Research Article
https://doi.org/10.33904/ejfe.1321075

Eur J Forest Eng 2023, 9(2):70-79

Estimating Soil Strength Using GIS-Based Maps - A case study in Sweden

Sima Mohtashami, Linnea Hansson, Lars Eliasson*

Forestry Research Institute of Sweden, Skogforsk, 751 83 Uppsala, Sweden

Abstract

Soil strength is an important parameter for planning of forest roads and harvesting operations. Locating roads to areas with high soil strength reduce both build and maintenance costs. Locating logging trails to high strength areas minimise soil disturbances, e.g., rutting and compaction of forest soils. GIS-based maps of soil type and soil moisture can be valuable tools to estimate soil strength. The aim of this study was to evaluate the use of soil moisture map, i.e., depth-to-water (DTW), maps and soil type maps, to estimate soil strength expressed as California bearing ratio (CBR). CBR, volumetric water content, and ground penetration depth were measured in 120 sample points, separated on three soil classes (clay-silt sediments, sand sediments, glacial till) and two soil moisture classes (wet, dry). In each point, soil samples were collected for validation of the soil type maps. There was a high conformance between soil moisture predicted by DTW maps and field measurements, but conformance of the soil type between maps and field estimates varied between soil types. For sediment soils, dry soils were consistently stronger than wet soils. Soil strength of glacial till soils was more complicated with a binary CBR distribution depending on soil stoniness. Glacial till soils possible to penetrate to 20 cm depth with the dynamic cone penetrometer had CBR values close to those for sand sediments. There is a potential to estimate soil strength from DTW and soil type maps, but these variables should preferably be complemented with other data.

Keywords: Soil disturbance, Soil moisture, Soil type, Logging operations, Planning.

1. Introduction

Forest roads and machine trails are vital parts of the supply chain of forest products to sawmills and pulp and paper industries. When planning for new forest roads and future harvesting operations, soil strength is an important parameter to consider. Locating roads to areas with high soil strength reduces both construction and maintenance costs for forest roads (Swift and Burns, 1999). Locating logging trails to areas with high strength can minimize soil disturbances, e.g., rutting and compaction of forest soils. GIS-based maps of soil type and soil moisture are valuable tools for planning for new roads or logging trials. At least in theory, these can be used to estimate soil strength in the office or in a decision support system for the machine operators. Almost all logging operations in the boreal forests of Sweden are fully mechanized, using single-grip harvesters and forwarders. Due to their weight, these machines may cause soil disturbances like rutting and compaction (Ilintsev et al., 2021; Labelle et al., 2022). Practical tools, like GIS-based soil strength estimates, are required to improve the planning of logging operations and reduce soil disturbances.

Under identical operational conditions, the risk of soil disturbances is higher in soils with low strength, such as soils with fine-to-medium texture and/or high moisture content (Wronski and Murphy, 1994; Hillel, 1998). Fine-to-medium-textured mineral soils are more susceptible to compaction than coarse-textured mineral soils, and their susceptibility is influenced by soil moisture content (Østby-Berntsen and Fjeld, 2018; Fisher and Binkley, 2000; Naghdi et al., 2020). The rut depths in logging trails increased with increasing moisture contents in mineral soils (Toivio et al., 2017; Uusitalo et al., 2020).

Some of the possible measures that reduce rutting and compaction in logging sites with low strength are (i) avoiding passages with forestry machines in areas with low soil strength, (ii) reinforcing the soil with logging residues where passage is necessary, or (iii) scheduling the logging operations for periods when soil is frozen or dry (Labelle et al., 2022). Thus, areas or sites with low soil strength needs to be identified. Both to avoid areas with low soil strength or take appropriate action to reduce the risk for rutting and soil compaction. One possibility for doing that is in-situ measurements of soil moisture content and soil texture (Labelle et al., 2022). However, it is labour-intensive and impractical for large-scale operational planning. Depth-to-water (DTW) maps and soil-type maps are readily available geospatial data that can be used to estimate soil strength.

Soil moisture can be estimated from DTW maps based on surface topography extracted from digital elevation models (DEM) (Murphy et al., 2007). The

*Corresponding Author: Tel: +46 702813332 E-mail: lars.eliasson@skogforsk.se
Received: 30 June 2023; Accepted: 30 October 2023

application of airborne laser scanning (ALS) has enhanced the captured detailed information about surface topography due to the increased penetration possibility of the laser beams through vegetation and forest canopies, compared to photogrammetry-based digital elevation models (Vepakomma et al., 2023). Therefore, ALS-based DEMs have improved mapping of hydrological features, like streams and flow channels, and the associated wet and moist areas closest to them. Cartographic DTW maps estimate the soil moisture by calculating the vertical depth of each unit/pixel in the landscape to a modelled groundwater table (Murphy et al., 2007; Murphy et al., 2009). In Sweden, DTW maps showed promising results in identifying sensitive terrain areas in commercial forest operations (Friberg and Bergkvist, 2016). The use of DTW maps, together with soil type information, facilitates identifying areas of high risk for rut formations (Mohtashami et al., 2017), although DTW maps cannot per se be used to predict rut positions in logging operations (Ågren et al., 2015; Mohtashami et al., 2017; Schönauer et al., 2021). DTW maps have been freely available to foresters in Sweden through the Swedish Forest Agency since 2015 and are now integrated into forest operation planning by many forestry companies (Mohtashami, 2022). DTW maps have also received wide applications in other northern and central European countries, due to their acceptable performance, relatively low input data demand, given availability of digital elevation models, and ease of production (Hoffmann et al., 2022).

Quaternary deposit (parent material) maps (hereafter called soil type maps), available from the Geological Survey of Sweden (SGU), are based on field inventories and supporting materials like aerial photographs and topographic maps. Soil type maps have varying quality and scale (1:25 000 - 1:750 000) from south to north Sweden and estimate the soil type for the upper 50 cm of the soil. SGU defines soil type based on terms of the method of formation and particle size composition (Karlsson et al., 2021; SGU, 2021a). The available soil maps usually lack high spatial resolution for precise forestry or agricultural planning applications. New techniques like digital soil mapping have been used to improve the description of soil type classes in arable lands (Piikki and Söderström, 2017), with positive indications for applications in forest operational planning (Mohtashami et al., 2018). Peat and mineral soils have also been mapped recently using an empirical approach, relating information on organic matter content from Swedish forest soil inventory and other data from national forest inventories to nationwide soil moisture maps (Ågren et al., 2022). Although these maps visualize the spatial extent of peat soils with higher accuracy compared to previously available maps, they do not include any classification of mineral soils. Reinforcing factors like the presence of stones and boulders (Niemi et al., 2017) or tree roots also affect soil strength and the level of soil disturbances occurring during logging operations (Cambi et al., 2015; Salmivaara et al., 2020).

Recently, parts of the soil type maps over Sweden have been updated with more precise soil class boundaries using ALS-derived digital elevation models (Anon, 2021b). The application of these updated soil type maps, together with other relevant data, is expected to improve the identification of areas with high risk of soil disturbances during logging operations.

The aim of this study is to evaluate the use of GIS-based DTW maps in combination with soil type maps for estimating soil strength in boreal forests in Sweden. Improved estimation of soil strength facilitates the choice of effective measures to reduce the adverse effects of forest machine passages in logging operations.

2. Materials and Method

2.1. Study Area

The study had a factorial design with soil type (clay-silt sediments, sand sediments, glacial till soils) and soil moisture (Dry, Wet) as factors and 20 replicates per factor combination. It was carried out in June 2022 in hemi-boreal forests around Uppsala, Sweden (17.7961541° E, 59.8905069° N, orange area in upper right part of Figure 1), where updated soil maps were available. The climate is classified as Dfb by the Köppen-Geiger system with an average annual temperature of 6°C and yearly precipitation around 500 mm.

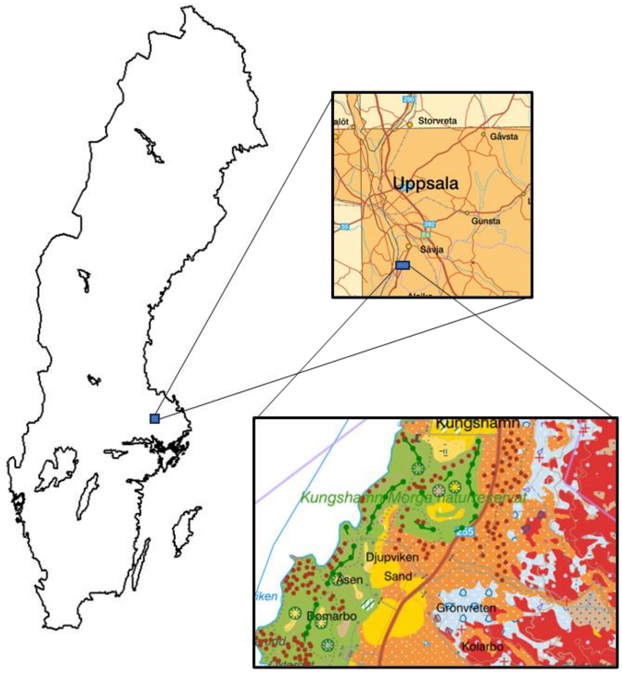

Figure 1. The location of the study sites within Sweden. The magnified orange square in the upper right part of the figure shows the area within which the sample points were located, and the lover right is a further magnification of the soil type map in part of this area. In the soil map (lower right), green depicts sand sediments (glaciofluvial deposits), orange post glacial sand sediments, yellow postglacial clay and silt, blue glacial till, and red shallow soils/bedrock.

2.2. GIS Data

Non-forest lands within the study area were excluded using the national land cover maps (10 m resolution) (Anon, 2022). Thereafter, GIS-based soil type maps from the Geological Survey of Sweden (SGU) were used to select areas around Uppsala where the soil class boundaries had been updated using ALS-borne digital elevation models. Three soil types (Karlsson et al., 2021) common to this area, were selected for the study: 1) clay-silt sediments, 2) sand sediments, and 3) glacial till soils. The group clay-silt sediments included glacial silt, glacial clay, and postglacial clay, and the sand sediments included postglacial sand and glaciofluvial deposits. Soil types like peat soils and bedrock were excluded due to their apparent expected strength. The soil type map has a separate layer visualizing where surface boulders are abundant, and these areas were also excluded from the study area. The surface boulder data layer; however, do not cover the whole land area of Sweden.

Soil moisture in the GIS was estimated by DTW maps (2 m resolution) over the study area, procured from the Swedish forestry agency (Anon, 2020). A threshold value of 1 m is conventionally used to reclassify DTW maps to binary classes of wet and dry, assuming DTW ≤ 1 m = wet and DTW > 1 m = dry.

2.3. Field Data Measurements

Based on soil type maps, DTW maps and land cover maps 120 sample points were randomised over the three soil types and two soil moisture classes using ArcGIS Pro (Version 3.0.3, ESRI, Redlands, CA, USA). This corresponds to 20 replicates per factor combination.

In each sample point, a soil sample was taken for soil classification, and measurements were made of soil strength (expressed as California bearing ratio, CBR), volumetric soil water content (VWC, m^3_{water} m^{-3}_{soil}), penetration depth (cm), depth of moss- and litter layer (cm). A Dynamic Cone Penetrometer (DCP), built according to the specifications in Anon (1996), was used to measure soil strength. The soil strength is estimated through a depth penetration index (DPI), which is the sinkage of the cone per drop of the hammer of the penetrometer. DPI measurements were started beneath the moss and litter layer and continued at each point until a minimum sinkage of 200 mm was exceeded, counting from the starting point after the initial sinkage of DCP into the soil by its own weight (Figure 2). Soil strength at each sample point was calculated as a Californian Bearing Ratio per hammer blow according to Webster et al. (1992):

$$Log\ CBR = 2.46 - 1.12 * log(DPI) \tag{1}$$

where DPI is the depth penetration index (mm/blow). An average CBR value for the top 200 mm of the soil was thereafter calculated at each point. In some glacial till soils, DCP measurements for the top 200 mm profile were not possible due to too many stones and boulders in the topsoil. These points were assigned a CBR value of “no data,” and the soil strength is expected to be high enough for traffic with forest machine.

Volumetric soil water content was measured using Time Domain Reflectometers (TDR). A TDR measures the transmission of an electromagnetic signal through the soil, proportional to the dielectric permittivity of the soil. For each sampling point, five soil moisture measurements were made in a 2×2 m^2 centred around the sample point and averaged to reflect VWC at that point. Volumetric water content was measured in the topsoil, beneath the moss, and litter layer when existing. The VWC measurements were carried out using a Field ScoutTM TDR 350 (Spectrum Technologies Inc., USA, calibration: universal soil, 7.5 cm probe) in 65 sample points. The remaining 55 points were measured using an SM150T (DeltaT Devices, Ltd, UK, calibration: mineral soil, 5 cm probe). The change of probes was caused by a damaged display. The two probes have previously shown similar VWC with the same calibration (Hansson et al., 2022).

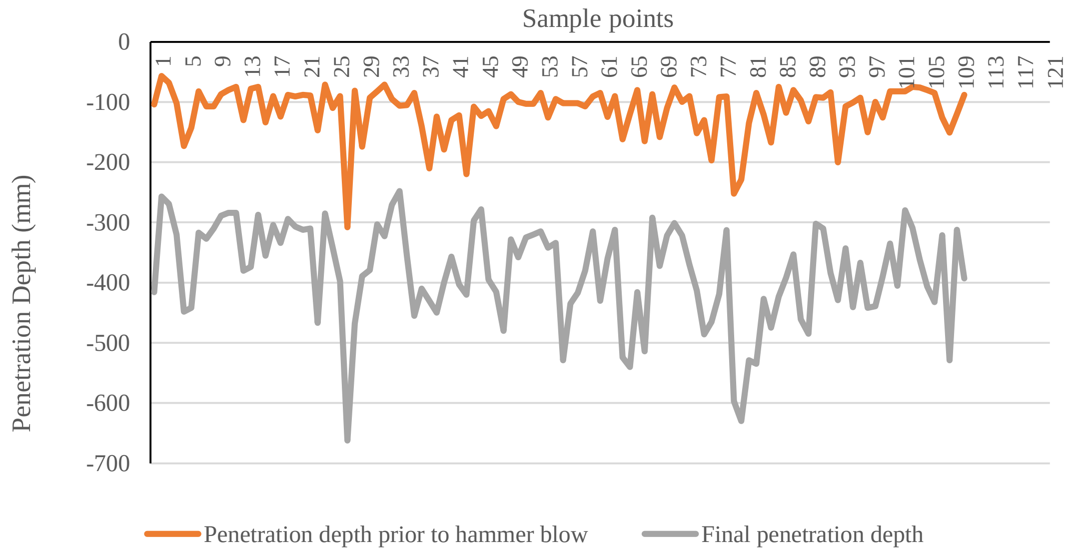

Figure 2. Penetration depth prior to first hammer blow (i.e., initial sinkage, orange) and final penetration depth (gray) measured by dynamic cone penetrometer (DCP), across all sample points where DCP-measurements were possible

Soil penetration depths were measured with a simple handheld Soiltax soil sampler (Haglöf, Sweden, Diameter: 14 mm, length: 70 cm). Maximum soil penetration depth (SPD) was measured after manually pressing down the Soiltax soil sampler in topsoil for as long as possible. Nine soil penetration depth measurements, taken within a square of 4×4 m, were averaged for each sample point.

For validating the cartographic soil type maps, soil samples were collected at 20 cm depth of the topsoil for each sample point for determination of the soil type according to SGU definitions (Karlsson et al., 2021). Descriptive statistics of all field measurements are presented in Table 1.

Table 1. Descriptive statistics of field-measured data, Volumetric water content (VWC), depth penetration index (DPI), soil penetration depth (SPD) and soil type samples including the total number of successful samples taken (n), the mean values (Mean), standard deviation (SD), minimum (Min) and maximum (Max) values for each parameter.

Parameter	n	Mean	SD	Min	Max
VWC (m^3_{water} m^{-3}_{soil})	120	0.25	0.13	0.06	0.60
DPI (mm)	109	52	63	5.3	501
SPD (cm)	116	23	10	1.4	57

2.4. Statistical Analysis

The estimated soil moisture and soil type classes in GIS-based maps were evaluated against VWC and soil type class measurements in the field using Tukey t-tests. To get a linear response, and normally distributed residuals, soil strength, measured as CBR values, had to be transformed using a log transformation before analysis. The log transformed soil strength was analysed with soil moisture (M) and soil type (S), from either GIS-maps or field measurements, as factors using a factorial general linear model (GLM) that can be expressed as:

$$LOG(CBR) = M + S + MxS + \mu \quad (2)$$

The explanatory power of CBR prediction models was evaluated using coefficient of determination (R^2) values. Significant factors were distinguished using a level of $p < 0.05$. The statistical analysis was carried out using statistical software SAS Enterprise guide (Ver 8.3 SAS Institute Inc.).

Soil strength was also modelled using a general linear model (GLM) with soil penetration depth (SPD) as a covariate added to the model in (Equation 2). The models were used to evaluate the suitability of SPD for identifying areas with low soil strength compared to the CBR soil strength models.

Finally, an analyse using a GLM (Equation 3) with soil penetration depth as response and soil moisture (M) and soil type (S), from either GIS-maps or field measurements, as explanatory factors were made to describe the dependencies between SPD and M and S:

$$SPD = M + S + MxS + \mu \quad (3)$$

An α-level of 0.05 was used to decide when the effect of a factor is significant.

3. Results

3.1. Agreement Between Field and Map Estimates

Comparing volumetric water content (VWC) measurements to wet/dry soil moisture estimates in DTW maps and soil types indicated varied conformance between these variables (Figure 3). The VWC significantly differed between the DTW-derived wet and dry soil moisture classes for the clay-silt sediments. There was a logical but insignificant difference in VWC between the DTW-derived wet and dry soil moisture classes for the glacial till and sand sediment soil type classes.

Comparing soil type class estimates in the map against field estimates indicated good agreements for the soil type classes clay-silt and sand sediments, with only 2-8% classification disagreement between the soil samples and the soil type map. The highest disagreement (10%) between map and field estimates occurred for glacial till soils (Figure 4).

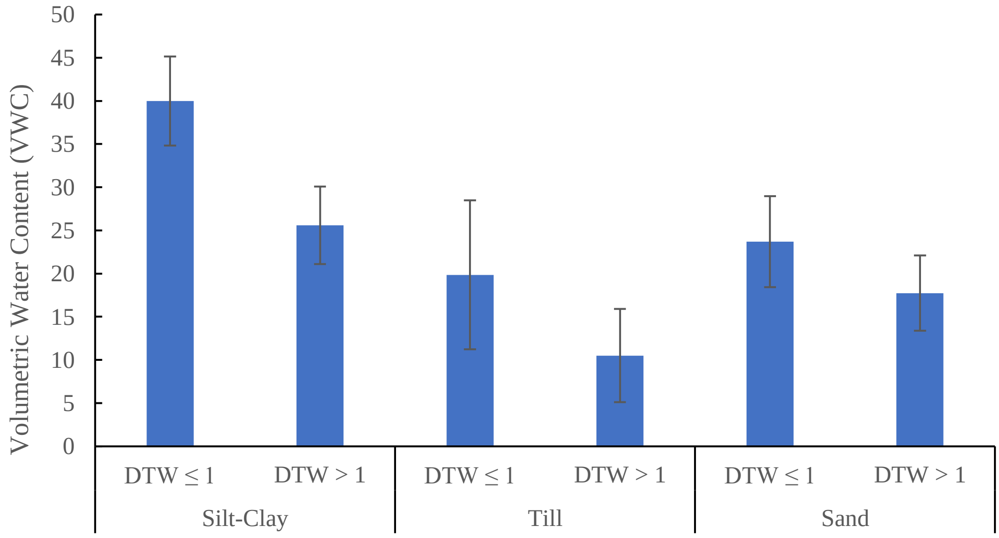

Figure 3. Volumetric water content (m^3_{water} m^{-3}_{soil}) with 95% confidence interval for DTW soil moisture estimates and soil type classes in soil type maps (DTW ≤1 indicates wet soils, DTW>1 dry soils)

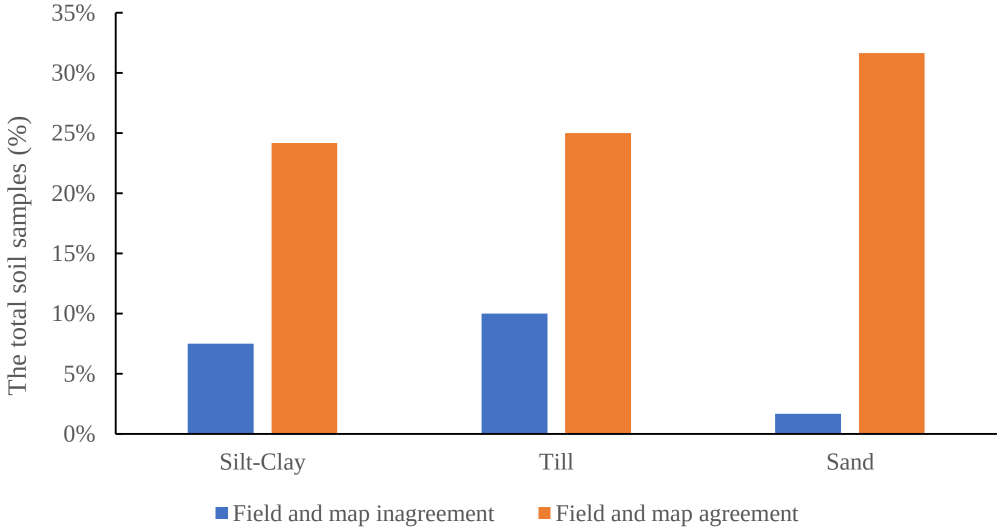

Figure 4. Conformance of soil type class estimates in field versus soil type maps

3.2. Observed Soil Strength

Analysing CBR values measured from 20 cm soil depth (after DCP sinkage due to its weight) over map estimates of soil type and soil moisture indicated significant differences in soil strength for dry vs. wet soil in the sandy soils (Figure 5). For the silt or clay soils, there was a logical difference that could not be proven significant due to the large variability in CBR values for the dry sample points. CBR values and the variation in CBR for glacial till soils are underestimated in the dataset. This is caused by the exclusion of 11 sample points where stones and boulders in the till soil prevented measurements. According to DTW maps, nine of these till soil sample points were situated on dry soils and two of them on wet soils.

3.3. Possibilities to Model Soil Strength

When modelling soil strength as CBR, using data extracted from soil maps and DTW maps, only 11% of the observed variation could be explained by the explanatory variables ($R^2 = 0.11$, Model 1; Table 2). At an α-level of 5% DTW, soil moisture was the only significant factor in the model. This is a too low explained share of variation for a reliable model for soil strength. When soil penetration depth (SPD) was added to explanatory variables, 50% of the observed variation of CBR values could be explained ($R^2 = 0.5$, Model 2, Table 2). Soil type classes and soil penetration depth measured in the field were the significant factors in this case, probably as soil penetration depth helps to explain some of the soil type variations in the material. Soil penetration depth is negatively correlated with CBR (Figure 6). However, as soil penetration depth is a field-estimated variable, model 2 cannot be used solely based on available GIS data.

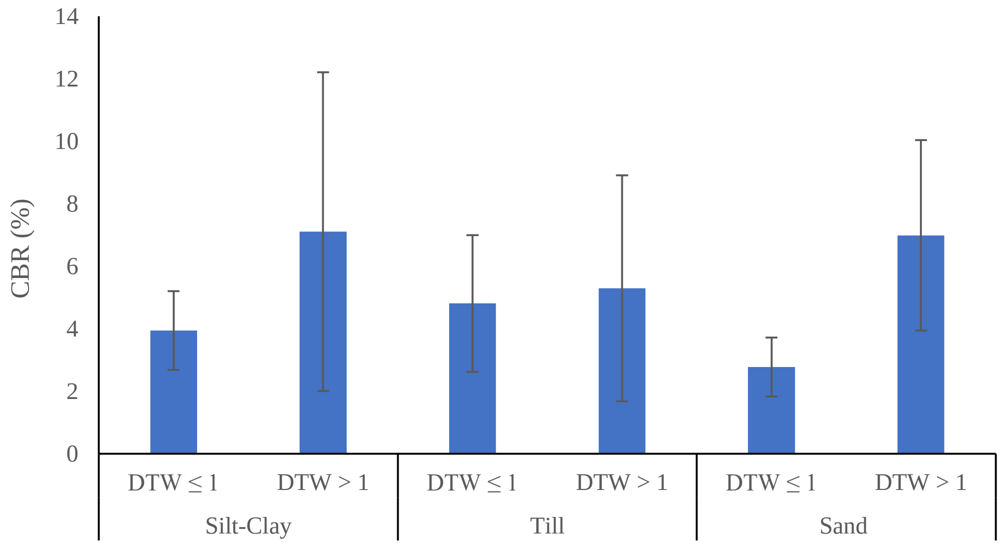

Figure 5. Averaged CBR values with 95% confidence interval over 20 cm sinkage depth, across soil type and soil moisture estimates in corresponding maps (DTW ≤1 indicates wet soils, DTW>1 dry soils). Note that 11 sample points on glacial till soils with stones and boulders at surface were assumed to have maximum strength and were excluded from the diagram.

Table 2. Summary of GLMs describing soil strength measured by California bearing ratio (CBR) and soil penetration depth (SPD) measured by the Soiltax soil sampler. Explanatory variables included were field measured volumetric water content (VWC), soil type class, as well as soil moisture (DTW) and soil type class estimates in corresponding maps.

Model	Dependent variable	Explanatory variables	Coefficient of determination, R^2
1	California Bearing Ratio	DTW*, Map soil type class, DTW × Map soil class	0.11
2	California Bearing Resistance	DTW, Map soil type class*, DTW × Map soil class, Soil penetration depth*	0.50
3	California Bearing Ratio	DTW*, Field soil type class*, DTW × Field soil class	0.13
4	California Bearing Ratio	DTW, Field soil type class*, DTW × Field soil class, Soil depth penetration*	0.23
5	California Bearing Ratio	Volumetric water content (Field soil type class) *, Field soil type class	0.25
6	California Bearing Ratio	Volumetric water content (Field soil type class), Field soil type class, Soil penetration depth*	0.50
7	Soil penetration depth	DTW*, Map soil type class*, DTW × Map soil type class *	0.29
8	Soil Penetration Depth	Volumetric water content (Field soil type class)*, Field soil type class	0.39

* significant at the 0.05 level

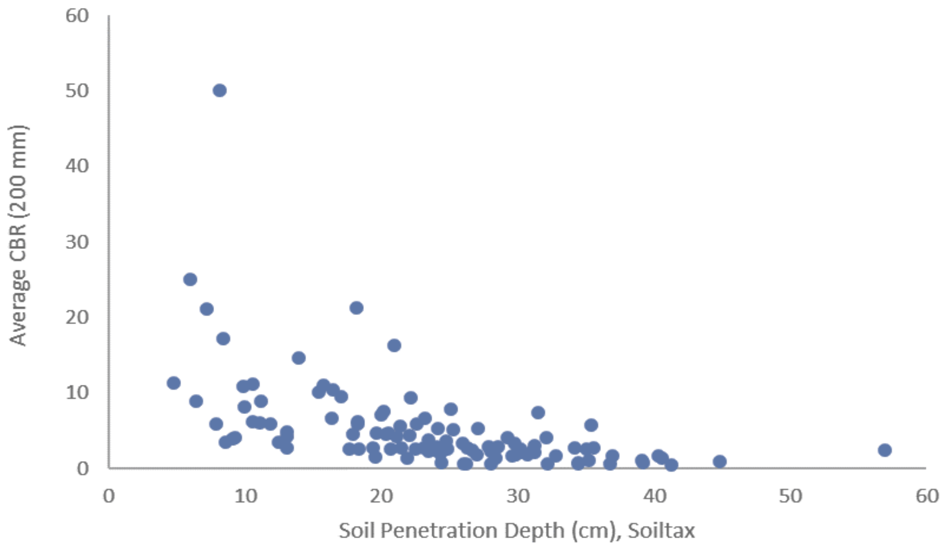

Figure 6. Average CBR value in the top 20 cm of the soil versus soil penetration depth with the Soiltax soil sampler

Using soil type class estimates from the field in combination with DTW soil moisture estimates provides a slight improvement in the model (R^2= 0.13, Model 3, Table 2) compared to using soil map estimates (R^2= 0.11, Model 1, Table 2). Adding soil penetration depth to Model 3 improved the model performance by 10 percentage points (R^2= 0.23, Model 4, Table 2), i.e., less than the improvement between models 1 and 2.

The explanatory power of the CBR models, estimated from field data, VWC and soil type class, was better than the model built on map estimates (Model 5, R^2= 0.25 vs. Model 1, R^2= 0.11, Table 2). Once again, inclusion of soil penetration depth measurements led to improved performance of CBR predictions (Model 6, R^2= 0.5, Table 2).

Modelling soil penetration depth from map soil type class and DTW soil moisture estimates and their interactions as explanatory variables explained 29% of the observed variation in the dataset (Model 7, R^2=0.29, Table 2). Substituting the cartographic data (DTW soil moisture and soil type class) with field estimates enhanced the predictive power of the model by 10 percentage points (Model 8, R^2= 0.39, Table 2).

4. Discussion

Soil strength estimates of forest soils have many possible applications. The obvious one is as a decision support tool to reduce the risk of soil disturbances during forest operations. Another one is as a decision support in planning forest road networks, showing areas where road building is necessary to avoid soil disturbances during logging operations and areas where the soil is strong enough to locate those access roads.

Different conformance levels were found when comparing soil moisture estimates in DTW maps to field measurements of volumetric water content and soil type class estimates in maps to estimates in the field. Volumetric water content significantly differed between dry and wet silt-clayey sediment soils but not in glacial tills or sand sediments. This is probably due to the fact that most soils were Cambisols, containing varying organic matter content in the top layers, and thereby varying water holding capacity. The increased water holding capacity by higher organic matter content was probably more evident in the sand and glacial till soils but had less effect in the silty-clayey sediment soils that have an inherent high water holding capacity. Thus, measuring the organic matter content of the top mineral soil might increase the explanatory power of the statistical models. However, it would not be possible to use such models for predictive purposes since the organic matter content is usually unknown.

Soil type class estimates in the field had the lowest agreement with soil type classes in soil maps for the glacial till soil classes. Glacial till soils have been formed by several glaciation eras in Sweden and consist of unsorted sedimentary deposits with varying particle sizes (0.002 to over 20 mm), including larger stones and boulders. The non-uniform particle size distribution in glacial till soils makes them extra challenging for correct classification in thematic soil maps. For example, some of them have a high content of clay and silt, which gives very different properties to e.g. an out-washed till that only consist of sand and coarser particles. In many soil maps, they are all grouped as till soils. Glacial till soils are the dominant soil type in Swedish forest areas, covering almost 69% of the land (Nilsson et al. 2015). Improved classification of this soil type, describing soil particle size distribution or just separating them by their fine-particle content may considerably enhance the quality of soil maps.

The study area is characterized by variable terrain, where both soil type and moisture vary on a relatively small spatial scale. Thus, many sample points were in proximity of borders between wet and dry soils or between soil types. The variability between measurement points might be smaller in areas with large homogeneous areas with the same soil type or soil moisture classes.

The results of this study indicated possibilities to estimate soil strength in terms of California bearing ratio (CBR) when using soil moisture and soil type class estimates in corresponding GIS-based maps. However, the conformance between maps and field data needs to be improved. Although DTW soil moisture maps had relatively better performance than soil type maps, explaining the observed variation of CBR values, probably due to higher spatial resolution, they could contribute to explaining only 10% of variations in CBR measurements. It can be explained by the nature of DTW maps, such as, applying only surface topography captured in digital elevation models to model the flow channels and associated wet and moist areas nearby. DTW soil moisture estimates do not account for the hydrological properties of the soils associated to soil texture, porosity, and organic matter content, affecting the soil water conditions. Also, as they are static, they neither reflect the changes in VWC due to changing weather conditions (Jones, 2019; Larson et al., 2022). To achieve optimum performances by DTW maps, adjustment of threshold values, both to extract flow channel and to distinguish wet/dry soil moisture conditions, to local, topographical, and temporal weather conditions is recommended (Murphy et al, 2011; Jaeger et al., 2019). Lack of these adjustments may result in over- or underestimations of soil moisture (Lidberg et al., 2020; Ågren et al., 2021), especially in soils with varied particle size distribution like glacial till soils, reducing their functionality in predicting soil strength. The performance of DTW soil moisture maps to estimate soil strength (CBR) in our study improved when field estimated soil type class and/or soil penetration depth with the Soiltax soil sampler were added to CBR estimation models. This indicates the importance of correct soil type maps and that additional data sources are needed to make useful predictions.

As expected, soil strength measured by CBR was the lowest in fine-grained soils with high estimated soil moisture/volumetric water content (Figure 4). Soil strength estimated by CBR was best modelled using field measured volumetric water content, estimated soil type class and soil penetration depth by the Soiltax soil sampler, describing 50% of the observed variation among the soil samples (Model 6). Similar results were achieved when CBR values were modelled using data from soil type maps and DTW maps, together with soil depth measurements of the Soiltax soil sampler as explanatory variables (Model 2). This implies that using of a simple field measurement by Soiltax sampler can enhance the estimation of soil strength using DTW and soil type maps and provides an initial perception of expected soil strength in the field. However, the Soiltax sampler necessitates a field visit and is thus less useful for, in the office, pre-screening of the soil strength in possible harvesting sites.

It is necessary to mention that the standard method for measuring soil strength in terms of CBR using a dynamic cone penetrometer (DCP) is intended for use when measuring road strength. This implies that the initial sinkage of the penetrometer due to its weight is usually negligible. In our case, the initial sinkage varies with soil type and volumetric water content (Figure 2). The initial DCP sinkage was negatively correlated with CBR readings, such as higher in fine-grained moist/ wet soils compared to coarse-grained and dry soils.

The inclusion of new maps containing information about boulder content/surface boulders to all parts of the soil type maps improves the soil strength estimates especially in the glacial till soil classes, leading to improved planning of forest operations. The available data layer visualizing this information needs to include both the whole land coverage and the required resolution for operational planning since it is built on field inventories of varied qualities. Information on large stones or boulders on the soil surface could be more easily extracted using the original point clouds of high-resolution airborne laser scanning data.

5. Conclusion

The five main conclusions of this study are:
1) Field measurements and estimates of soil type classes and soil moisture in GIS-based maps confirm the well-known fact that fine-grained soils have lower bearing capacity when wet. 2) GIS-based soil type and DTW soil moisture maps can be used to estimate soil strength. The accuracy of estimations depends strongly on the quality and accuracy of the input maps. It should be noted that soil moisture content is dynamic and variable according to local weather and hydrological conditions. 3) Soil penetration depth measurement with Soiltax was valuable complementary information to the soil type maps and soil moisture estimates in DTW maps when estimating soil strength in forest soils. 4) The addition of a map layer of boulder frequency information in soil type maps would enhance classification of glacial till soils, thereby enhance estimation of soil strength. 5) GIS-based estimates of soil strength can be used to enable better planning of forest operations and reduce soil disturbances.

Ethics Committee Approval: N/A.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept: S.M., L.H., L.E.; Design: S.M., L.H., L.E.; Supervision: S.M., L.H., L.E.; Resources: S.M., L.H., L.E.; Data Collection: S.M., L.H., L.E.; Analysis S.M., L.H., L.E.; Literature Search: S.M., L.H., L.E.; Writing Manuscript: S.M., L.H., L.E.; Critical Review S.M., L.H., L.E.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors thank Nils & Dorthi Troedssons Research Foundation for funding this project.

Cite this paper as: Mohtashami, S., Hansson, L., Eliasson, L. 2023. Estimating Soil Strength Using GIS-Based Maps - A case study in Sweden, *European Journal of Forest Engineering*, 9(2):70-79.

References

Ågren, A., Lidberg, W., Ring, E. 2015. Mapping Temporal Dynamics in a Forest Stream Network-Implications for Riparian Forest Management. *Forests*, 6(9):2982-3001. https://doi.org/10.3390/f6092982

Ågren, A.M., Larson, J., Paul, S.S., Laudon, H., Lidberg, W. 2021. Use of multiple LIDAR-derived digital terrain indices and machine learning for high-resolution national-scale soil moisture mapping of the Swedish forest landscape. *Geoderma*, 404. https://doi.org/10.1016/j.geoderma.2021.115280

Ågren, A.M., Hasselquist, E.M., Stendahl, J., Nilsson, M.B., Paul, S.S. 2022. Delineating the distribution of mineral and peat soils at the landscape scale in northern boreal regions. *Soil*, 8(2):733-749. https://doi.org/10.5194/soil-8-733-2022

Anon. 1996. User Guide to the Dynamic Cone Penetrometer; Office of Minnesota Road Research. http://www.dot.state.mn.us/materials/researchdocs/User_Guide.pdf.

Anon. 2020. Markfuktighet - Produktbeskrivning (DTW maps - product description). Swedish forestry Agency. https://www.skogsstyrelsen.se/globalassets/sjalvservice/karttjanster/geodatatjanster/produktbeskrivningar/raster-markfuktighetskartaproduktbeskrivning.pdf

Anon 2021a. Soil types 1:25 000-1:100 000. Geological survey of Sweden. https://www.sgu.se/en/products/maps/map-viewer/jordkartvisare/soil-types-125-000-1100-000/

Anon. 2021b. Nya jordartsdata finns tillgängliga: (New soil type maps available). https://www.sgu.se/om-sgu/nyheter/2021/januari/nya-jordartsdata-finns-tillgangliga/

Anon. 2022. National Land Cover Database. https://www.naturvardsverket.se/en/services-and-permits/maps-and-map-services/national-land-cover-database/

Cambi, M., Certini, G., Neri, F., Marchi, E. 2015. The impact of heavy traffic on forest soils: A review. *Forest Ecology and Management*, 338:124-138. https://doi.org/10.1016/j.foreco.2014.11.022

Friberg, G., Bergkvist, I. 2016. Så påverkar arbetsrutiner och markfuktighetskartor körskador i skogsbruket (How operational procedures and depth-to-water maps can reduce damage on soil and water and rutting in the Swedish forestry). Working paper, 904-2016. Uppsala: Skogforsk.

Fisher, R.F., Binkley, D. 2000. Ecology and Management of Forest Soils. New York: Wiley-Blackwell.

Hansson, L., Andersson, M., Johannesson, T. 2022. Bättre brandriskbedömningar, Skogforsk rapport. Uppsala: Skogforsk.

Hillel, D. 1998. Environmental Soil Physics. Academic Press, San Diego, CA.

Hoffmann, S., Schönauer, M., Heppelmann, J., Asikainen, A., Cacot, E., Eberhard, B., Hasenauer, H., Ivanovs, J., Jaeger, D., Lazdins, A., Mohtashami, S., Moskalik, T., Nordfjell, T., Stereńczak, K., Talbot, B., Uusitalo, J., Vuillermoz, M., Astrup, R. 2022. Trafficability Prediction Using Depth-to-Water Maps: the Status of Application in Northern and Central European Forestry. *Current Forestry Reports*, 8:55-71.https://doi.org/10.1007/s40725-021-00153-8

Ilintsev, A.S., Nakvasina, E.N., Högbom, L. 2021. Methods of Protection Forest Soils during Logging Operations (Review). *Lesnoy Zhurnal [Russian Forestry Journal],* 5:92-116. https://doi.org/10.37482/0536-1036-2021-5-92-116

Jones, M.-F. 2019. Mapping soil trafficability by way of temporal hydrology modeling and spatial wet-areas-mapping. PhD-thesis. The University of New Brunswick, Forestry and Environmental Management. Canada. 224 p.

Karlsson, C., Sohlenius, G., Peterson Becher, G. 2021. Handledning för jordartsgeologiska kartor och databaser över Sverige. (Tutorial for Quaternary map viewers and databases over Sweden) Nr. 2021:17, SGU, Geological survey of Sweden, Uppsala.

Labelle, E.R., Hansson, L., Högbom, L., Jourgholami, M., Laschi, A. 2022. Strategies to Mitigate the Effects of Soil Physical Disturbances Caused by Forest Machinery: a Comprehensive Review. *Current Forestry Reports*, 8(1):20-37. https://doi.org/10.1007/s40725-021-00155-6

Larson, J., Lidberg, W., Ågren, A.M., Laudon, H. 2022. Predicting soil moisture conditions across a heterogeneous boreal catchment using terrain indices. *Hydrology and Earth System Sciences*, 26(19):4837-4851. https://doi.org/10.5194/hess-26-4837-2022

Lidberg, W., Nilsson, M., Agren, A. 2020. Using machine learning to generate high-resolution wet area maps for planning forest management: A study in a boreal forest landscape. Ambio. https://doi.org/10.1007/s13280-019-01196-9

Mohtashami, S., Eliasson, L., Jansson, G., Sonesson, J. 2017. Influence of soil type, cartographic depth-to-water, road reinforcement and traffic intensity on rut formation in logging operations: a survey study in Sweden. *Silva Fennica*, 51(5). https://doi.org/10.14214/sf.2018

Mohtashami, S., Eliasson, L., Willén, E. 2018. Effects of soil clay content on rut formation. In: FORMEC 2018, 51st International symposium of Forestry Mechanisation, Madrid, Spain, September 25th-27th, 2018. Technical University of Madrid.

Mohtashami, S. 2022. GIS-based decision support systems to minimise soil impacts in logging operations. Doctoral Thesis. Acta Universitatis Agriculturae Sueciae. No. 2022:67. Faculty of Forest Sciences: Swedish University of Agricultural Sciences (SLU). https://doi.org/https://doi.org/10.54612/a.qq3cqbcknd

Murphy, P.N.C., Ogilvie, J., Connor, K, Arp, P.A. 2007. Mapping wetlands: a comparison of two different approaches for New Brunswick, Canada. *Wetlands*, 27(4):846-854.

Murphy, P.N.C., Ogilvie, J., Arp, P. 2009. Topographic modelling of soil moisture conditions: a comparison and verification of two models. *European Journal of Soil Science*, 60(1):94-109. https://doi.org/10.1111/j.1365-2389.2008.01094.x

Naghdi, R., Solgi, A., Labelle, E.R., Nikooy, M. 2020. Combined effects of soil texture and machine operating trail gradient on changes in forest soil physical properties during ground-based skidding. *Pedosphere*, 30(4):508-516. https://doi.org/10.1016/s1002-0160(17)60428-4

Niemi, M.T., Vastaranta, M., Vauhkonen, J., Melkas, T., Holopainen, M. 2017. Airborne LiDAR-derived elevation data in terrain trafficability mapping. *Scandinavian Journal of Forest Research*, 32(8):762-773.https://doi.org/10.1080/02827581.2017.1296181

Nilsson, T., Stendahl, J., Löfgren, O. 2015. Markförhållanden i svensk skogsmark – data från Markinventeringen 1993-2002 (Soil conditions in Swedish forest soils – data from the Swedish Forest Soil Inventory 1993-2002). Rapport 19. Institutionen för mark och miljö, Sveriges lantbruksuniversitet, Uppsala.

Østby-Berntsen, Ø., Fjeld, D. 2018. Mulighetsstudie lassbærere på bæresvak mark [Feasibility study of forwarders for soils of low bearing capacity], Norskog & Nibio (Norwegian Institute for bioeconomy). (3). Lilleaker.

Piikki, K., Söderström, M. 2017. Digital soil mapping of arable land in Sweden – Validation of performance at multiple scales. *Geoderma*, 352:342-350. https://doi.org/10.1016/j.geoderma.2017.10.049

Salmivaara, A., Launiainen, S., Perttunen, J., Nevalainen, P., Pohjankukka, J., Ala-Ilomäki, J., Sirén, M., Laurén, A., Tuominen, S., Uusitalo, J., Pahikkala, T., Heikkonen, J., Finér, L. 2020. Towards dynamic forest trafficability prediction using open spatial data, hydrological modelling and sensor technology. Forestry: *An International Journal of Forest Research*, 93(5):662-674. https://doi.org/10.1093/ forestry/cpaa010

Schönauer, M., Hoffmann, S., Maack, J., Jansen, M. &, Jaeger, D. 2021. Comparison of Selected Terramechanical Test Procedures and Cartographic Indices to Predict Rutting Caused by Machine Traffic during a Cut-to-Length Thinning Operation. *Forests*, 12(2). https://doi.org/10.3390/f12020113

Swift, L.W., Burns, R.G. 1999. The Three Rs of Roads: Redesign, Reconstruction, and Restoration. *Journal of Forestry* 97(8): 40-44.

Toivio, J., Helmisaari, H.-S., Palviainen, M., Lindeman, H., Ala-Ilomäki, J., Sirén, M., Uusitalo, J. 2017. Impacts of timber forwarding on physical properties of forest soils in southern Finland. *Forest Ecology and Management*, 405:22-30. https://doi.org/10.1016/j.foreco.2017.09.022

Uusitalo, J., Ala-Ilomäki, J., Lindeman, H., Toivio, J., Siren, M. 2020. Predicting rut depth induced by an 8-wheeled forwarder in fine-grained boreal forest soils. *Annals of Forest Science*, 77(2). https://doi.org/10.1007/s13595-020-00948-y

Vepakomma, U., Cormier, D., Hansson, L., Talbot, B. 2023. Remote Sensing at Local Scales for Operational Forestry. In: Boreal Forests in the Face of Climate Change: Sustainable Management. (74): 657-682.

Webster, S.L., Grau R.H., Williams, T.P. 1992. Description and application of dual mass dynamic cone penetrometer. US Army Corps of Engineers, Waterways Experiment Station, Geo technical Laboratory. Instruction Report GL-92-3. Vicksburg, MS. USA.

Wronski, E.B., Murphy, G. 1994. Responses of forest crops to soil compaction. In: Soil Compaction in Crop Production. *Elsevier Science*, 317-342.