PREDICTING SOIL FREEZING DEPTH FOR TRAFFICABILITY

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1. Introduction

In northern countries, soil frost supports vehicle movement on unpaved surfaces and roads and does not have a serious impact on soil properties, whereas unfrozen areas make trafficking difficult or impossible. Such areas include permanently wet soils (*Gleysols*) of various textures, and peat soils (*Histosols*), bogs and high moors. These types of unfrozen soils can only support vehicles with low contact pressures. The soil bearing capacity – the ability of a soil to support vehicle movement – changes with freezing conditions and can be 5–10 times higher than that of unfrozen soil [1]. On *Histosols* it is estimated that a 20–30 cm frozen layer is necessary to ensure safe driving and to retain the soil properties [2]. The higher the moisture content of the soil during freezing, the more similar it is to ice, which will subsequently raise the soil bearing capacity. The bearing capacity can vary from 1000 to 2000 kPa depending on the depth of the frozen layer, the density of the soil, and the properties of the vehicle [3]. For example, in the case of a 60 ton tracked tank, the ice depth should be at least one meter, but in the case of a 26 ton armoured wheeled vehicle the ice depth need only be approximately 70 cm.

The freezing of the soil depends not only on the degree of negative temperatures and the frost duration, but also, in particular, on the snow or plant cover at the soil surface. Snow and plants prevent the frost from reaching the soil. The heat conductivity of snow is low and depends on snow density. The average heat conductivity of snow is 0.113 W/m/K, while that of wet snow is 0.335 W/m/K [4]. If the snow cover is over 20 cm and the soil did not freeze prior to the snowfall, then the snow will prevent the soil from freezing, even if there is a severe frost. Plant residues on the soil surface create a similar effect. Flerchinger *et al.* [5] found that soil freezing under plant cover depends on the type and the architecture of the residues. When compared to standing residues and bare soils, a flat residue cover can delay freezing and thawing by 5–9 days. Under the forest cover, freezing can be delayed even longer, and when the soil does finally freeze, the frozen layer is more porous and tends to be half of the depth of that of frozen bare soil [6]. Together with snow cover, dense plant cover can completely prevent the soil from freezing, even in the coldest of winters. The presence of snow cover can also severely hinder movement of wheeled vehicles. Vehicle movement depends on the snow density [3] and whether the snow depth is 30% of the wheel diameter or 50% if there are chains on the wheels. Generally speaking, if the snow layer is approximately 30 cm in depth, and it is loose, or not compacted, then it will create problems for wheeled vehicles. Tracked vehicles are less affected by snow. Tank trafficability is only affected if the snow cover is over one meter and is wet [7]. According to Saarilahti [2], the bearing capacity of fresh snow is 10–30 kPa, while that of old snow at −10°C is 50–100 kPa, and that of hard compacted snow at −10°C can reach up to 400–800 kPa.

However, landscape conditions can change drastically during thawing and wet conditions, and during rain and snow events. For this reason, measuring or predicting the freezing and moisture conditions of the soil is extremely important. The most common model used for predicting soil freezing is the *Simultaneous Heat and Water* (SHAW) model [8], which predicts the climate and management effects on snow depth and soil freezing, and gives quite precise results. The advantage of the model is that it takes into account data from different canopies, including those of plant and snow cover. Nonetheless, applying the model towards Estonian conditions is somewhat complicated by the fact that it requires a high degree of data input. In Estonia, measurements are often either not gathered, or they are gathered at rather long intervals. In order to implement the model, soil water content, texture, air permeability, density, water permeability, and soil temperature at different depths are needed. Some of this data can be predicted based on existing data but the initial soil moisture content, for example, still needs to be measured anyway. For soil data, the soil types, water regimes, and textures are available at a 1:10 000 scale for the whole of Estonia, but there is still a lack of soil density, air and water permeability data. For meteorological data, the soil temperatures are available, but the Estonian Weather Service does not provide the data of water content at different depths. Measurement of freezing is done manually at 10-day intervals [9]. Snow cover and precipitation data from all over Estonia are available on a daily basis, but snow density data is only obtained from limited locations at 10-day intervals. Due to the lack of quick direct measurement data and the high variability of the local microclimatic and soil conditions, a simpler and quicker model for predicting soil freezing is needed.

One simple model, the Stefani equation, for predicting soil freezing depth is presented by Suvinen [3]:

$$z = k\sqrt{F}, \quad (1)$$

where z – freezing depth in cm; k – coefficient depending on soil type; F – cold content, °Ch [10].

The cold content is the sum of daily average air temperature less than 0°C period multiplied with the days when the temperature was below 0°C.

The formula was initially designed to predict the freezing of water. In order to apply the formula to soil, Onninen [11] added the k values to account for soil texture types. The following values were determined for each soil type: gravel and sand 1.159, gravelly and sandy to 1.146, fine sandy and sandy to 0.986, fine sand 0.921 and clay 0.906–0.828. Yet these coefficients are more suitable for bare materials than they are for natural soils. Therefore, the coefficients should be adjusted for natural conditions. In fine texture materials, freezing depends more on water content at the moment of freezing than it does on the material itself.

As snow has low heat permeability, Knutsson [12] added the coefficients to account for the cold content according to snow cover depth:

$$F_{mod}=aF, \quad (2)$$

where, *a* is the correction coefficient according to snow cover: 10 cm – 0.9, 20 cm – 0.6; 30 cm – 0.4; 40 cm – 0.2; 50 cm – 0.15; 60 cm – 0.10; >70 cm – 0.05.

For trafficability purposes, the freezing time and depth, as well as the thawing time and the depth are important. The same Stefani formula can also be used to predict the thawing of soils:

$$d=1,1\sqrt{F}. \quad (3)$$

where *d* is the thawed layer depth in cm, *F* – is heat content in °Ch, wherein the temperature is over 0°C (found in the same way as cold content).

When implementing this equation, it must be borne in mind that it only predicts the thawing of the soil surface. However, thawing speed depends on positive temperatures, as well as on precipitation (rain) during the thawing period. For soils that are usually stable problems with trafficability can be expected when the soil over the frozen layer fills with water, reaches its liquid limit, and then exceeds it.

The aim of the current study was to investigate soil freezing and thawing in areas of low trafficability during unfrozen conditions, such as bogs and high moors. Furthermore, the aim was also to find a simple model to estimate freezing and thawing depending on the temperature, soil, plant and snow cover.

2. Material and Methods

Soil freezing and thawing was measured in the winters of 2013/14 and 2014/15. The measurements were conducted on a daily basis, and were manually gathered at noon during the freezing and thawing periods. Various terrains were monitored. These included compacted soil, grassland, a mown bog and a natural bog near Tartu, a cultivated field near Tartu, from which data was gathered at 3 to 7 day intervals, a high moor at Alam Pedja (2013/14) and a high moor at Valgesoo (2014/15) (Tab. 1). To penetrate the frozen layer, a knife, a spade or a crowbar was used depending on the density and depth of the frozen layer. The depth of the layer was then measured and its density was described (loose, dense, very dense, hard). If the layer was covered with snow, the depth of the snow was measured and its density described. The plant cover of each of the study locations was described as well. The locations of the measurements took place in open landscapes, as the forest was not relevant for the current study. However, measurements under forest cover were conducted in 2014/15 in order to estimate the effect of plant cover. In those areas where the soil was compacted, and the fields where there was no plant cover, or where the cover was very sparse (winter rapeseed) the effect of the plant cover on freezing and thawing was negligible. In the grassland area, and in one location of the bog where the grass had been mown, the plant cover was quite thick and approximately 8 cm high (Table 1). In the natural bog area, where there was thick grass and sedge (*Carex* sp.), the cover was 40–80 cm high at the beginning of the winter. In the high moor, peat moss (*Sphagnum* sp.) was the dominant species, together with sparse pines (*Pinus* sp.), downy birches (*Betula pubescens*) and wild rosemary (*Ledum palustre*). The soils were chosen according to comparable water regime and texture conditions (Table 1).

Table 1. Characterization of the investigated areas

Location	Year	Soil		Plant	
		Type	Texture	Cover, cm	Species
Tartu	2013/14 2014/15	Drained bog, Eutric Histosol	Well decomposed peat	thick 40–80 cm	grasses, sedges
Alam-Pedja	2013/14	High moor, Dystric Histosol	Poorly decomposed peat	scarce	peat moss, pines, birches, wild rosemary
Valgesoo	2014/15				
Tartu	2013/14 2014/15	Field, Stagnic Luvisol	Silty loam	bare or scarce	oilseed rape
Tartu	2014/15	Grassland, Stagnic Luvisol	Silty loam	thick 7–8 cm	grasses
Tartu	2014/15	Compacted soil, Stagnic Luvisol	Silty loam	bare	

In both years, the freezing period was quite short with no permanent snow cover in several of the locations. Figure 1 presents the average temperatures for the 2013/14 freezing period, and Figure 2 displays the data for the winter of 2014/15 in the Tartu area.

Freezing predictions were calculated using equations 1 and 2 of the Stefani formula while thawing predictions were calculated using equation 3. As the soil of the investigated areas was fine textured, but not clay, the coefficient k was 0.828. In the 2013/14 season, a plant cover factor of 0.4 was applied to the freezing model, and 0.2 to the thawing model, which corresponds to 30 and 40 cm of snow, respectively, in areas with plant cover. For the 2014/15 season, the snow factor was taken into account according to real cover as presented earlier in the introduction. In addition, a plant factor of 0.3 was used for both the freezing and thawing models over this period for areas with plant cover.

3. Results and Discussion

Season 2013/14

The stable period of negative temperatures (below 0°C) began on the 11th of January, 2014 and was followed by a sudden drop in temperature below –10°C, which lasted for several days (Fig.1). The decrease in temperature continued (average –16°C) with the lowest temperature, –23.6°C, occurring on the 24th of January.

Low negative, –20°C, temperatures persisted until the end of January. After that period the temperature started to rise. On the 6th of February, temperatures below –10°C were still measured. However, thawing began on the 7th of February, as temperature rose over 0°C, and did not drop below zero again for any length of time for the rest of the season.

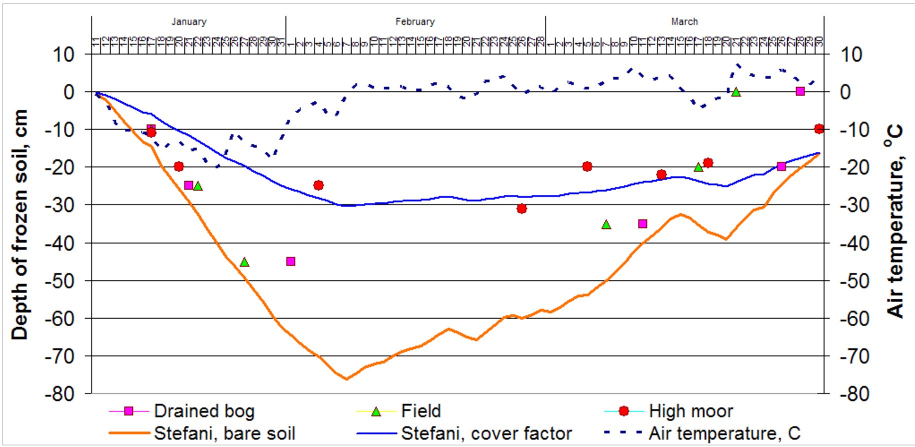

Figure 1. Daily average temperatures (°C) in the Tartu area from January to March 2014, and the soil freezing depth (cm) of different soils under different plant cover as measured and predicted by the Stefani formula

During the 2013/14 winter season, measurements of soil freezing revealed that for peat soils, in order for the dense frozen layer that extends to more than 20 cm deep and which is suitable for supporting heavier vehicles to form, there must be a duration of 1.5 weeks of temperatures below –10°C. The frozen layer depth in such conditions increases at a rate of 2–3 cm per day. However, when compared to the bare field soil, the freezing intensity of the drained bog and the high moor was lower at the beginning of the sub-zero temperatures. During the cold periods, the frozen layer was hard and monolithic, but when the temperature rose, the frozen layer became more friable. It was then possible to dig into it with a shovel. Even at the end of the continuous cold periods from the 7th of February, the 20 cm frozen layer persisted until the middle of March in the bog, and until April in the high moor. Complete thawing for these areas took between one and five weeks longer than it did in the field. The low heat permeability of the peat slows soil thawing in the spring.

Season 2014/15

More sites were investigated during the 2014/15 season than were for the 2013/14 season. In addition to the field, a drained bog and a high moor, as well as mown grassland and compacted bare soil areas were also included in the study.

In 2014, the period of negative temperatures began on the 22nd of October, with a drop in temperature below –6°C and lasted until the 27th of October. This short period did not cause any freezing under the mown grassland, nor did it cause freezing for the natural drained bog with the thick plant cover. The temperature started to decrease again on November 16th, which caused the freezing of the bare field soil and the compacted soil, but did not cause the soil of the grassland and natural vegetation to freeze (Fig. 2). As in the previous season, the stable periods below –10°C that lasted more than 2 days were few. Under vegetation the soil only froze to a depth of 8 cm. As the sub-zero period was short (5 days), the frozen layer became friable and thawed quickly when temperature rose over 0°C.

The soil of the high moor area froze more quickly than that of the grassland and the drained bog, and its freezing pattern was comparable to that of the field. Nevertheless, in places where the peat moss was not fully saturated with water, a hard human bearing layer formed only after multiple sub –10°C temperatures. In the high moor, it must be taken into consideration that the edges of the area with proper plant cover (under forest) do not freeze with the same intensity as do the areas in the centre, and the depth of the frozen layer depends on the presence of snow, which reduces the trafficability of moors even during cold periods.

One week of above zero temperatures completely thawed the soil of the bog and the grassland and the frozen surface layer decreased by 4–5 cm in the field and in the high moor. Another week with rain thawed the soil in all of the locations (Fig. 2). As the temperatures decreased again at the end of December and the beginning of January, the very loose snow cover, (approx. 0.15 g cm^{-3} according to the National Weather Station Tõravere measurements) which was up to 20 cm deep, prevented the soil from freezing in most locations.

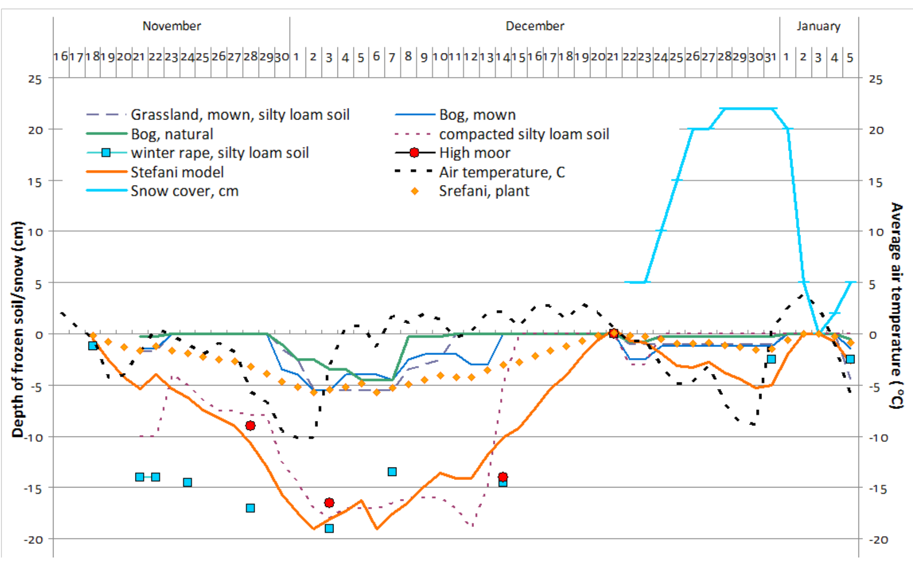

Figure 2. Daily average temperatures (°C) in the Tartu area in November and December 2014 and January 2015, and soil freezing depth (cm) of different soils under different plant cover as measured and predicted by the Stefani formula

Similar cycles of freezing and thawing continued into January and February of 2015 and in those places where the snow did not melt (approx. 15–20 cm snow cover), the soil did not freeze any more that season. During the stable negative temperatures in the middle of February the drained natural bog froze to a depth of 10–15 cm. When the temperatures began to rise at the end of February (February 25th), the field and mown grassland were the first to thaw. These areas had already thawed by the 8th of March while at the same time a 10 cm frozen layer was still visible in some parts of the bog. On the 10th of April, final measurements revealed a 2 cm friable frozen layer remaining in the bog, and a 4–5 (10) cm frozen layer in the high moor below the 15 cm of peat moss. Although the total thawing of the high moor took a long time, the edges of the moor, and the areas between plants had already thawed with the first positive temperatures.

The accumulated data was used to test the suitability of the Stefani model to predict freezing depths and the thawing of natural soils with plant cover in negative/positive temperatures. Without the plant cover factor, the model overestimated the freezing of the soil in natural conditions of the bog in 2013/14 and 2014/15. It underestimated the freezing in the field and correlated (r = 0.8) best with compacted silty soil in 2014/15 (Stefani bare in Figure 1 and 2). The Stefani formula (1) does not take into account the plant cover factor. However, as the effect of plant cover is similar to that of snow cover, the snow cover coefficients from Knutsson [12], which can be found in the introduction, were used to correct the freezing depths and to allow the formula to reflect the natural conditions. The original thawing formula (3) also does not take snow or plant cover into consideration either. As plant or snow cover prevents heat from reaching the soil, it is advisable to also use the same coefficients for thawing as well. According to the calculations, the most suitable coefficients for improving the fit of the Stefani formula to the 2013/14 data were 0.4 for the freezing and 0.2 for the thawing (Figure 1), and 0.3 for both the freezing and the thawing (Fig. 2). However, the fit of the model to the beginning of the freezing, and to the sustained below freezing temperatures was quite good. The model slightly underestimated thawing at the end. As was explained earlier, this formula does not take into consideration the heat from the deep soil layers, or the effect of rain, which is why thawing, occurs more quickly than is predicted by the model. If the soil does not freeze deeply, then the ground beneath the snow will thaw even before the snowmelt begins in the spring [4].

Our results reveal that when the plant cover is thicker, it is necessary to include a lower factor *a* (for deeper snow) in the Stefani formula in order to predict freezing and thawing. If there is both plant cover and snow, then the depth of plant cover should be adjusted to the depth of snow before calculating the freezing depth. The plant and snow factors should be taken into consideration for thawing as well, due to the fact that thawing under plant cover takes a longer time than it does for bare soil. As the Stefani equation only takes into account thawing from the surface, the plant factor should be lower for thawing than it is for freezing in order to better reflect real conditions.

4. Conclusions

1. The simpler Stefani model can be used to predict the freezing and thawing depth of soils when they are bare and when there is plant cover during sustained negative/positive temperatures.
2. More precise factors than have been suggested in the literature should be implemented to reflect the actual conditions of soils due to the fact that most of the coefficients overestimate freezing. In addition to the snow factor, plant cover should be considered as well.
3. Under plant cover (dense grasses), real freezing only begins when the average air temperature has been below –10°C for at least 2 or 3 days. The freezing intensity in such conditions is 3–4 cm per day, and the frozen layer that is more than 20 cm dense and that is capable of supporting heavy vehicle operations in bogs takes 1.5 weeks to form. Under a thick loose (approx. 20 cm) snow cover no soil freezing takes place.
4. Under plant cover, if the soil freezes deeply, then thawing will take at least 2 weeks more than in open areas. The freezing of bogs and high moors is uneven – in open areas it is similar to water, but at the edges, or under bushes, and near the forest, the soil can remain unfrozen.

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