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USING THE RATE OF ACCUMULATED FREEZING AND THAWING DEGREE DAYS AS A SURROGATE FOR DETERMINING FREEZING DEPTH IN A TEMPERATE FOREST SOIL

Stephen Vermette[1] and Sheila Christopher[2]
[1]Department of Geography and Planning
[2]Great Lakes Center
Buffalo State College
1300 Elmwood Avenue
Buffalo, NY 14222

ABSTRACT: *A changing climate may bring about more precipitation but less snowfall to Northeastern North America. A decreased snowpack may impact soil freeze-thaw cycles. The objective of this study is to evaluate the usefulness of Freezing Degree Days (FDDs) and Thawing Degree Days (TDDs) as a surrogate for a direct measure of frost depth in soils in a temperate forest. Frost tubes were used as a direct measure of soil freezing depth. While a strong correlation is found linking total accumulated FDDs with soil freezing depths in areas free of snowpack, a better predictive tool is to relate soil freezing depth with the rate at which FDDs are accumulated (expressed as FDD/day). Accumulating FDDs at a rate of more than 4.0 FDD/day resulted in a growing freezing depth, while accumulations of less than 4.0 resulted in the thawing of the frozen soil. The degree-day approach was not successful in determining frost depths in the presence of a snowpack.*

Keywords: *freezing degree day, thawing degree day, soil, soil freezing depth, climate change*

INTRODUCTION

Climate simulations generally indicate that precipitation will increase in northeastern North America, especially during winter (Hayhoe et al. 2006). This climate change may differentially affect precipitation patterns due to local geographic influences. In leeward regions of the Laurentian Great Lakes, an increase in lake-effect snowfall during the 20th century was a result of warmer surface water temperatures and decreased ice cover (Leathers and Ellis 1996; Burnett *et al*. 2003). Despite potentially greater amounts of winter precipitation, reductions in snowpack depth are projected, due to an increased occurrence of sleet and rain-on-snow events (Goodrich 1982; Hayhoe et al. 2006; Huntington et al. 2004). Without an insulating snowpack, more frequent freeze-thaw cycles in soil will occur (Goodrich 1982; Edwards & Cresser 1992).

Altered soil freeze-thaw cycles due to climate change would affect a number of economic and ecological activities. Changed freezing depth could have a direct impact on construction, with subsequent damage by frost heave to waterlines, buildings and roadbeds (CBD, 1976). Altered soil freezing regimes also could strongly influence water infiltration and runoff patterns. When soil frost forms in open areas, such as agricultural ecosystems, it is typically continuous and highly impermeable (Hart 1963). This hard frost layer causes snowmelt and rainwater to run off the soil surface directly into surface waters, without infiltrating soil. Soil frost which develops in covered areas, such as forest ecosystems, is more likely to be granular (porous), and results in higher infiltration rates and negligible surface runoff. Flooding and erosion rates would be greatly compromised by altered frost depth since frozen soil water and groundwater reservoirs usually store great quantities of water and buffer against flooding. Biogeochemical cycles such as enhance litter decomposition, mineralization rates, nutrient leaching, and trace gas fluxes would also be affected by alterations of the freeze-thaw activity (Campbell et al., 2005; Christopher et al., 2008); therefore, modification of the freeze-thaw cycle could have important effects on the cycling of nutrients such as carbon and nitrogen. In fact, carbon cycling, photosynthesis and microbial respiration are all controlled in part by soil temperature (Lloyd and Taylor, 1994). Changing land use coupled with climate change adds a degree of uncertainty in understanding the affect of altered freeze-thaw dynamics. Michelsen-Correa and Scull (2005) describe a central New York landscape succeeding from field back to forests, and show how fall and winter forest soils are warmer than field soils, while spring forest soils are cooler. With changing seasonal temperatures and snowfall depths over time affecting the depth and timing of frozen soils, understanding soil freezing dynamics is challenging but necessary in order to make predictions about ecological and economic responses to future changes in freeze-thaw dynamics.

Soil freezing (frost) depth can be determined using a number of direct approaches, including the digging of a pit to observe the presence of ice crystals; the burying of solid moisture blocks and recording conductivity (reaches zero when the soil freezes); the burying of thermocouples at various depths, and the installation of frost tubes (McCool and Molnau, 1984; Hardy et al., 2001). Another approach is to use the concept of 'degree days' - Freezing Degree Days (FDDs) and Thawing Degree Days (TDDs) - as a surrogate for frost depth. The advantage of the 'degree-day' approach is that meteorological data is easier to obtain and less intrusive than the other approaches described. A limitation of the degree-day approach is the representativeness of temperature data taken off-site.

The temperate forest examined here is located on the valley floor of the Point Peter Brook Watershed (PPBW), located at 42^o 26' 30” N 78^o 55' 30” W, approximately 75 km south of Buffalo, New York (Figure 1). The forest plots used for the frost tubes covers approximately 120 m^2. The surface geology is made up of sandstone and shale, with gravelly loam soils. A tight clay layer occurs at a depth of between 1.2 and 1.5 meters. The vegetation is mixed deciduous/coniferous forest (sugar maple, american beech, yellow birch, hemlock and white pine). The PPBW is a demonstration watershed, well instrumented with various monitoring wells, stream flow gages, piezometers, lysimeters, pressure tranducers, and rain gauges. Previous research has focused on the impact of storm events on biogeochemical cycling (Inamdar et al., 2006).

Figure 1. Location of PPBW. Area in blue shows location of monitoring site.

The objective of this study was to evaluate the impact of snow cover on soil frost depth in a temperate forest, as well as the usefulness of FDDs and TDDs as a surrogate for a direct measure of frost depth under both snow and non-snow conditions.

METHODOLOGY

Frost tubes were used as a direct measure of soil freezing depth. The frost tubes were constructed of 15.9 mm (outer dimension), 12.7 mm (inner dimension) clear Tygon tubing, built to a length of one meter. Construction of the frost tubes followed a design as first described by Ricard et al. (1976) and later modified by McCool and Molnau (1984). The tubes were filled with a solution of methylene blue (0.5 g/L). Freezing depth was indicated by a color change in the dye (blue to clear). The length of the color change from the surface was observed and measured with a ruler approximately once every week. Each frost tube was installed into a 30 mm diameter PVC pipe. The lower end of the pipe was capped. An auger was used to dig a 60 cm hole in which the PVC pipe was gently hammered perpendicular into the ground. The frost tube was installed into the PVC pipe, with a tape on the frost tube marking ground level. The tube was attached to the upper PVC cap (a modification of the rubber stopper), thus the removal of the cap allowed for the raising and lowering of the frost tube (Figure 2a).

Six PVC pipes, and associated frost tubes, were installed at the Point Peter Brook Watershed. Three of the pipes were installed in an area (Area 1) where snow was removed weekly. The size of this area was approximately 60 m^2. A second area of the same size (Area 2) also included three PVC pipes, but snow was not removed from this area.

Ambient air temperatures were collected within each of the study areas. Temperature was recorded hourly, using a HOBO K-8 data logger (Onset Computer Corporation). The data loggers were installed about 1.5 meters above the ground, housed within a protective shield - protected against direct sun and precipitation (Figure 2b). Air temperature data was uploaded monthly and maintained on an Excel spreadsheet.

Degree-Days were calculated by subtracting mean daily temperatures from 0^{o}C. A negative value was recorded as a FDD, while a positive value was recorded as a TDD. While total FDDs and TDDs were recorded, a running total was maintained through the winter and spring seasons.

Figure 2. Frost tube inserted into a PVC pipe (a). Uploading air temperature from the data logger (b). The temperature data logger protective housing is shown.

RESULTS AND DISCUSSION

Over the period 11/23/2007 to 04/08/2008 the mean daily temperature was calculated at -1.3^{o}C, with the coldest and warmest days averaging -13.0^{o}C and 12.7^{o}C, respectively. Over this period, a total of 691 FDDs and 323 TDDs were recorded. A maximum accumulated total of 584 FDDs occurred on 03/30/2008, after which TDDs dominated, reducing the FDD accumulated total.

Area 1 (Snowpack Removed)

The maximum freezing depth was 11.7 cm, occurring on 03/04/08. Accumulated FDDs and freezing depths over time are plotted in Figure 3. Accumulated FDD's were somewhat intermittent, including a mid-January thaw, before rising steadily through the month of February. Accumulated FDD's peaked on 03/30/2008. A strong correlation (r^2 = 0.95) exists between accumulated FDD's and freezing depth (Figure 4). While freezing depth appears to increase with accumulated FDD's, this occurs only after an initial accumulation of about 100 FDDs, and does not occur in the later part of the season where freezing depths tend to decrease even as FDDs continue to increase.

The explanation for these opposing trends can be found by not looking at accumulated FDDs, but by examining the rate at which FDD's are accumulated. During the period of the first trend (02/08/2008 and 03/04/2008), the coldest part of the winter season, an average accumulation rate of 11.4 FDDs per day relates to an increase in freezing depth of 0.39 cm per day. During the period of the second trend (03/04/2008 and 03/24/2008) an average accumulation rate of only 3.0 FDDs per day results in soil thawing (from the bottom up as the freezing depth decreases) at a rate of 0.06 cm per day. Soil temperatures, as measured at 30 cm, never fell below freezing. Thus, thermal energy stored at depth worked to thaw previously frozen soil, outpacing any surface freezing that may be attributed to the accumulation of FDDs. A look at an earlier period, between 12/23/2007 and 01/30/2008 (100 to 250 FDDs), shows another strong relationship of increasing freezing depth with accumulated FDDs – an accumulation of 7.2 FDDs per day results in an increase in freezing depth of 0.21 cm per day.

Neither total, nor accumulated, FDDs are an accurate measure of freezing depth; rather it is the rate at which FDDs accumulate (expressed as a FDD/day) that more accurately predicts soil freezing depth. Using the three periods, as previously discussed, a rating curve was developed to predict soil frost depth based on the rate that FDDs are accumulated (Figure 5). Based on this curve, just under 4.0 FDD/day are required to maintain a given depth of freezing soil, while rates equal to and greater than 4.0 are required to deepen the soil freezing depth. As this rating curve was developed for varying frozen soil depths, the 4.0 FDD/day rate is believed constant.

Further evidence that the accumulation of degree-days is not a good surrogate for soil freezing depth can be found by examing accumulated TDDs. As shown in Figure 3, the soil thawed well before the accumulated TDDs equaled the accumulated FDDs – giving a value of zero. As with FDDs, it is the rate of TDDs that is a good surrogate of soil freezing depth. A depth of 9.6 cm of frozen soil, as shown in Figure 3 on 04/03/2008 thawed completely by 04/09/2008 due to a rapid warming – even with 482 accumulated FDDs remaining. Here 13.3 TDDs per day melted 1.6 cm of soil per day, resulting in the complete thawing of the soil column. This rate of melting is more than double the FDD rate as projected in Figure 5. This thawing rate can be explained by melting occurring simultaneously at the surface and at depth, thus doubling the rate calculated for freezing attributed to a FDD rate alone.

Area 2 (Snowpack Not Removed)

The maximum freezing depth reached a depth of only 2.9 cm, occurring early in the winter season (01/21/2008) and can be attributed more to a snowpack (a mean snow depth of 14.5 cm, with a maximum depth of 48.5 cm) than accumulated FDDs. Temperature data, as measured at 5 cm and 30 cm (temperature data loggers were placed in the soil), shows that soil temperatures never froze below 5 cm. A weak correlation (r^2 = 0.27) exists between FDDs and freezing soil depths. Clearly, snow acts as an insulator, preventing soil from freezing to depths that would otherwise occur without a snowpack.

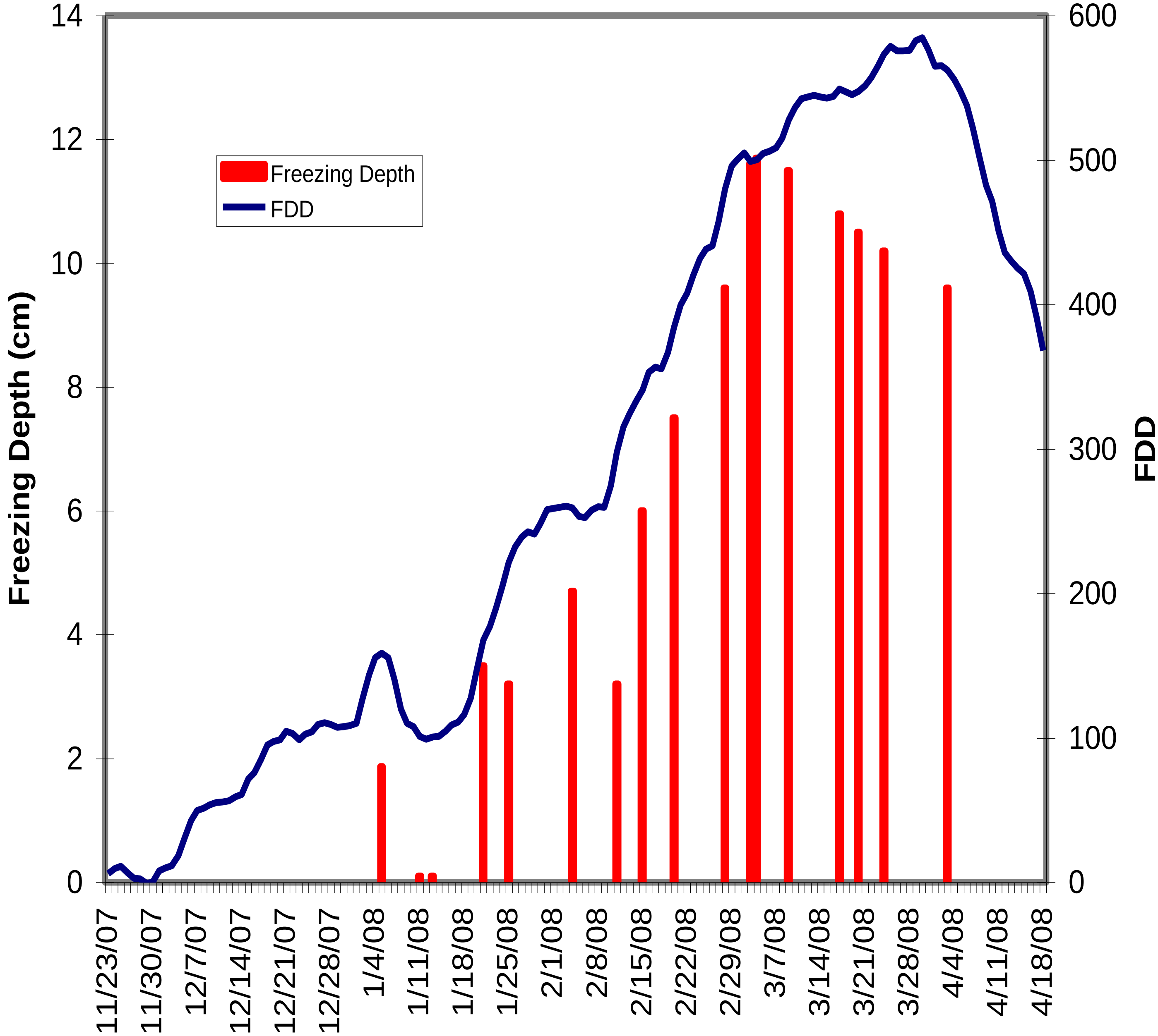

Figure 3. Accumulated FDD's and soil freezing depths.

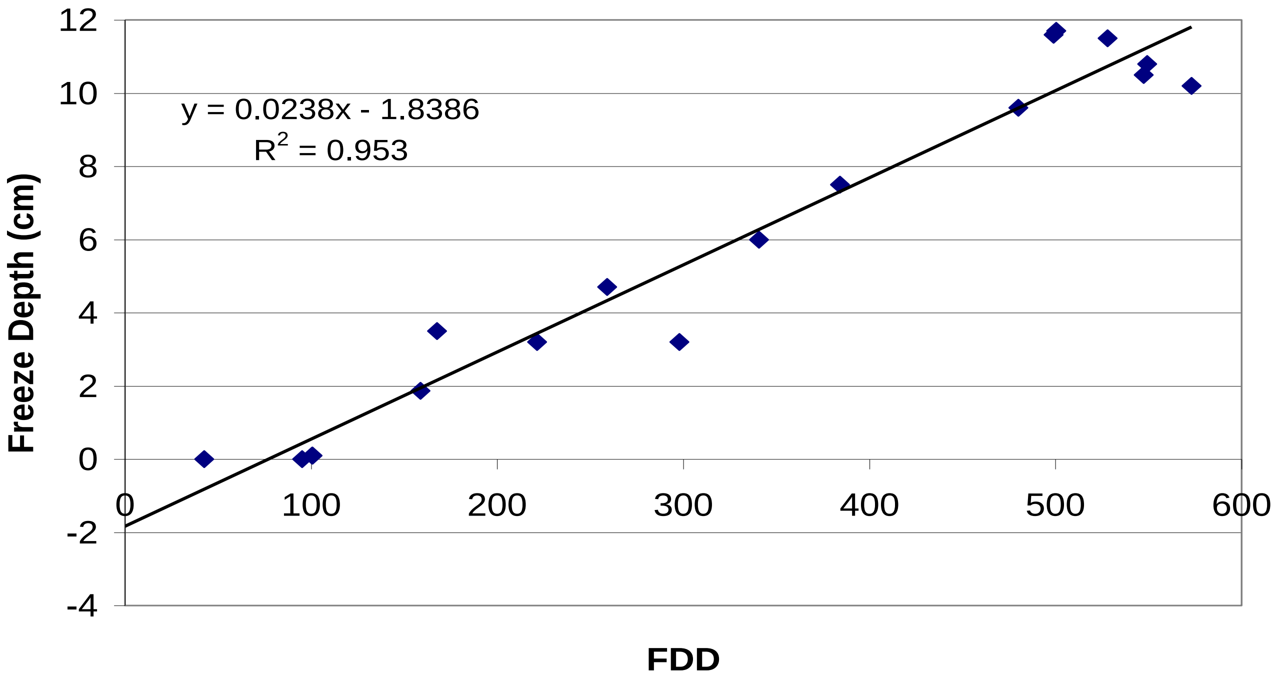

Figure 4. Correlation between FDDs and soil freezing depth.

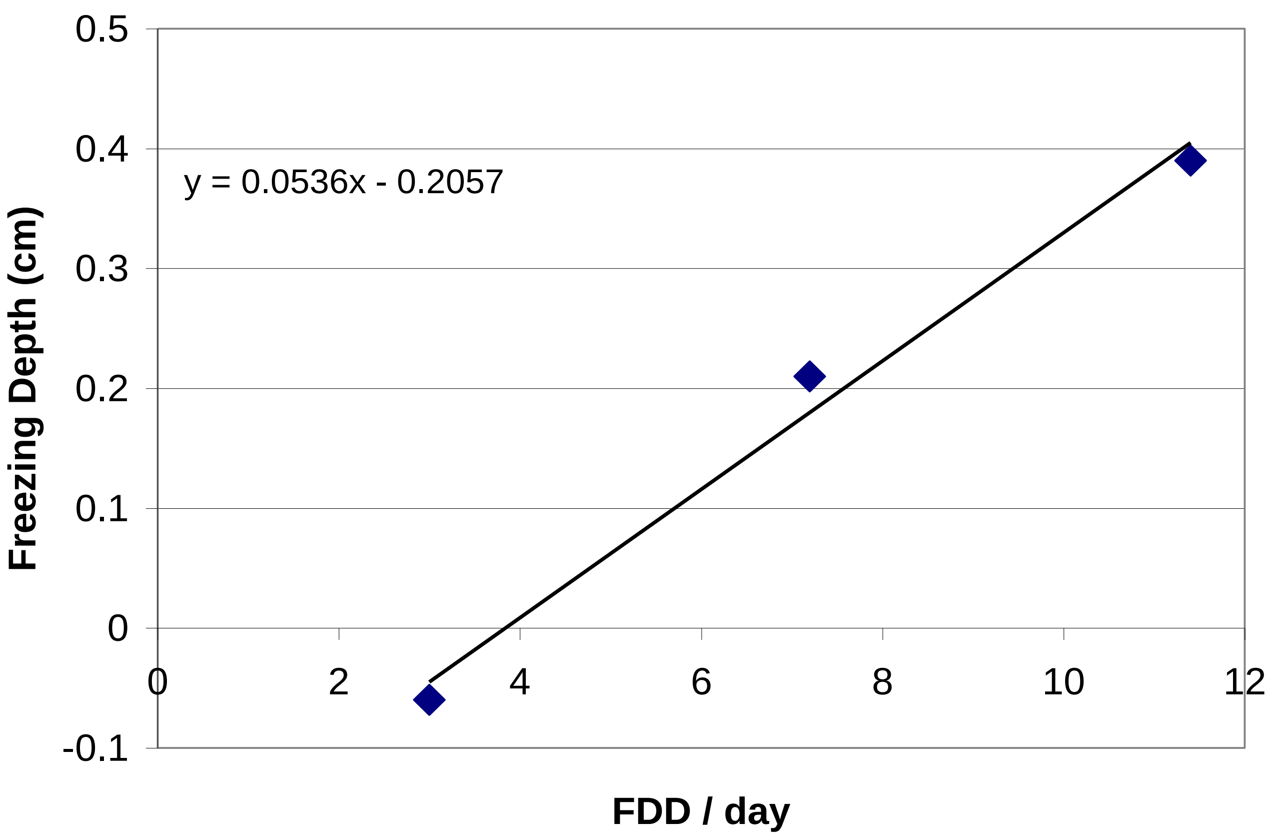

Figure 5. Rate of FDDs (expressed as FDD/day) and soil freezing depth.

CONCLUSION

Snow cover greatly inhibits freezing depths in soils, such that freezing depths can vary from year-to-year or spatially within a given time period, solely dependent on the presence or absence of a snow cover. The implication of a future climate without a snowpack or an increasingly intermittent snowpack is for greater freezing depths or varying depths, respectively. These changes in freezing depths would impact economic and ecological activities within the watershed.

While a strong correlation is found linking total FDDs with soil freezing depths in areas free of snowpack, a better predictive tool is to relate soil freezing depth with the rate at which FDDs are accumulated (expressed as FDD/day). Accumulating FDDs at a rate of less than 4.0 FDD/day will result in the thawing of frozen soils from the bottom up, while rates equal to or greater than 4.0 will increase the depth of frozen soil, the depth dependant on the rate of accumulated FDDs. As with soil freezing, the thawing of frozen soil is dependent on the rate that TDDs are accumulated. However, the rate of thawing is double that of the freezing rate, as the soil is thawed both from above and below.

The presence of a snowpack reduces the freezing depth of soil, such that the rate at which FDDs or TDDs are accumulated is not a good predictor of freezing depth. As a surrogate method, the use of degree-days is currently not recommended for determining freezing depth in the presence of a snowpack.

While this study has shown that the rate of accumulated degree-days can be useful to determining soil freezing depth in the absence of a snowpack, further study is required to better define the rating curve presented here, evaluating it under varying temperature and soil-type regimes. In addition, more work needs to be done to better understand the dynamics of soil freezing depths, and to determine whether a degree-day approach, or perhaps another surrogate method, can be used to predict soil freezing depths under a snowpack.

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