Journal: Hydrology and Earth System Sciences
Title: Projected decrease in wintertime bearing capacity on different forest and soil types in Finland under a warming climate
Authors: I. Lehtonen, A. Venäläinen, M. Kämäräinen, A. Asikainen, J. Laitila, P. Anttila and H. Peltola
MS No.: hess-2017-727
MS Type: Research Article
Iteration: First review
Referee #2

We would like to thank the referee for the comments and suggestions. Our replies to the comments are given in "Italics" after the comments given in the beginning of this document.

Wood harvesting is an important part of the Finnish economy. The current national strategy (2014-2020) is also to increase the economic output from this industry, and over the next decades increasing demand is expected to put further pressure on the annual wood harvesting. This has traditionally been a winter activity when the ground is frozen and the mobility is greater and impacts on the natural areas are smaller. The paper aims to evaluate the projected decrease in the bearing capacity of Finnish soils, especially dried peatland, under two different projected warming scenarios for the 21st century. The wood harvesting should preferably be undertaken (and increased) throughout the year, due to a steady demand by the processing industry. The results are presented across Finland for different combinations of three soil types and four forest types, in addition to forest truck roads. Hence, the results take into account that for a given location, the soil and/or forest might change in the future. The relevance of the study is therefore clear but the potential or expected impact could be better explained (in the context of year-round harvesting with new methods and machinery in a changing climate) also because this study should have interest outside Finland and Finnish interests. The abstract provides a concise and complete summary, with the exception of not mentioning the snow model and using vague terms like "largely determined by" and "mainly determined by". Overall the paper is well structured and clear but could be shortened. The language is generally good with a few exceptions which will be fixed by a critical shortening of the text.

We agree with these remarks by the reviewer.

The bearing capacity of frozen soil is an important parameter is this study. The authors claim, with reference to Eeronheimo (1991), that a 20 cm thick layer of frozen soil or 40 cm thick layer of ground snow can bear standard (heavy) vehicles (15-30 tons) used in forest harvesting. Eeronheimo is written in Finnish with an English summary at the end where it is stated: "The logging conditions in peatland forests are often unfavourable. The bearing capacity of the ground is poor most of the year and difficult to determine, which complicates felling and extraction practices. According to forest harvesting specialists there should be either frost layer of at least 20 cm or, when there is no frost, snow cover of 40 cm or more to facilitate extraction with medium-sized forwarders." Using published guidelines, Shoop (1995) proposed a relationship for bearing capacity of frozen ground, including as a function of dry and wet soil conditions. Dry conditions (dried peatlands are abundant in Finland) require a deeper freezing layer and a 10-ton truck needs 0.35-0.50 m frozen soil thickness, according to Table 1 in Shoop (1995), where the upper limit (0.50 m) is said to be a conservative estimate (page 555). (In the list of studies citing Shoop there are also more recent studies although they do not seem to bring any

significant new knowledge on bearing capacity of frozen soil). In addition the distribution of the ground pressure (e.g. wheel load) from the vehicles/machines may impact the bearing capacity (breakthrough failure versus localized crushing). The relationship between the frozen soil layer and vehicle/machine bearing-capacity therefore seems more complex than put forward by the authors in this study. At least soil freezing depth and bearing capacity requires a more in-depth discussion (explaining also what is meant by "idealized approach" on page 13 line 8), but possibly a new analysis of the results. The claim that 40 cm thick ground snow (over frost free soil) ensures the same bearing capacity as 20 cm frozen soil should be supported by more evidence than from Eeronheimo. For instance, is this regardless of snow density? I guess not.

We agree that soil moisture affects to the critical soil frost depth. However, dried peatlands are not "dry" soils literally speaking, they are rather the wettest sites where some kind of forest grows in Finland. We can add more discussion considering the chosen thresholds, e.g., based on the study by Suvinen (2006).

With the "idealized approach" we mean that we use these certain classes for soil types and forest types but in reality, there are much more variability in soil conditions, so the inspected conditions are idealized in that sense that exactly the same kind of conditions probably occur nowhere.

It is correct that there are "several models designed for calculation of soil temperatures" (page 3 line 14) but the authors list only a few. For instance SURFEX (including different snow pack models like Crocus), see Special Issue in GMD at https://www.geosci-model-dev.net/special_issue14.html), where FMI has experience and expertise. There are most likely good reasons for the author's choice of land surface model but they are not well presented (and discussed) in the paper. Moreover, the employed GCMs and RCMs use land surface models and it should be explained why direct use of these results for soil temperature, or stand-alone high-resolution implementations, are not presented or used. This also applies to snow depth. I can speculate about the answer but not all readers might be well enough into surface modelling to do so. More details are also relevant for the validation of the modelled temperatures and snow depth. For soil temperatures the validation of the optimized model shows that either correlation or the number of days with soil temperatures below freezing can be well represented (but what is meant by "greatly overestimated" or "dramatically worse", top of page 6?). The results (correlation and number of freezing days) after introducing soil freezing points below zero are also not presented. These below zero freezing points are based on a study in Finnish and therefore difficult to use as reference – are there other studies which are more appropriate to use?

The climate models themselves tend to have too much soil frost but as we used bias-adjusted simulation data, the use of soil temperature or snow depth data directly from the models was not even possible as the similar bias-adjustment approaches could not be meaningfully applied to these data. With our own model we were moreover able to calculate the results for desired combinations of soil and forest types. Furthermore, we will pay more attention to the points mentioned by the referee.

Another reference should also be used for the determination of precipitation phase. Also, it should be explained why this classification is needed as not all readers are familiar with the (limited) output from numerical weather and climate simulations.

We can remove the reference to Hankimo (1976) and refer only to Vehviläinen (1992) and moreover add a short explanation why the classification is needed.

About the snow model, it is based largely on another study. From the text it is not very clear what is new and what is taken from the existing model. Can the text be shortened accordingly?

Vehviläinen (1992) describes different approaches that can be used in snow cover modelling and we have took relevant pieces from these approaches. As Vehviläinen (1992) concentrates mainly on snow water equivalent, we have added also features describing the density of snow cover.

Is the modelled snow depths validated for RMSE? Or for the snow depth threshold of 40 cm?

The snow model was optimized based on RMSE. R^2 and relative error are used to describe the validity of the model.

The calibration periods for soil temperature and snow depth are relatively short. Is there a risk that they are too short when the resulting models are used on future climate conditions, cf. last sentence in Section 2.2.3?

We suspect that the issue mentioned in the end of the section 2.2.3 is rather related to changes in precipitation measurements than an indication of different physical relationship between the weather and snow conditions. Of course, this possibility cannot be excluded that the calibration period may be too short.

The study "modelled the number of days with good bearing capacity in the forest harvesting point of view. (...) soil frost (...) at least the depth of 20 cm or when the snow depth exceeded 40 cm" (page 9, lines 27-29). I think it would add to the study to present the bearing capacity separately for soil frost thickness and snow depth. Both variables are dependent on climate change but their sensitivities to changes might be different, e.g. freezing temperature before or after snowfall affects the soil freezing layer differently. Also, such a separation should be beneficial both for the validity of the used model and when projected values are compared to current conditions (baseline period).

This kind of comparison can be added.

The evaluation of the methodology (Section 4.2) should be extended, following the suggestions above. Also, the comparison to Eeronheimo (and his Fig. 4) – page 13, lines 9-12) – could be done more thoroughly, perhaps using a map of soil bearing capacity which reflects the actual soil and forest properties in each grid point.

We will take these points into consideration. Many grid points have all kind of terrains because the size of individual grid points is close 100 km^2.

Are the GCM and RCM ensemble means used in Fig. 2?

Yes, the multi-model means are shown in the figure.

I might be wrong, but it seems that in several of the panels in Figs. 2-6 the bearing capacity also extends over sea. I am guessing this is related to model resolution and the many Finish islands. But are these of interest to this study or can they be omitted from the presentation for (this readers) improved readability?

In the figures based on the GCM ensemble the cover the same area as the Finnish gridded climate data set as that data set was used in the bias-correction. In the figures based on the RCM ensemble, the data coverage is different and data are missing from some coastal inland areas as well.

Shoop, S. A., Vehicle bearing capacity of frozen ground over a soft substrate.
Canadian Geotechnical Journal, 1995, Vol.32, No.3 :pp. 552-556. https://doi.org/10.1139/t95-057(http://www.nrcresearchpress.com/doi/abs/10.1139/t95-057#.Wr9Lki5uapo)

We can add this reference.