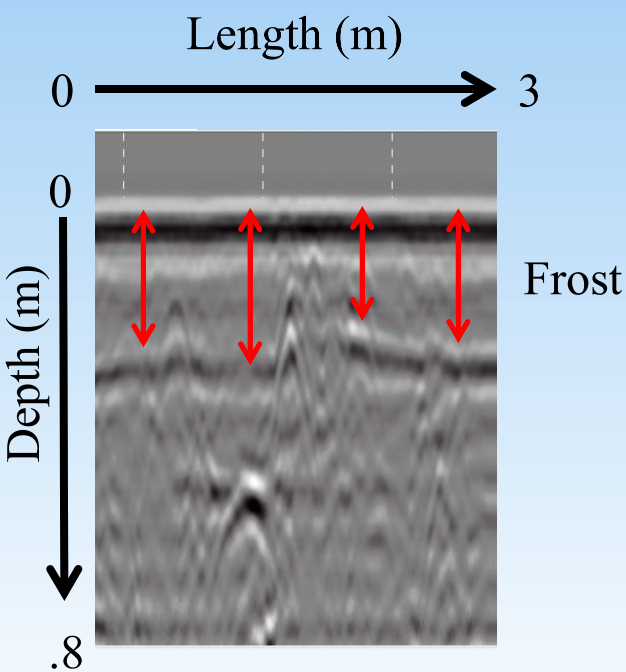
Results

GPR was able to detect soil frost and delineate depth when conditions were suitable.

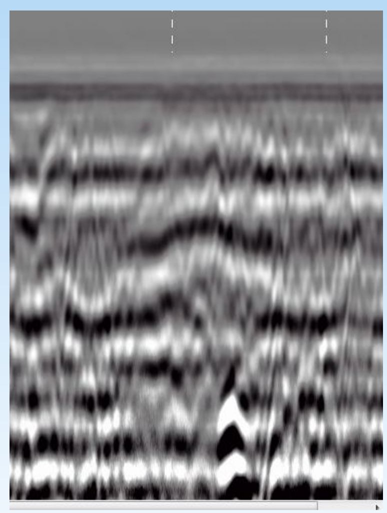
Favorable conditions
- Bare soil
- Shallow snow
- Frost depth >10 cm

Poor conditions
- Water on soil surface
- Wet snow
- Shallow frost
- Deep snow pack
- Surface thawing

Favorable sampling days
- HB 1 of 5 days
- SB 11 of 15 days
- SR 5 of 5 days



01-23-12 South Burlington frost tube -28 cm

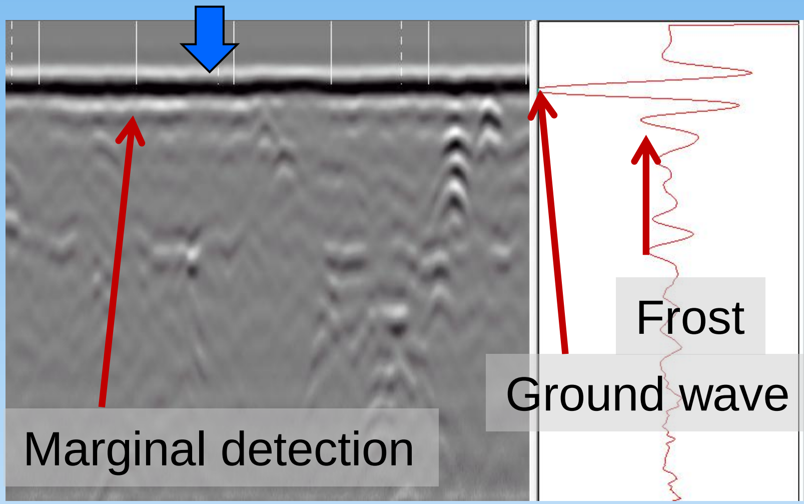


Over night rain and surface moisture preclude detection

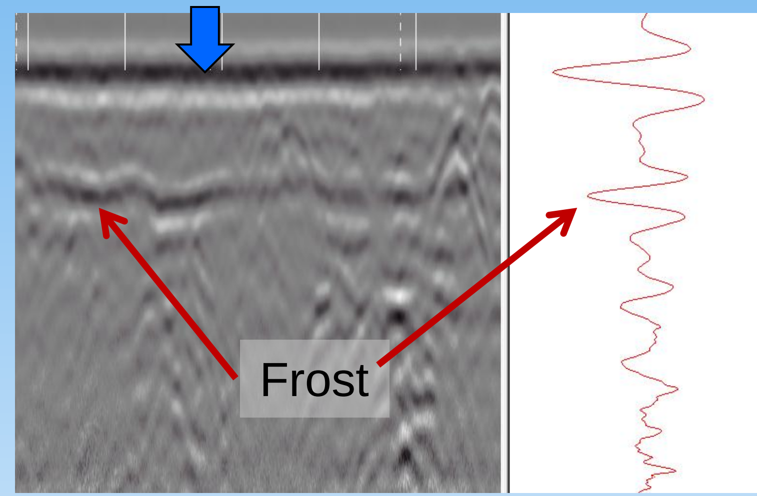
01-24-12 South Burlington frost tube -28 cm

Seasonal frost penetration

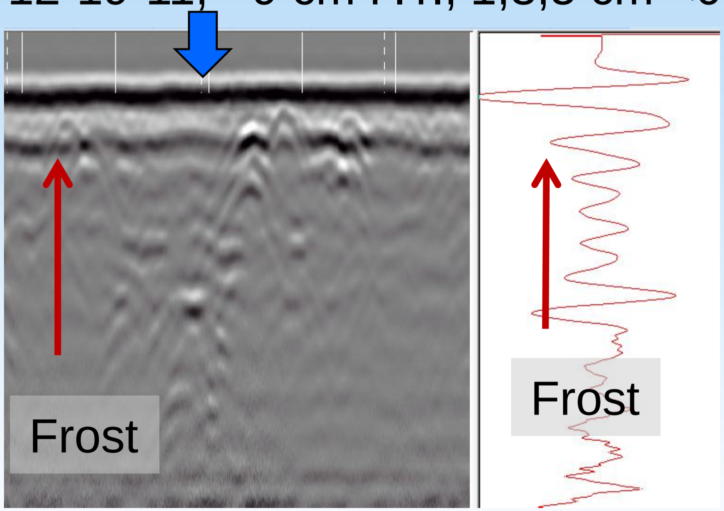
- Blue arrows indicate frost tube location and featured waveform (right)
- Hundreds of waveforms are used to create a radargram (left)



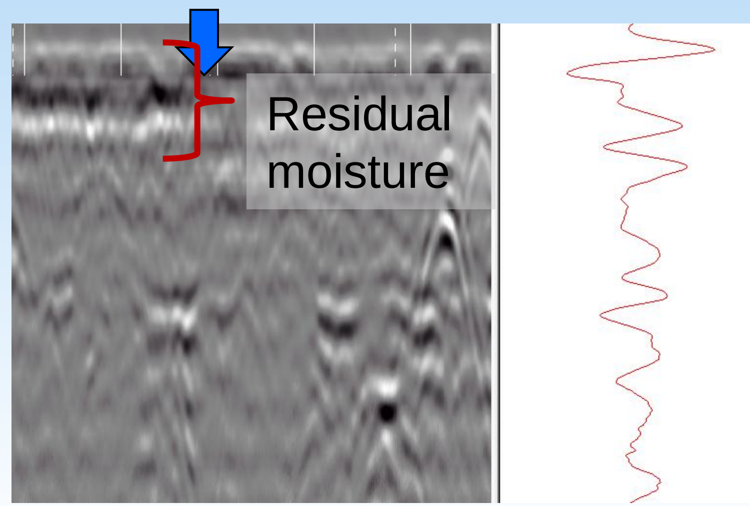
12-19-11, -9 cm F.T., 1,3,5 cm <0 C



02-14-12, -31 cm F.T., 1-25 cm <0 C

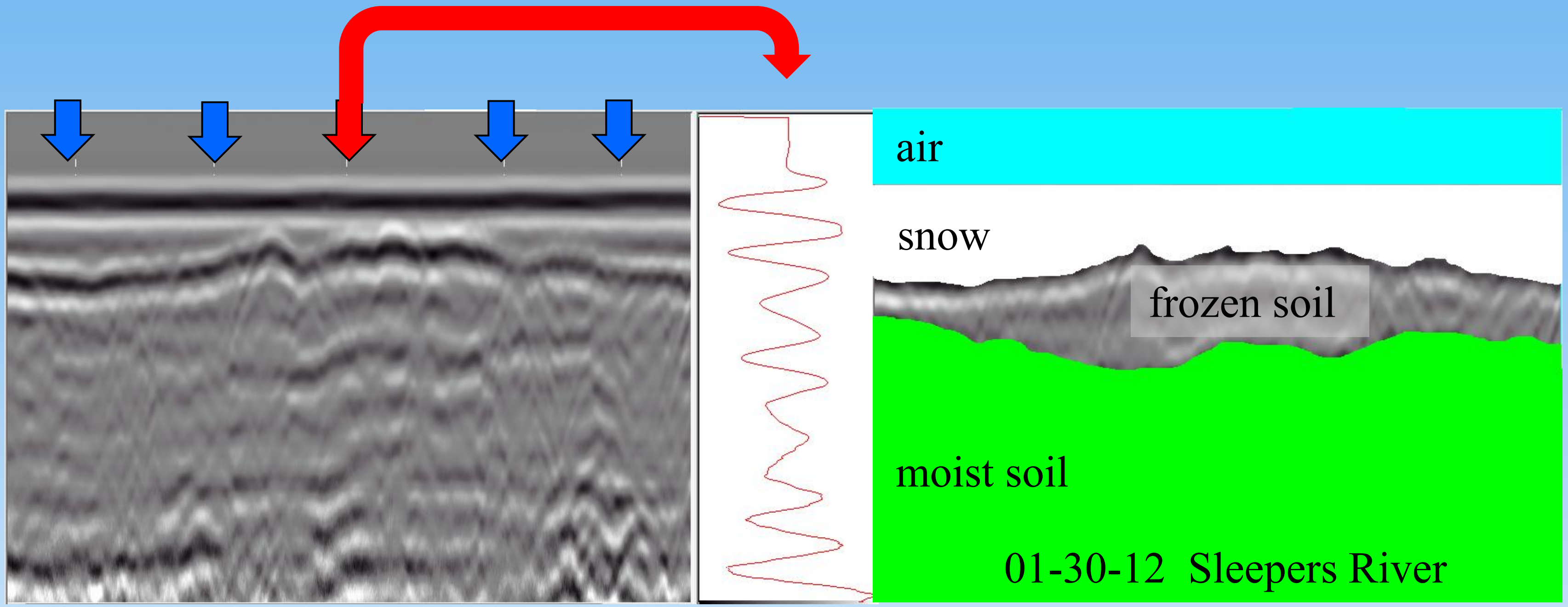


01-05-12, -17 cm F.T.,1-15 cm <0 C



03-20-12, No frost

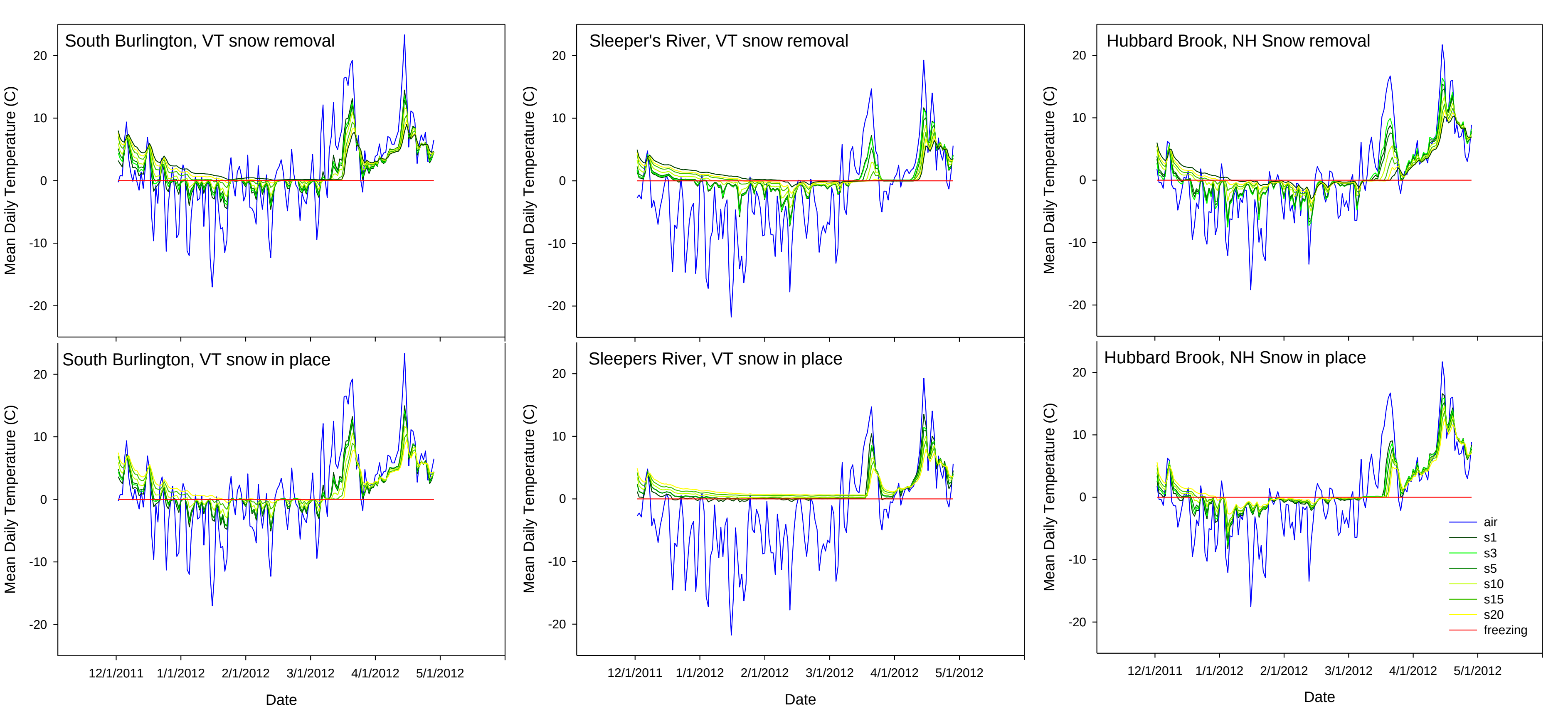
Frost detection through snow



37	23	20	25	22	Snow (cm)
4	10	14	12	12	Frost tube reading (cm)

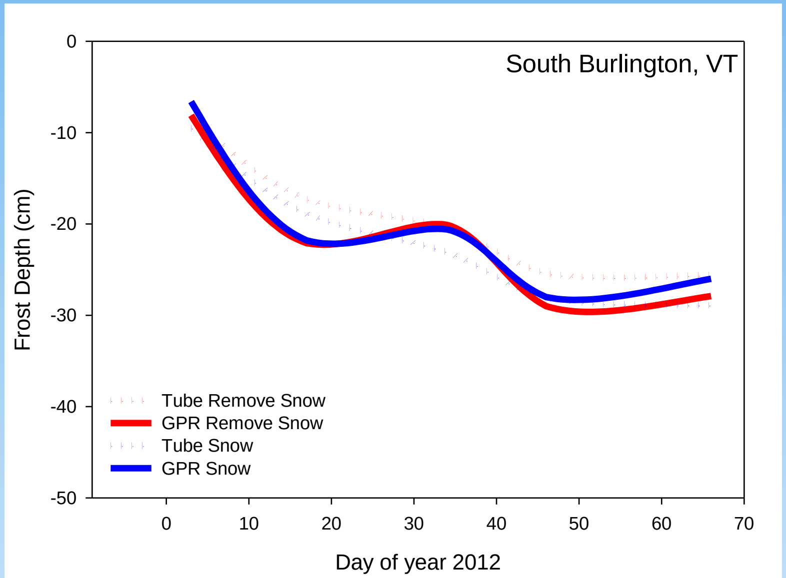
Frost detection through snow is possible. In this example from SR, the signal becomes faint at depths averaging 25 cm. At deeper snow depths which are common in most years, the signal may be lost and interpretation subjective.

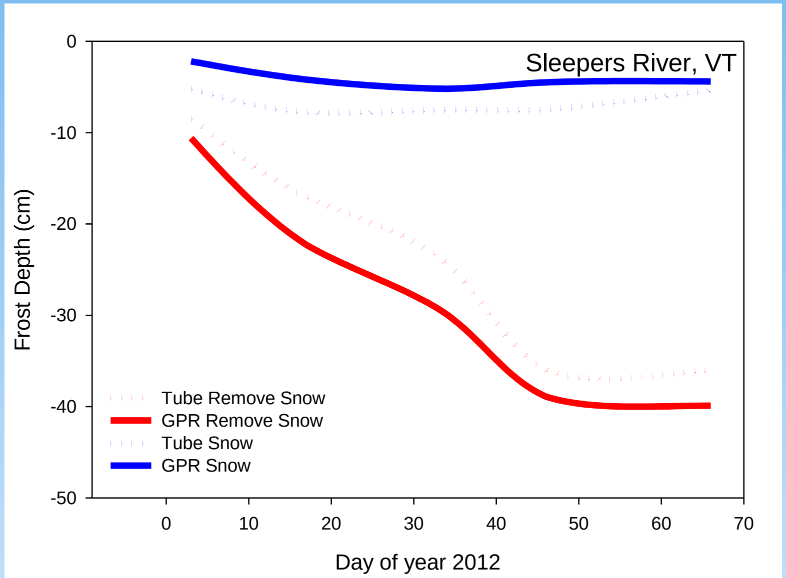
Snow Manipulation and Soil Temp.



Snow removal resulted in deeper frost penetration at SR and HBEF. The SB site had minimal snow accumulation, so there was little difference between treatments.

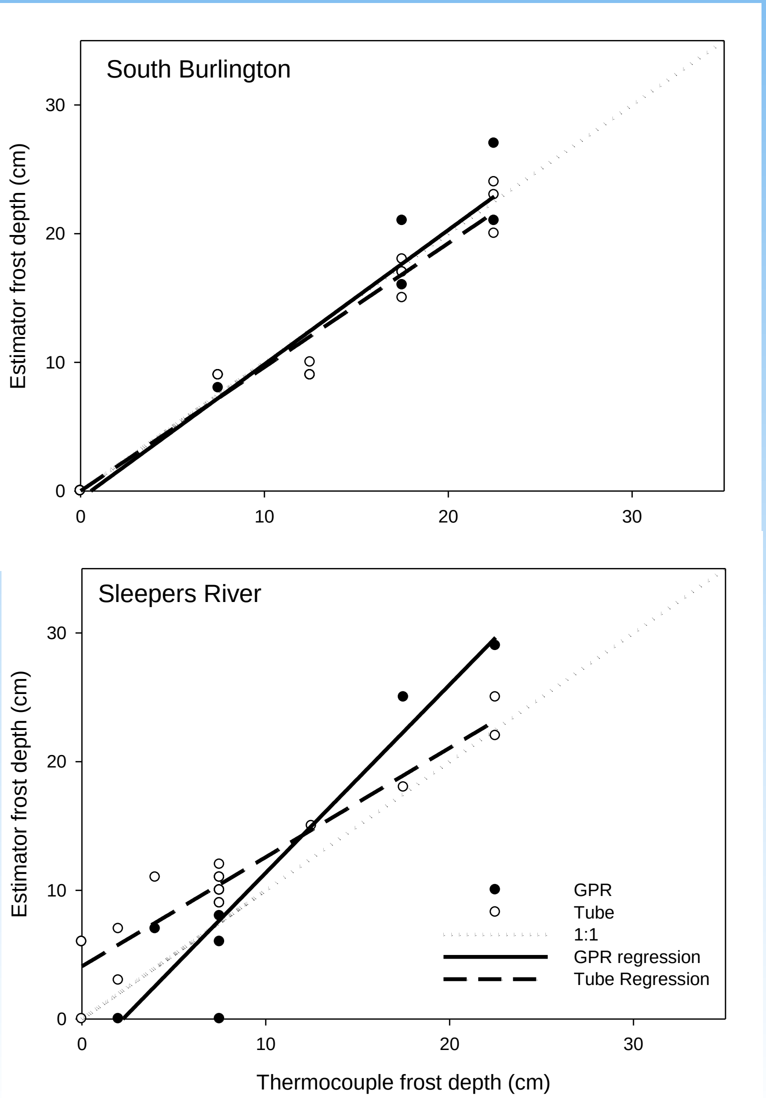
Snow Manipulation and Frost Depth





- There was no snow accumulation at the SB site, hence no difference between snow treatments. Depth estimates were similar using tubes and GPR.
- Snow removal at SR resulted in very deep frost penetration. Depth estimates using GPR and tubes tracked each other closely.
- GPR was only successful at HB for one (01/04/2012) of five sample periods (data not shown).

Comparing Indirect Methods with Thermistors



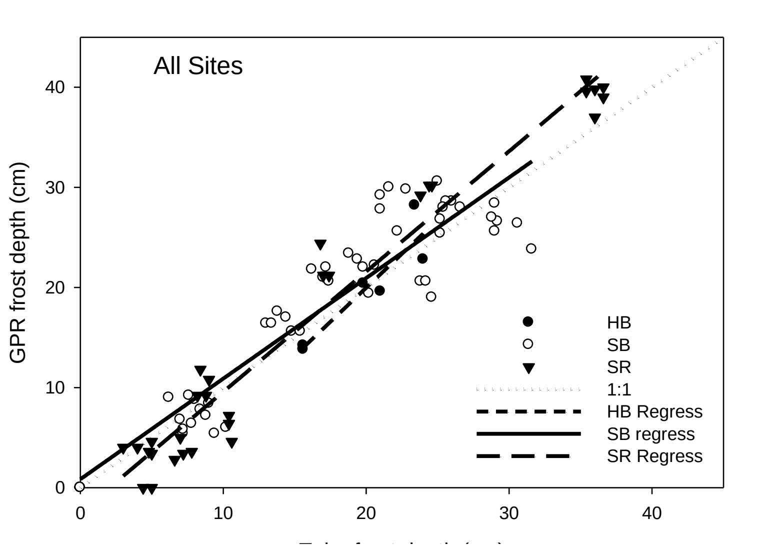
Precise determination of frost depth can be very difficult without destructive sampling.

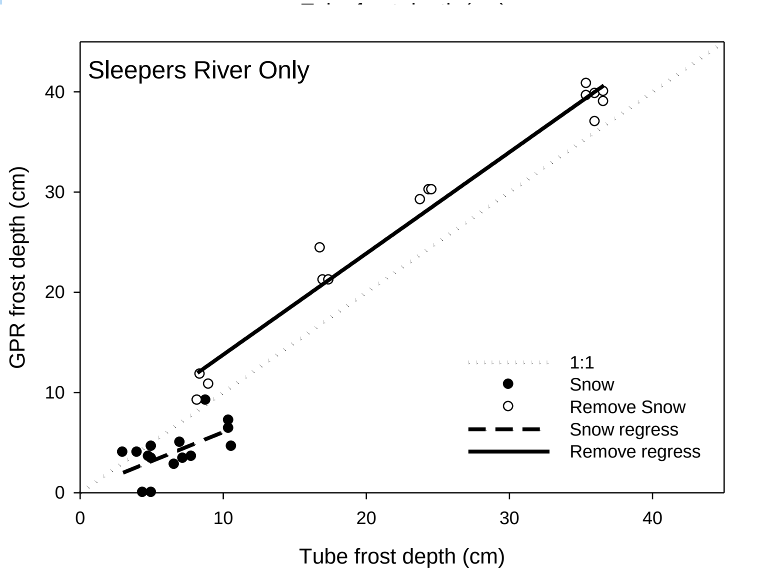
A reference frost depth was calculated by averaging the depth between a thermistor reading <0 C and the next lower sensor reading >O C and compared to the other methods.

At SB, linear regressions were not significantly different between methods or the 1:1 line.

At SR, the linear regressions were statistically different between methods and deviated from the 1:1 line.

Comparing GPR and Frost Tubes





There was a much larger sample for comparing GPR and frost tubes using plot-level means n=90.

There was no significant difference between GPR and frost tubes across sites (and snow treatments) at the 0.05 alpha level. (SB n=54, HBEF n=6, SR n=30).

SR was the only site to have good GPR data throughout the winter and have robust snow accumulation. The slope of the regression line was 1 in the snow removal treatment. Since the snow treatment and the shallow frost co-occur, its difficult to determine which is causing the slope divergence.

Implications and applications in the Northern Forest region

- GPR can estimate soil frost depth in forests on bare soil and through shallow snowpack.

- Site specific soil and surface conditions (i.e. wet snow, surface thaw or standing water) have the potential to interfere with delineation.
  - The HB site had coarse, well-drained mineral soil at depths of 30-60 cm, which had a low dielectric and did not contrast with frost.

- Accuracy of GPR detection is best at depths >10 cm.

- Predictions of frost depth using GPR and frost tubes were in good agreement with soil thermistors.

Implications and applications cont.

- The best use of GPR would be intensive campaigns, where capturing spatial variability is important.

- Snowpack depth and frost tend to be inversely related. Winters with deep snow and shallow frost will make frost detection with GPR difficult. Removal of snow provided the best detection, though it significantly alters frost dynamics.

- GPR could be readily used to map snow depth.

Future directions

- Winter 2011-2012 was rather mild in northern New England, resulting in reduced snow accumulation and very deep frost penetration. Frost tubes are being left in place at South Burlington and Sleepers River, to study deep snow if the opportunity arises.

- The largest obstacle to wider adoption of GPR to monitor soil frost on suitable sites is variable snow depth.
  - Deeper the snow, the shallower the frost.
  - Shallow (<10cm) frost detection is variable to begin with and through deep snow seems unlikely.

- Under proper site conditions, GPR could be equipped with a GPS logger to create 3D maps of soil frost.

List of products

- Butnor, J.R., Campbell, J.L, and Shanley, J.B. 2012. Using Ground Penetrating Radar to Characterize Soil Frost for Ecological Applications. Ecological Society of America 97th Annual Meeting, August 5-10, Portland, OR.
- Butnor, J.R., Campbell, J.L, Shanley, J.B., and Zarnoch, S.J. 2013. Monitoring Soil Frost in Forests with Ground Penetrating Radar. Symposium on the Application of Geophysics to Engineering and Environmental Problems. March 17-21, Denver, CO.
- Butnor, J.R., Campbell, J.L, Shanley, J.B., and Zarnoch, S.J. 2013. Monitoring Soil Frost in Forests with Ground Penetrating Radar. peer reviewed journal submission *In Preparation.*