Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2022:67
Faculty of Forest Sciences

GIS-based decision support systems to minimise soil impacts in logging operations

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OF AGRICULTURAL
SCIENCES

DOCTORAL THESIS
Umeå 2022

Acta Universitatis Agriculturae Sueciae
2022:67

ISSN 1652-6880
ISBN (print version) 978-91- 8046-010-1
ISBN (electronic version) 978-91- 8046-011-8
https://doi.org/10.54612/a.qq3cqbcknd
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Print: SLU Grafisk Service, Uppsala 2022

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Abstract

Mechanised logging operations can leave negative impacts, like ruts, on forest soils. To avoid this, forestry planners and machine operators need decision support systems that can estimate soil trafficability and help to minimise soil impacts.

The main objective of this thesis was to evaluate whether or how different data, stored in a geographic information system (GIS), can contribute to improved estimation of soil trafficability. Requirements for implementation of soil trafficability maps in forestry GIS applications were also described.

A soil trafficability map, based on several GIS data using multi-criteria decision analysis (MCDA), was proposed in Paper I. Availability and implementation of soil trafficability maps, mainly depth-to-water (DTW) maps, in some European countries, was reviewed in Paper II. Effect of DTW map resolutions to predict soil moisture was evaluated in Paper IV, and the study showed that a spatial resolution of 1–2 m was sufficient. Risk for rutting was analysed in relation to field-measured and GIS data in Papers III, V and VI. GIS data included digital elevation models, DTW maps, hydrological data, soil type, and clay content maps. The results showed that planning forwarder trails and evaluating different alternatives can be improved by using a soil trafficability map. GIS data of high quality is required to achieve acceptable results. Easy or free access to soil trafficability maps facilitate their application in forestry operations. DTW maps, together with other data, can be used to estimate risk for rutting. Clay content maps and hydrological data, at current resolution, need further development but showed potential to predict risk for rutting. More studies are required to estimate temporal and spatial variability of soil trafficability maps. In conclusion, GIS-based decision support systems should be used for planning of logging operations to minimise risk for rutting.

Keywords: soil trafficability, soil moisture, soil texture, rutting

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GIS-baserade beslutsstöd för att minimera markpåverkan vid avverkningar

Sammanfattning

Mekaniserade avverkningar kan påverka skogsmarken negativt, exempelvis genom spårbildning och markpackning. Avverkningsplanerare och maskinförare behöver beslutsstöd för att bedöma markens bärighet och välja körvägar som minimerar markpåverkan.

Syftet med avhandlingen var att undersöka hur olika typer av kartdata, i ett geografiskt informationssystem (GIS), kan bidra till förbättrade skattningar av markens bärighet. De grundläggande kraven för att implementera beslutsstöden i skogliga GIS-applikationer diskuteras också.

Baserat på GIS-data och multikriterieanalys utvecklades en körbarhetskarta i artikel I. Tillgänglighet och implementering av körbarhetskartor i delar av Europa analyserades i artikel II. Hur Depth-to-Water (DTW)-kartornas prestanda påverkas av dess upplösning studerades i artikel IV. Studien visade att en rumslig upplösning på 1–2 m är tillräcklig för att prediktera markfuktigheten. I artikel III, V och VI analyserades risken för spårbildning baserat på fält- och GIS-data. GIS-data som inkluderades i analyserna var digitala höjdmodeller, DTW-kartor, hydrologiska data, jordartskartor och lerhaltskartor. Resultaten visade att GIS-baserade beslutsstöd kan användas för att förbättra planeringen av körvägar och för att utvärdera olika körvägsalternativ. Lättillgängliga körbarhetskartor, baserade på GIS-data med hög kvalitet, är en förutsättning för en storskalig implementering i skogliga applikationer. DTW-kartor, tillsammans med andra data, kan användas för att skatta risken för spårbildning. Lerhaltskartor och hydrologiska data behöver vidareutvecklas då dagens upplösning är för låg. Fler studier behövs för att anpassa beslutsstöden till spatiala och temporala variationer i skogsmarkens bärighet. Slutligen bör GIS-baserade beslutsstöd användas vid avverkningsplanering för att minimera risken för spårbildning.

Nyckelord: markens körbarhet, markfukt, textur, körskador, drivningsplanering

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Dedication

To my family & my parents

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. **Mohtashami, S**., Bergkvist, I., Löfgren, B., & Berg, S. (2012). A GIS approach to analyzing off-road transportation: a case study in Sweden. *Croatian Journal of Forest Engineering*, 33(2), 275-284.

II. 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(1), 55-71.

III. **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).

IV. **Mohtashami, S.**, Eliasson, L., Hansson, L., Willén, E., Thierfelder, T., & Nordfjell, T. (2022). Evaluating the effect of DEM resolution on performance of cartographic depth-to-water maps, for planning logging operations. *International Journal of Applied Earth Observation and Geoinformation*, 108, p.102728.

V. **Mohtashami, S**., Thierfelder, T., Eliasson, L., Lindström, G., & Sonesson, J. (2022). Use of hydrological models to predict risk for rutting in logging operations. *Forests*, 13(6), p.901.

VI. **Mohtashami, S.**, Eliasson, L., & Willén, E. (2018). Effects of soil clay content on rut formation. In: Proceedings of *FORMEC*– 51st *Edition of International Symposium of Forest Mechanisation*, 24th-28th September 2018, Madrid, Spain.

Papers I-VI are reproduced with the permission of the publishers.

The contribution of Sima Mohtashami to the papers included in this thesis was as follows:

I. Participated in formulation of the original idea, literature review, modelling, analysis of the results, writing the manuscript, coordination between authors*.

II. Contributed to literature review, summarised Swedish experiences and literature, assisted the main author in writing these parts, and commented on the rest of the manuscript in collaboration with co-authors.

III. Participated in the formulation of the research question, literature review, calculations, assisted in analysis of results, writing the manuscript, coordination between authors.

IV. Proposed the original idea, literature review, study design, collaborated in field data collection, prepared spatial data (DEM), calculations, analysis of the results, writing the manuscript, coordination between authors.

V. Literature review, data preprocessing before calculations, calculations, analysis of results, writing the manuscript, coordination between authors.

VI. Participated in the formulation of original idea, literature review, calculations, participated in analysis of results, writing the manuscript.

* *Parts of Paper I were previously published in Sima Mohtashami's master's thesis (Mohtashami 2011). In Paper 1, the literature review and scope of the study are much more extensive compared to the master's thesis and includes practical aspects of forestry operations in Sweden. Writing and reporting the study results in a scientific style, acceptable for publishing in a peer-reviewed journal, was also the extra work involved in Paper I compared to the master's thesis.*

Abbreviations

ALS	Air-borne Laser Scanning
BMP	Best Management Practice
CAN bus	Controller Area Network bus
DEM	Digital Elevation Model
DTM	Digital Terrain Model
GIS	Geographic Information System
HYPE	Hydrological Prediction for the Environment
LiDAR	Light Detection and Ranging
MCDA	Multi Criteria Decision Analysis
SGU	Geological Survey of Sweden
S-HYPE	Swedish Hydrological Predictions for the Environment
SMHI	Swedish Meteorological and Hydrological Institute
UAV	Unmanned Aerial Vehicle

1. Introduction

1.1 Logging operations in Sweden

Ground-based roundwood harvesting can be performed using either Whole-Tree/Tree-Length (TL) or Cut-To-Length (CTL) methods (Lundbäck 2022). Almost all roundwood harvesting in Sweden is fully mechanised and performed with the CTL method, incorporating a single grip harvester and a forwarder (Lundbäck *et al.* 2021a). The harvester fells, processes, and measures the length and diameter of the cut trees and marks the logs according to assortment. The forwarder collects and carries the logs out to landing areas at roadsides for onward truck transportation.

The total annual harvested volume of roundwood from final fellings in Sweden increased from 182 to 257 m^3 solid wood (with bark) per hectare from 1984 to 2018. In the same period, the total annual harvested forest area was fairly stable at around 200 000 ha, although the area suddenly increased to 231 000 ha in 2018 (Anon 2021).

Mechanised logging operations constitute 40% of the total direct cost of forest management in Sweden (Eliasson 2020). To recoup investment costs and keep the productivity of the machines at acceptable levels, harvesters and forwarders need to operate all year round. The great interest for biobased-material from forest, to substitute fossil-based material and energy and mitigate the effects of climate change, is increasing the intensity of forest management. Forestry operations are therefore conducted even when soil conditions are unfavourable. This can increase the risk of soil impacts during logging operations. A risk that needs to be minimised through detailed planning before and during the operations.

1.2 Soil impacts of mechanised logging operations

Over time the machines used for mechanised logging operations have become heavier (Horn *et al.* 2007; Nordfjell *et al.* 2019). The average total weight of the machines used in Swedish forestry has increased from 20.4 to 31.8 Mg, from the 1970s to 2010 (Nordfjell *et al.* 2019). Off-road traffic of heavy machines may cause soil impacts in forms of rutting and compaction, which change the soil's physical properties (Horn *et al.* 2007; Hansson 2019), and consequently affect the chemical and microbial processes in the soil (Kozlowski 1999; Jourgholami *et al.* 2019). Impacted soil areas can constitute 10-70% of logging sites in ground-based mechanised logging operations (Wronski & Murphy 1994; Eliasson 2005; Cambi *et al.* 2015; Naghdi *et al.* 2016). In a survey study of logging areas close to lake Mälaren in Sweden, it was reported that rutting was visible in 89% of logging sites (Mohtashami *et al.* 2016). The ruts had an average depth of 5–25 cm over the whole area of logging sites but were deeper (25–50 cm) in areas close to surface waters.

1.2.1 Rutting

Rutting is a visible impact of mechanised logging operation on soil and occurs when compression and shear forces caused by the machines create tracks in the soil. When soil moisture content exceeds a critical level, the elastic behaviour of the soil is substituted with a plastic one. An extra applied stress leads to displacement of the soil and creation of ruts at this point (Horn *et al.* 2007). Deep ruts expose the mineral soil and increase the risk for surface runoff, erosion, and loss of fertile soils (Startsev & McNabb 2000; Ilintsev *et al.* 2021; Labelle *et al.* 2022). Ruts may become waterlogged in flat areas, and/or act as flow channels in sloped terrains (Wronski & Murphy 1994; Labelle *et al.* 2022). Risk for erosion and transport of eroded soil particles to nearby surface waters increase with rutting, which disturbs aqueous organisms (Hansson 2019; Ring *et al.* 2021). Waterlogged ruts connecting to streams facilitate mobilisation of soil-bound methyl mercury, increasing its concentrations in aquatic environments and affecting the biota and food-web structures there (Eklöf *et al.* 2018; Bishop *et al.* 2020). Rutting may also cause costly interruptions to logging operations (Ala-Ilomäki *et al.* 2020) and disturb the recreational value of the forest for the general public (Gundersen *et al.* 2015).

This thesis mainly covers logging-induced soil impacts in the form of rutting and provides examples of planning tools to minimise them. The risk for rutting has been used as an indicator for identifying areas with low trafficability.

1.2.2 Soil compaction

Soil compaction is another, usually invisible, impact of mechanised logging operations, occurring when vertical/horizontal or shear stresses change the soil structure (Alakukku *et al.* 2003). The total porosity and pore connectivity are reduced in compacted soil, impacting air permeability and hydraulic conductivity, and increasing water holding capacity (Ampoorter *et al.* 2012; Cambi *et al.* 2015; Hansson *et al.* 2018).

Productivity of forest sites, seedling establishment, and tree growth may be reduced in compacted soils due to impeded root activities when penetration resistance exceeds 2.5 MPa (Kozlowski 1999; Cambi *et al.* 2015). The effects vary, however, between tree species (Wronski & Murphy 1994; Cambi *et al.* 2015), in different soil textures (Ampoorter *et al.* 2011; Mariotti *et al.* 2020; DeArmond *et al.* 2021), and over time (Passauer *et al.* 2013; Slesak *et al.* 2017). Soil compaction, for example, may enhance water availability in coarse-textured soils and thereby contribute to improved tree growth (Agrawal 1991; Wronski & Murphy 1994; Mariotti *et al*. 2020).

The effects of soil compaction in fine-textured soils may be alleviated by high biological activity and more frequent wet-dry, freezing and thawing cycles (Cambi *et al*. 2015; Pousse *et al.* 2021) but vary depending on site and weather condition (Lang *et al.* 2016). However, the effects are more prolonged on coarse-textured soils (Wronski & Murphy 1994; Hansson 2019), especially at high removal rate of organic matter (Slesak *et al.* 2017). Soil amelioration methods, e.g., site scarification and liming of acidic soils, prior to new forest establishments have been reported to be effective in loosening compacted soil (Passauer *et al.* 2013; Pousse *et al.* 2021).

1.3 Factors affecting level of soil impacts

The most critical factors affecting severity and extent of soil impacts, rutting, and soil compaction, in logging operations can be categorised as: 1) nature given condition, 2) utilised forestry machines, and 3) operations of forestry machines (Wronski & Murphy 1994; Ilintsev *et al.* 2021; Labelle *et al.* 2022).

1.3.1 Nature given condition

The nature given condition largely determines the bearing capacity of forest soils, and thereby indicates its trafficability for off-road transportation. Important natural conditions affecting the soil's bearing capacity include soil texture, slope, and soil moisture content.

Soil texture, i.e., particle size and distribution, and how it affects load bearing capacity of forest soils, has been examined in several research studies (Dymov 2017; Slesak *et al.* 2017; Naghdi *et al.* 2020). Medium- to fine-textured mineral soils, which generally have low bulk densities, are more prone to compaction than coarse-textured soils with higher bulk densities (Hillel 1998; Fisher & Binkley 2000; Naghdi *et al*. 2020). However, their strength varies considerably, depending on the soil moisture content and underlying terrain condition, i.e., slope (Naghdi *et al*. 2020). The presence of cohesion particles (< 0.06 mm) such as clay and silt leads to more easily compactable soils during moist or wet conditions (Hillel 1998). Their fractions in mineral soil can therefore be used as indicators to determine the degree of soil compactability (Hansson *et al*. 2018; Heiskanen *et al*. 2018; Heiskanen *et al*. 2020).

Sloping terrain may cause the load distribution of forestry machines to become uneven, increasing the risk for rutting and soil compaction (Labelle *et al*. 2022). Despite varying terrain conditions in Sweden, 94.6% of forested areas have slopes of less than 15% (Lundbäck *et al*. 2021b).

Soil moisture content is also an important factor affecting soil bearing capacity, and thereby the level of soil impacts by forestry machines (McNabb *et al*. 2001; Alakukku *et al*. 2003; Jourgholami & Majnounian 2011). Soil moisture content is therefore a factor that can be used to predict risk for soil impacts (Allman *et al*. 2016), especially in fine-textured soils (Uusitalo *et al*. 2019; Uusitalo *et al*. 2020). Higher soil moisture content implies weaker forces among mineral soil particles and reduces the soil bearing capacity (Hillel 1998). This effect is highly dependent on soil particle size distribution, decreasing with increased particle size (Østby-Berntsen & Fjeld 2018), Figure 1. In a study area in Finland, a similar number of machine passages over comparable forwarder trails and different soil moisture conditions created deeper ruts at higher moisture content (Toivio *et al*. 2017).

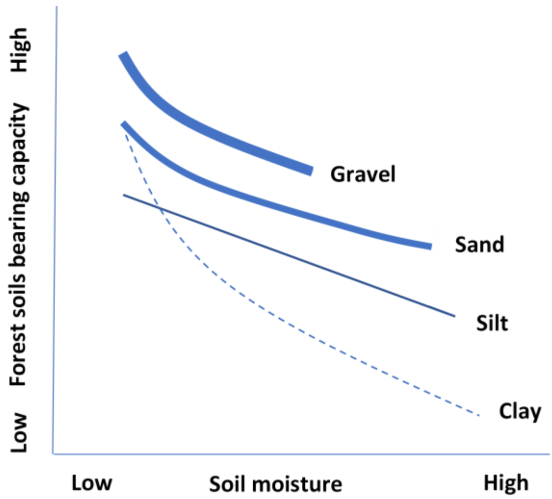

Figure 1. Variation in forest soil bearing capacity with soil moisture content for a number of sediment soils, after Østby-Berntsen and Fjeld (2018) and Björheden *et al*. (2022).

While slope and soil texture vary spatially across the landscape, the soil moisture content is attributed to both spatial and temporal variations (Seibert *et al*. 2007), making estimation of soil bearing capacity challenging. Soil moisture content varies between different periods of the year and different altitudes. During early spring (when snow and frozen soils start to melt), late autumn, or after frequent rain periods in summer, most of the forest soil is moist or wet and thereby sensitive to impact by moving forestry machines. During cold winter periods, when soil is frozen, the soil bearing capacity and trafficability improves considerably in otherwise sensitive soils (Susnjar *et al.* 2006; Mattila & Tokola 2019). The effects of global warming, however, are creating more fluctuations in soil moisture and the periods when soils are frozen (Lehtonen *et al*. 2019).

Other factors, such as organic matter content (Wronski & Murphy 1994), presence of stones and blocks (Niemi *et al*. 2017), and tree root systems (Cambi *et al.* 2015) also affect the soil bearing capacity and thereby the level of rutting and soil compaction.

In this thesis, soil moisture and texture (Papers I, III, V, VI), slope and aspect (Paper I) derived from available GIS data layers were analysed in relation to rut formations and/or soil trafficability.

1.3.2 Forestry machines

Heavy forestry machines often cause high ground contact pressure during mechanised logging operations. Reduced contact pressure between machine and ground can be achieved by either reducing the weight (and loading capacities) of the machines, or increasing the machine/soil contact area. Jansson and Wästerlund (1999) reported that the ruts caused by light machines (5-9 Mg) decreased by 40% after one year in sandy loam soils. Similar effects were reported when lighter machines (2 vs. 18 Mg) were used in final felling operations (Ampoorter *et al.* 2010). A lighter forwarder, however, means lower load capacity, which in practice leads to increased number of machines passages to collect the harvested roundwood. There is therefore a trade-off between suitable weight of machine and number of machine passages (Cambi *et al.* 2015).

The machine/soil contact area can be increased in different ways, e.g., wider tyres (Haas *et al.* 2016), reduced tyre inflation pressures (Alakukku *et al.* 2003; Eliasson 2005; Farhadi *et al.* 2019), using bogie tracks (Bygdén *et al.* 2004; Edlund *et al.* 2013; Cambi *et al.* 2016; D'Acqui *et al.* 2020), metal or rubber tracks (Gelin & Björheden 2020), and/or by adding auxiliary axles (Fjeld & Østby-Berntsen 2020). However, these techniques must be economically feasible to make them applicable in practical logging operations (Suvinen 2006b).

1.3.3 Operation of forestry machines

In addition to machine type, the operation of forestry machines plays an important role on level of soil impacts during logging operations. Increased traffic intensity, especially on fine-textured soils with high moisture content, increases the risk for compaction and deep ruts during logging operations (McNabb *et al.* 2001; Eliasson & Wästerlund 2007; Zenner *et al.* 2007; Toivio *et al.* 2017). Sirén *et al.* (2019) related rut depth to traffic intensity, soil moisture and soil strength, as measured by penetration resistance. The depth to which the negative impacts are transmitted is also affected by traffic intensity, with the first few machine passages having greatest impact on the soil (McNabb *et al.* 2001; Han *et al.* 2006). The effects of operator skill, velocity of passing machines, and radius of the curvatures when turning are among other machine/human factors affecting the level of soil impacts, but these have not been extensively studied so far (Jamshidi *et al.* 2008; Cambi *et al.* 2015).

Forwarder trails in a final felling logging site in Sweden are planned mainly by the machine operators. The planning routines, the amount of time spent in the field prior to planning (Willén & Andersson 2015), and level of expertise vary among practitioners. The forwarder trail systems consist of strip trails, main trails and main base trails based on the number of machine passages, 0–5, 5–10, and > 10 passages respectively (Figure 2). The average forwarding distances in final fellings in northern and southern parts of Sweden are about 467 and 345 m, respectively (Brunberg 2017). The machine operators' ambition is to locate the main base trails on areas with high ground bearing capacity. They also aim to reinforce the trails with logging residues where the ground bearing condition is presumed to be low.

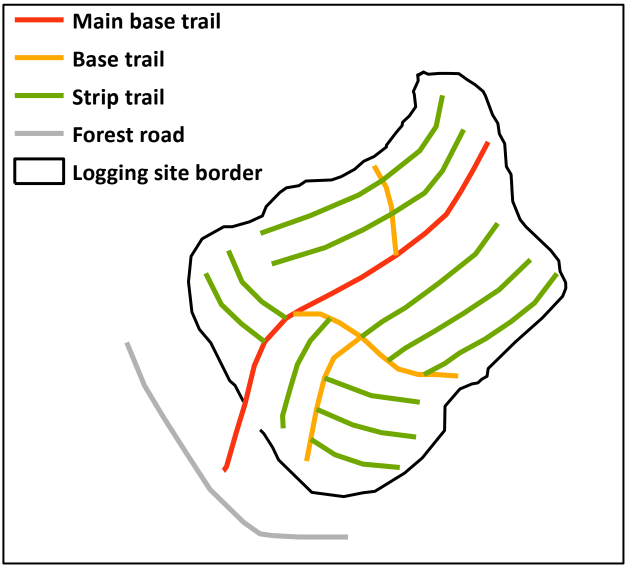

Figure 2. Schematic layout of forwarders' trail system in a final felling site.

1.4 Measures to minimise soil impacts

Various operative and planning measures, guidelines, and instructions are used to help machine operators minimise soil impacts during logging operations.

Restricting off-road traffic to confined trails is an example of an operative measure to control the soil impacts (Chamen *et al.* 2003). Off-road driving on permanent trails, as practiced in some forest areas in central Europe (Schäffer *et al.* 2012), is another way to reduce the impacted area (Horn *et al.* 2007; Picchio *et al.* 2020; Labelle *et al.* 2022). Reinforcement of forwarder trails with slash, i.e., logging residues after CTL operations, reduces the ground contact pressure and is an effective method to minimise soil impact (Eliasson & Wästerlund 2007; Labelle & Jaeger 2012). Placement of logging mats (Ring *et al.* 2021), or mulch (Labelle *et al.* 2022) on forwarder trails is another effective way to improve forest soil bearing capacity. Application of logging residues on forwarder trails after temporary machine passages, to close water crossings, has been shown to be a cost-effective best management practice (BMP) in the US to reduce total suspended solids transported to surface waters (Wear *et al.* 2013). Proper implementation of BMPs, in harvesting sites, was shown to be a significant factor affecting erosion rate in these sites (Garren *et al.* 2022).

Decision support systems to improve the choice of tyre and wheel systems based on actual soil strength, using data on tyre contact area, soil type, initial bulk density, and water content are examples of models developed for application in agricultural fields (Canillas & Salokhe 2002; Alakukku *et al.* 2003; Chamen *et al.* 2003). Rut depth prediction models based on penetration resistance and soil moisture for different soil textures have been developed to support decisions regarding planning of logging trails in forestry applications (Sirén *et al.* 2019; Uusitalo *et al.* 2019). A terrain classification system was developed in Sweden (Anon 1969), mainly to estimate terrain accessibility, using information like ground condition, surface structure and slope. This system can be helpful for scheduling sites for logging operations but can be challenging when planning trails on individual sites if not combined with high-quality GIS data.

Guidelines and instructions for use in decisions on when to harvest sites is another measure to minimise soil impacts (Wronski & Murphy 1994; Chamen *et al.* 2003). Sites with large areas of sensitive soils, for example, can be planned for winter or dry summer harvesting, when soil bearing capacity has improved due to frozen or dry soils.

Free access to wet area maps (since 2015), providing instructions for using wet area maps in practical forestry operations (Ring *et al.* 2020), training, and informing forestry operators about new tools are among other measures by the forestry sector aiming to minimise impacts of logging operations in Sweden.

1.5 GIS-based decision support systems

GIS-based Decision Support Systems (DSS) are used as effective planning tools in several disciplines, providing a high level of user interactivity and improved visualisation. Improved computational powers in recent years enable integration of several data sources and new forms of information, predicting, for example, soil trafficability in complex terrain conditions in forest landscapes. GIS-based soil trafficability DSS may facilitate implementation of measures to minimise soil impacts before and during logging operations.

1.5.1 Airborne LiDAR-based digital elevation models

Use of an airborne light detection and ranging (LiDAR) technique, also known as airborne laser scanning (ALS), makes it possible to build high-resolution digital elevation models (DEM) across forest landscapes. The laser beams can penetrate through tree and vegetation canopies and reach/reflect from the forest ground (Stereńczak & Kozak 2011), a feature not found in other scanning techniques like photogrammetry scanning (Uysal *et al.* 2015).

Detailed DEMs describe the topographic condition of the terrain, e.g., elevation and slope, and can be used to predict different soil properties (McBratney *et al.* 2003; Söderström *et al.* 2016) or delineate sensitive soils, in gently sloping or steep forest landscapes. Using multi-criteria decision analysis (MCDA), DEM-based topographic data (elevation, and slope) can be merged with other GIS data, like soil type maps, to form soil trafficability maps. Depending on the available GIS infrastructure, these maps can be adapted to the actual terrain condition.

1.5.2 DEM-based soil moisture indexes

Soil moisture indexes, based on elevation and slope data layers, i.e., surface topography, have been developed to predict water flow paths in terrains. Soil moisture prediction models are one important input for predicting soil trafficability. Topographic wetness index (TWI), for example, relates the upland areas to local slope at a given spatial extent, and provides a measure of soil wetness (Beven & Kirkby 1979). TWI has been studied in several forest terrain conditions (Grabs *et al.* 2009; Murphy *et al.* 2009) and was shown to be scale dependent (Ågren *et al.* 2014). TWI was shown to perform better for large-scale applications (Sørensen & Seibert 2007; Buytaert *et al*. 2008).

Depth-to-Water (DTW) is another index estimating soil moisture by calculating the vertical depth of each landscape unit (presented in pixels/cells) down to a modelled ground water level (Murphy *et al*. 2006). The DTW index has been studied in many different terrain conditions, including flat and hilly terrains (Schönauer *et al.* 2021b). DTW was shown not to be sensitive for spatial scale (Ågren *et al*. 2014), and improved mapping of flow channels, their associated wet areas, and wetlands (Murphy *et al*. 2007; Murphy *et al*. 2009; Ågren & Lidberg 2019). The DTW index can be adapted to develop rut depth prediction models (Campbell *et al*. 2013), or to improve optimisation models suggesting landing locations and trail layouts for logging operations (Flisberg *et al*. 2021).

Increased access to high-resolution DEM data and processed GIS data facilitates the development of more detailed soil trafficability maps. However, such maps vary in terms of implementation across European forest sectors. Despite great improvements in estimating soil moisture with DTW maps, they still require further development. One shortcoming of DTW maps is that the estimation of soil moisture condition is based on solely topographic conditions. DTW maps thereby provide a static image of the soil moisture condition, missing the actual temporal variation across season and landscape. One possible approach to introducing dynamic estimation of soil moisture is to adjust threshold values in DTW maps to reflect weather and regional conditions. Another alternative is to use hydrological models, to provide more dynamic estimation of soil moisture, including its temporal variation. Maps that present estimated soil moisture by combining several different GIS and in-field measured data using machine learning techniques has also been produced (Lidberg *et al.* 2020; Ågren *et al*. 2021).

1.5.3 Soil moisture using hydrological models

Hydrological models describe water fluxes, using landscape hydrological connectivity together with spatial and temporal variability (Launiainen *et al.* 2019). The advantageous inclusion of weather data in most hydrological models enables soil moisture content to be estimated dynamically, making them a potential tool for soil trafficability predictions. Soil moisture content and frost conditions are directly influenced by meteorological conditions and play a significant role in determining soil trafficability (Vega-Nieva *et al.* 2009; Campbell *et al.* 2013).

Jones and Arp (2019) used the hydrological model ForHyM (Arp & Yin 1992) to map the pore-filled soil moisture content, combined with field and spatial data from four forest sites in Canada, to develop a framework for soil trafficability. Salmivaara et al. (2020) also integrated a hydrological model, SpaFHy (Launiainen *et al.* 2019) with spatial data and sensor technology to improve soil trafficability predictions in a study site in Finland. Despite permissible approaches, the results of these studies were site specific and require further evaluation with spatial variation prior to large-scale forestry implementations.

A nationwide hydrological model (S-HYPE) has been developed by the Swedish Meteorological and Hydrological Institute (SMHI) (Lindström *et al.* 2010). Using GIS data, including meteorological data from 37 000 sub-basin areas, S-HYPE simulates water and nutrient fluxes across the whole country. S-HYPE provides several other attributes in addition to soil moisture estimation, such as frost depth and soil temperature, which could be relevant in assessing the risk for rutting in logging operations.

1.5.4 Soil texture using digital soil mapping

Most land areas in Sweden are covered with geologically young sedimentary deposits, approximately 10 000–12 000 years old, formed by the Weichselian glaciation, melting of the inland icecap and subsequent land uplift, and sea level fluctuations. Glacial till is the dominant sedimentary deposit in Sweden, covering 75% of the land area. Peat (13%), and bedrock and other deposits, like glaciofluvial and post-glacial sedimentary deposits (12%), cover the rest of Swedish landscape (Nilsson *et al*. 2015). Till is an unsorted mineral soil with particle sizes ranging from <0.002 mm to 20 mm and contains larger stones and boulders.

Developing detailed and precise digital maps that describe soil type is challenging. The nationwide soil type maps, or Quaternary soil deposit maps, have varying quality and resolutions from the south to the north of Sweden (1:25 000–1:750 000). These soil type maps have few soil classes, especially in low-resolution areas in northern Sweden, a cause of uncertainty when planning forestry operations. Large areas of the forest landscape are classified as till soils in these maps. However, the ground bearing capacity of till soils varies considerably, depending on dominant particle size and presence of stones and gravels. Higher precision in soil type maps is therefore required to improve the functionality of soil trafficability maps and minimise soil impacts.

New and efficient techniques like Digital Soil Mapping (DSM) enables field and laboratory measurements to be combined to improve estimation of soil particle size distribution (Minasny & McBratney 2016; Söderström *et al.* 2016). This also enables calculations of the uncertainties of the estimations. A digital soil map over arable land in Sweden has been developed for applications in precision agriculture (Söderström *et al.* 2016; Piikki *et al.* 2017). The accuracy of these maps for forest soils has not been evaluated, so their value in planning of logging operations is unknown.

2. Objectives

Mechanised logging operations can leave impacts on forest soils. Forestry planners and operators need decision support systems to improve the decisions on where to drive and when to perform logging operations to minimise soil impacts. Soil trafficability maps are examples of GIS-based decision support systems that can be used to minimise soil impacts.

The overall objective was to evaluate whether or how different GIS data can contribute to reliable estimation of soil trafficability or risk for rutting. Requirements to make such systems available for forestry applications are also described. The specific objectives for each paper (I-VI) were therefore to:

- Develop a soil trafficability map to plan and evaluate different forwarder trail layouts (I).
- Provide an overview of status of soil trafficability maps, mainly DTW maps, in Sweden and across Europe (II). Requirements to implement them in practical forestry were discussed.
- Examine whether DTW maps, together with field and GIS data, can predict risk for rutting (III).
- Examine whether higher DEM resolution, comparing 2, 1 and 0.5 m, can lead to better prediction of soil moisture condition by DTW maps (IV).
- Examine whether application of hydrological data, reflecting actual soil conditions, can improve prediction of risk for rutting (V).
- Examine whether clay content maps, based on digital soil mapping, can be used to identify soils with low bearing capacity (VI).

3. Materials

3.1 Study areas

The thesis comprises five papers covering logging sites in different parts of Sweden (Figure 3), and a review paper covering Northern and Central Europe.

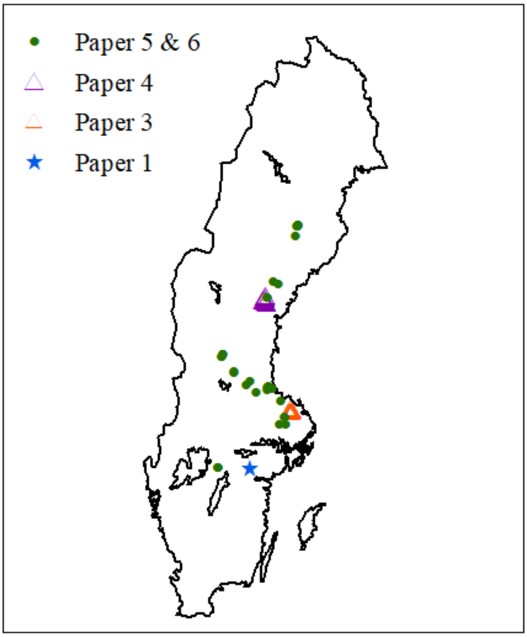

Figure 3. Distribution of studied logging sites, in Papers I, III, IV, V & VI.

Paper I included one logging site (6.7 ha), located in Selesjö, south-east Sweden. The logging site belonged to the forest company Bergvik Skog AB.

Paper II reviewed the status of soil trafficability maps in countries in Northern and Central Europe with large forestry sectors (Sweden, Norway, Finland, Latvia, Austria, France, Germany, Poland).

Paper III included 16 logging sites located in Österbybruk, south-east Sweden. These sites, also owned by Bergvik Skog AB, were harvested between October 2011 and March 2013, and surveyed in summer 2013. Field data was collected on forwarder trails and ruts.

Paper IV included eight logging sites, located in north-east Sweden. The logging sites, which belonged to the forest company SCA AB, were harvested during spring 2020 and surveyed during Sept-Nov 2020. Field data was collected on soil moisture classes at these logging sites.

Paper V included 27 logging sites, spread from southern to northern Sweden. The logging sites belonged to six forestry companies and were part of a previously field-surveyed database. The logging sites were surveyed in 2015, after being harvested at various times of the year in 2014–2015. Field data was collected on forwarder trails and ruts.

Paper VI included four sites, located in north-east Sweden, where estimated clay content maps were available. The logging sites were part of the surveyed data in Paper V.

3.2 Field data measurements

The data measured in the field included information on forwarder trails and ruts (Papers III, V, VI), and estimated soil moisture (Paper IV).

Ruts were defined as machine tracks where mineral soil was exposed, having a minimum depth of 10 cm and minimum length of 1 m. Rut length and depth were categorised into the predefined classes shown in Table 1.

Table 1. Rut depth and length classifications, used in Paper III, V & VI.

Rut length classes	**Rut length (m)**	**Rut depth classes**	**Rut depth (cm)**
1	1 – 5	1	10 - 20
2	6 – 10	2	21 - 50
3	11 – 20	3	> 50
4	> 20		

The number of machines passages along forwarder trails were also estimated in the field. Three and four levels of forwarder trail classes were defined and used in Paper III and Papers V & VI respectively (Table 2).

Table 2. Forwarder trail classification, based on number of machine passages. Four classes in Study III (left), and three classes in V & VI (right).

Forwarder trail classes	**Machine passages**	**Forwarder trail classes**	**Machine passages**
Small strip trails	1 – 2	Strip trails	1 – 5
Strip trails	3 – 5	Main trails	6 - 10
Main trails	6 - 10	Main base trails	> 10
Main base trails	> 10		

Field data on ruts and forwarder trails was collected using field computers (Yuma Trimble/iPads of different models in Paper III/ Paper V & VI). Field data on soil moisture classes was collected at sample points along forwarder trails at logging sites (Paper IV). Soil moisture was categorised as follows: 1) wet, 2) moist, 3) mesic-moist, 4) mesic, and 5) dry, according to definitions in National Swedish Forest Inventory instructions (Anon 2013). Vegetation cover, soil profile characteristics, and humus layer thickness were assessed visually at the sample points to estimate the soil moisture class, reflecting the average soil moisture condition. Full definitions and characteristics of each soil moisture class are provided in Table A1 of Paper IV. A minimum sample distance of 50 m was used to prevent autocorrelative effects among the field-measured data.
An iPad Air 2 equipped with a GNSS receiver (Global Navigation Satellite System) was used for data collection, with a positioning accuracy of around 2.5–5 m on clear-cut sites (Hannrup *et al.* 2020).

3.3 GIS data

Soil type maps for Sweden, also known as Quaternary deposit maps, are provided by the Geological Survey of Sweden (SGU) and depict the soil texture condition of the 50 cm topsoil. SGU's Quaternary deposit maps were used to determine soil types in all studies, except those in Papers II & VI.

All digital elevation models (DEM) used in this thesis were derived from Airborne Laser Scanning (ALS). Data providers, however, varied in the different studies. DEM (2 m) was provided by the Swedish Mapping, Cadastral and Land Registration authority (Lantmäteriet), and was used in Papers III, IV, V, VI. DEM (1 m) was created by the author, using point clouds from the Swedish Mapping, Cadastral and Land Registration Authority (Paper IV). DEMs (0.5 m) were provided by Foran Remote Sensing AB and SCA AB, and were used in Papers I & IV, respectively.

The Depth-to-Water (DTW) maps used in Paper III were created by the University of New Brunswick (UNB), Canada. The DTW maps of different resolutions used in Papers IV & V, were created by the author using ArcMap 10.8.

The clay content maps, estimated by digital soil mapping, were developed by the Swedish University of Agricultural Sciences (SLU). Clay content maps cover 90% (2.4 million ha) of Swedish arable land, but only have small coverage across forest land (Söderström & Piikki 2016). Different data sources like reference soil samples, DEM, Quaternary deposit maps, and airborne gamma-ray radiation data, were used to estimate and depict clay, sand, and soil organic matter (SOM) contents of 20 cm topsoil with 50-m resolution raster maps. The quality of clay content maps varied spatially, due to the varying quality of input data from sources such as soil type maps. The logging sites studied in Paper VI were located in areas where low-resolution soil type maps (1: 750 000) had been used to model topsoil clay content.

The HYPE (HYdrological Prediction for Environment) model was developed by the Swedish Meteorological and Hydrological Institute (SMHI) to simulate flow of water and nutrients such as nitrogen and phosphorous across Sweden. The Swedish version of HYPE, S-HYPE, subdivides Sweden into 37 000 hydrological sub-basins with a typical size of 700–1000 hectares. Using the SGU soil type map, DEMs, and weather data as input, the S-HYPE models generated hydrological data that was relevant for predicting soil trafficability (Table A2, Paper V).

4. Study methods

4.1 A soil trafficability map using GIS and MCDA (Paper I)

GIS data layers, including soil type, elevation, slope, and aspect, were merged to create a soil trafficability map (cost-index surface) across a logging site in Selesjö, south-east Sweden. The model suggested forwarder trails by optimising travel distance while minimising soil impacts.

Elevation, slope and soil type data layers were used to proxy sensibility to traffic, while aspect data layer was used to quantify topographic difficulty regarding forwarder passages. Multi-criteria decision analysis (MCDA) and operational insights from a panel of experts were used to merge the data layers into a soil trafficability map. Different levels of trafficability were visualised on the map using a cost-index scale of 1–5, with 1 being the best and 5 the worst trafficability condition. Sensitive areas like wetlands and ditches were excluded from possible forwarder passages.

Two scenarios for forwarder trail layouts were evaluated in terms of estimated time and cost of operation. A PONSSE Elephant King forwarder was presumed to perform the forwarding part of the logging operation.

4.2 Soil trafficability maps in Europe (Paper II)

This review provides an overview of available soil trafficability maps supporting low-impact forestry operations in Sweden and seven other European countries across Northern and Central Europe. The focus was on the availability of high-resolution DEMs as input data for such tools, and the processing of DEMs into soil moisture models like DTW maps. Practical implementation of soil trafficability maps in forestry operations was also addressed. As co-author in the process of writing this review, I was responsible for describing the Swedish status, while other authors decided on the general structure and chose participating countries.

The articles included in this review paper were chosen through a snowball searching approach, where a key recently published article and its bibliography was reviewed for other relevant publications. The new candidate articles and their corresponding bibliographies went through a similar iterative review procedure, until no new articles of relevance could be found. A total of 112 articles and technical reports published in the period 2011–2021, addressing soil trafficability predictions, were reviewed.

4.3 Factors affecting rut formation (Paper III)

After final felling, 16 logging sites were surveyed to collect data on forwarder trails and rut formations on the trails. The logging sites varied in size (2–39 ha) and included a total of 100 km forwarder trail (Table 3, Paper III). Field data contained information regarding traffic intensity (Table 1, Paper III), reinforcement of the trails with treetops and branches, i.e., slash, geographical positions of logging trails and ruts, as well as length and depth of the ruts.

GIS data, including soil texture and estimated soil moisture by DTW index, were extracted from relevant digital maps. DTW values were grouped into wet/dry classes, using a DTW threshold value of ≤ 1.

The soil type map was used to classify the expected soil bearing capacity into three classes: coarse-textured soils and bedrocks had the best bearing capacity (Class 1), while fine-textured soils had the lowest (Class 3) (Table 2, Paper III).

Using a mixed linear model, the proportion of logging trails with ruts was inferred *across the logging sites* per combination of trail class, soil type, DTW, and slash reinforcement, including their respective interactions. The proportion of logging trails was also inferred *within the logging sites*, using a general linear model to exclude the variation deriving from different time-periods of operation, different operator teams, and different weather conditions across the logging sites. The modelling was performed using SAS® software package (Ver 9.4. SAS Institute Inc.). A significance level of $p \leq 0.05$ was used for identifying factors with an effect on rut formation.

4.4 Effect of DEM resolution on DTW maps (Paper IV)

DTW soil moisture maps with resolutions of 2, 1 and 0.5 metres were created from corresponding DEMs from airborne laser scanning.

Soil moisture was estimated in the field and categorised into wet, moist, mesic-moist, mesic, and dry. Field data was collected from 385 sample points, along logging trails and spread across eight logging sites. The mean DTW values were compared over all field-estimated soil moisture classes, for all resolutions.

The conformance of the modelled and field-estimated soil moisture classes was evaluated, using the well-established instruments of Accuracy (ACC, %), and Matthews Correlation Coefficient (MCC). The higher the values of ACC and MCC, the better conformance of the model.

DTW values were compared against field estimated soil moisture expressed in a binary scale, e.g., wet and dry. Two different limits (DTW $\leq$1 m, and DTW $\leq$ 1.5 m) for separating wet/dry soils were evaluated. The statistical analysis was performed using the software package Dell Statistica 13.0.

4.5 Hydrological data to predict risk for rutting (Paper V)

A field-surveyed database regarding forestry ruts was used to evaluate whether hydrologically modelled data can be used for predicting rutting risk. The database contains 5021 rut sample points from 27 logging sites spread across Sweden. The rut samples were originally measured for objectives others than those addressed in this paper and were therefore collected sufficiently close together to introduce autocorrelative redundancy. A subset of ruts was resampled from the original database to reduce the autocorrelative redundancy in the database. A minimum distance of 35 m was assigned between the sample points in accordance with results from fitting a semivariogram and a scree plot to the original data. The field-measured rut subset was supplemented with null ruts, extracted in ArcMap 10.8, to account for logging trail parts without rutting.

Two regressor subsets comprising 1) field and GIS data, and 2) field and GIS including hydrological data, were used to infer the variation of ruts. *Rut depth* and *proportion of logging trails with ruts* were used as dependent variables. The models were tested and compared in terms of efficacy in explaining the observed variation of the dependent variables.

In order to infer rut depth variation, all GIS data were extracted from the corresponding digital maps at sample positions within logging sites. The GIS data were aggregated at site level and to infer the proportion of logging trails with ruts across logging sites. The variables of relative precipitation (Rel_prec), ground water level (Rel_gwat), and soil moisture at root zone (Rel_srfd) were extracted from S-HYPE models and calculated by relating the values of the respective variables during logging periods (approximately two weeks) to an extended time-window of the previous 15 years.

Partial Least Squares (PLS) was used to estimate the dimensionality of the regressor matrix and to rank regressor variables by their performance in describing the observed rut variations. The final regressions were made with generalised mixed logit-linked models, based on the PLS top-ranked variables, for all regressor subsets. The logging sites were provided with unique identities to account for possible intra-site covariance structures arising from similarities within logging sites, such as similar geographical conditions and/or logging routines. Logging site identities were used as random variable when the first regressor subset (field and GIS data) was used and were nested into random sub-basin identities when using the second regressor subset (field and GIS including hydrologic data). All other regressor variables were considered fixed. Statistical inferences were performed in the Dell Statistica 13.0 and SAS® software package (Ver 9.4. SAS Institute Inc.).

4.6 Clay content maps to predict risk for rutting (Paper VI)

This study used field-measured data on ruts and forwarder trails across four logging sites. The logging sites were part of the larger study area addressed in Paper V. The field-measured ruts were evaluated specifically against the clay content maps generated by digital soil mapping techniques.

The estimated clay content across the logging sites was categorised into four classes to simplify the analysis (Table 3). The suitability of clay content maps for predicting risk for rutting was evaluated by overlaying logging sites, ruts, and forwarder trails on the clay content map. Possible trends in rut variation in relation to clay content and varying traffic intensity were evaluated using standard GIS tools. All GIS work was performed in ArcMap version 10.8.

Table 3. Classification of estimated clay content in the logging sites.

Clay content classes	Estimated clay content in maps (%)
1	0 – 4
2	5 – 9
3	10 – 14
4	> 15

5. Results

5.1 A soil trafficability map using GIS and MCDA (Paper I)

A soil trafficability map was generated in GIS, estimating different scales of terrain suitability (1–5) for machine passages. Forwarder trail systems were modelled over a logging site, for two scenarios (Figure 4).

In Scenario 1, the model suggested a trail system that excluded a ‘no-go area’, i.e., wetland, from machine movements. In Scenario 2, a new trail system enabling a passage over the wetland using a corduroy bridge was suggested. A volume of 1 573 Mg of solid wood under bark was expected to be extracted from the logging site, requiring 79 passages of the (assumed) loaded forwarder.

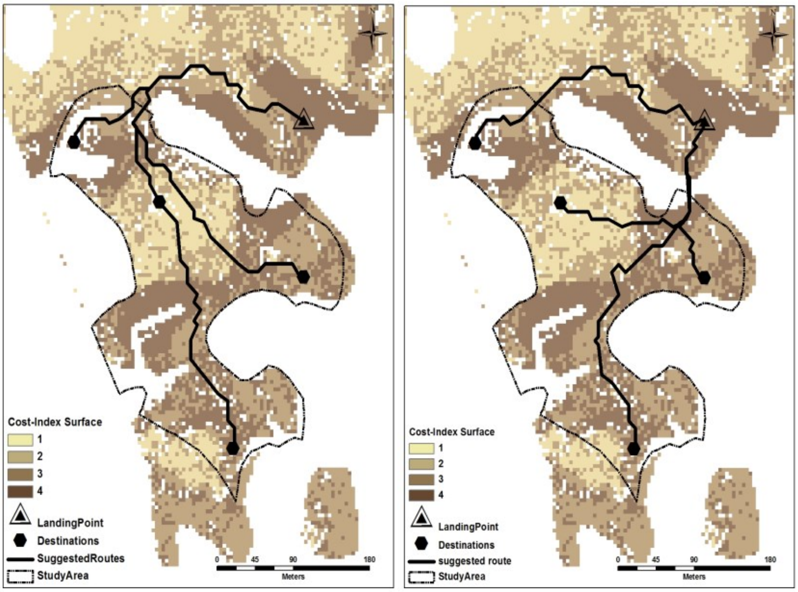

Figure 4. Soil trafficability model on a logging site. The lower the cost index, the better conditions for trafficability. White parts are excluded from machine movements. Two possible scenarios for managing sensitive areas are presented in Scenario 1 (left) and Scenario 2 (right) (Mohtashami *et al*. 2012).

The two scenarios were compared in terms of time and cost of operation, and Scenario 2 was found to be economically superior (Table 4). However, the economic gains should always be seen in relation to other environmental and practical gains.

Table 4. Estimated length of operating trails, required time, and forwarding cost shown for each scenario. The PONSSE Elephant King forwarder had a loading capacity of 20 Mg, an operating velocity of 0.8 m/s, and an operating cost of approximately EUR 85/h (at the time of the study).

	Forwarding trail (m)	Required time (h)	Forwarding cost (EUR)	Corduroy bridge (EUR)
Scenario 1	1616	89	7 536	-
Scenario 2	929	51	4 323	500

5.2 Trafficability maps in Europe (Paper II)

The review showed that national campaigns in most forest-rich countries, apart from France, have led to the public provision of open access/partly open access digital elevation models (DEM) (Hoffmann *et al*. 2022). In Nordic countries, like Sweden, Finland, Norway, and Latvia, these input data have been further processed to produce free DTW maps available to forestry operations. These maps will help to minimise soil impacts caused by these operations.

The review of soil trafficability map status indicated that the forestry sector in Sweden has had access to high-resolution ALS-derived DEMs (2 M) at national level since 2009. This made it possible to use and process the DEMs for different applications (e.g., soil trafficability and forest growth estimations) in forestry management and planning at an early stage. The first laser scanning campaign was conducted by the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet), with a point density of 0.5–1 pts/m^2. The point clouds from ALS are freely available to all users. The processed product, DEM (2 m), is freely available only for research and educational applications, while an annual subscription fee is charged for other applications. A more recent national campaign, started in 2018 and planned for completion in 2024, is scanning the entire country at a resolution of 1–2 points/m^2 and is providing DEM at a resolution of 1 m.

Since the DTW maps were evaluated in Swedish forest conditions (Bergkvist et al. 2014), they have been freely available as web-based services at national level through the Swedish Forest Agency (Anon 2022).

New versions of soil moisture maps have recently been developed using Artificial Intelligence (AI). Several different GIS and field data across the country are used to estimate the soil moisture shown in these maps (Lidberg et al. 2020). The new maps are available on the same platform as the DTW maps.

5.3 Factors affecting rut formation (Paper III)

An analysis of the surveyed data from studied areas indicated that soils with low, medium, and high bearing capacity sustained 7%, 77, and 16% of forwarder trails. A higher proportion of trails in soils with medium and high bearing capacity were located on areas where DTW > 1 m. In soils of low bearing capacity, on the other hand, a higher proportion of trails were located on areas where DTW < 1 m. Strip trails (with 3-5 machine passages) were the dominant trail type in all soil bearing capacity and DTW classes (Figure 5).

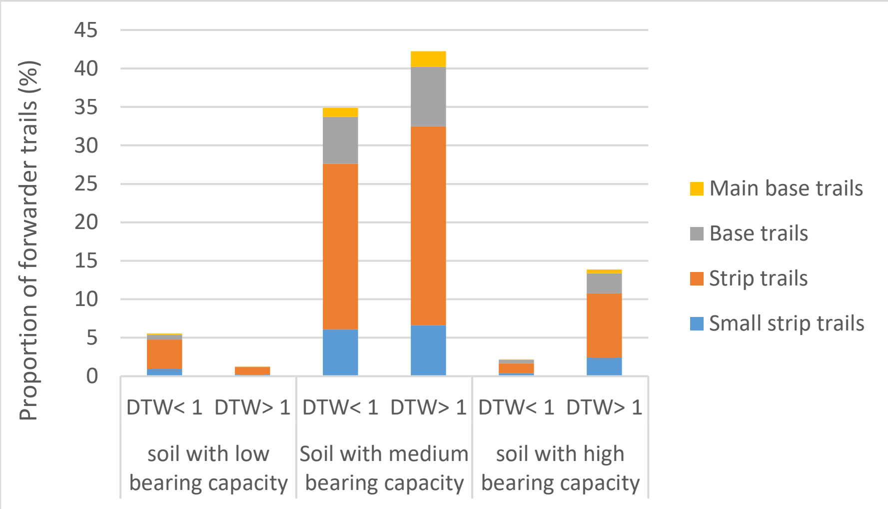

Figure 5. Distribution of forwarder trails in relation to DTW, soil bearing capacity, and traffic intensity, after Mohtashami et al. (2017).

The analysis of the proportion of trails with ruts, using a mixed linear model, indicated that traffic intensity (trail type), and soil bearing capacity classes were identified as significant factors ($p < 0.05$) for describing the variation in proportion of forwarder trails with ruts, while DTW and slash reinforcement were not significant (Table 4, Paper III). The proportion of trails with ruts increased with the number of machines passages and was largest on trails with medium bearing capacity (Figure 4, Paper III).

The analysis of forwarder trails with ruts in a general linear model, per logging site, also identified traffic intensity and soil bearing capacity classes as significant factors for describing the variations in ruts, in eight and nine (out of 16) logging sites, respectively. The DTW index, most commonly in interaction with other factors, helped to explain the variation in the proportion of ruts in eight logging sites (Table 5, Paper III).

5.4 Effect of DEM resolution on DTW maps (Paper IV)

The analysis of logging sites in relation to DTW maps of different resolutions indicated that DTW soil moisture classes were almost equally distributed over the logging sites (Figure 3, Paper IV & Figure 6).

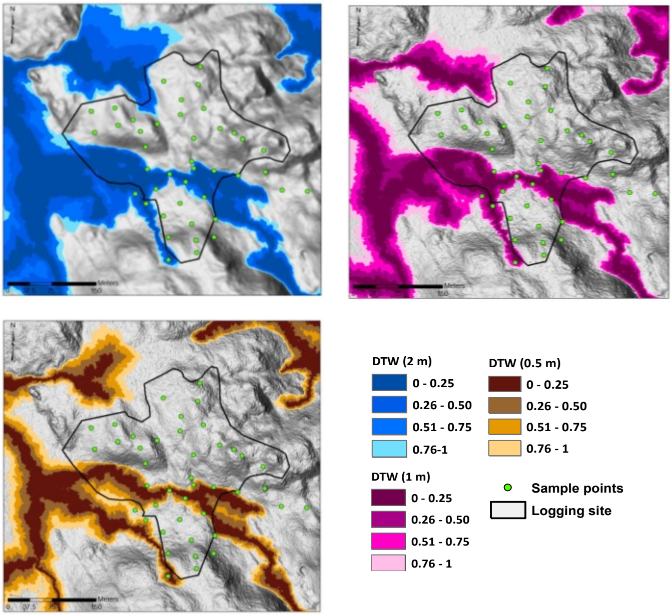

Figure 6. One of the surveyed logging sites and field-collected sample points superimposed on DTW maps of 2 m, 1 m and 0.5 resolutions. The underlying maps are multiple hillshade of DEMs with the same resolution as DTW maps. DEM (2 m & 1m) were based on data from the Swedish mapping, cadastral and land registration authority. DEM (0.5 m) was provided by SCA AB.

The mean DTW values for the field-estimated soil moisture classes ‘wet’ and ‘moist’ were approximately 1.2 m. The mean DTW value increased as the field-estimated classes became drier and was approximately 2 m in ‘mesic-moist’ and ‘mesic’ moisture classes and increased to approximately 4 m in the ‘dry’ moisture class (Figure 7). The same trend was also confirmed in a general linear model, where adjusted R^2 values, the power of the DTW model in explaining field-measured soil moisture classes, did not change significantly with resolution (Table 5, Paper IV). The large confidence interval of the 2-m resolution DTW map in the 'wet' moisture class was due to an outlier, where DTW was 4.9 m but the area was classified as wet in the field.

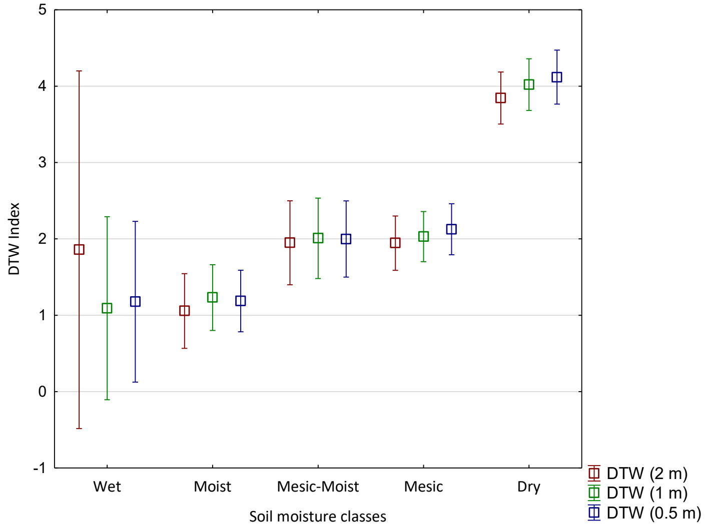

Figure 7. 95% interval of averaged DTW index values in relation to field-estimated soil moisture classes, in DTW maps of resolution 2 m, 1 m and 0.5 m (Mohtashami et al. 2022a).

The conformance of DTW maps in relation to field-estimated soil moisture in binary classes, measured by ACC% and MCC, changed slightly by increasing resolutions for both wet/dry limits (Table 6 & 7 Paper IV). Changing the wet/dry limit from 1 to 1.5 m, however, resulted in improved MCC values for all DTW resolutions. DTW maps with a resolution of 1 m showed best conformance among all DTW resolutions, using the limit DTW ≤1.5 m.

5.5 Hydrological data to predict risk for rutting (Paper V)

Inference of *rut depths* using field and GIS data explained 18.8% of the observed variation (R^2= 18.8%). Inclusion of hydrological data, S-HYPE variable sml-2 which is soil moisture at the second layer of the soil, slightly improved the model's efficiency (R^2=19.3%).

Inference of the proportion of logging trails with ruts with explanatory regressors consisting of field and GIS data, including the relative values of hydrological data, slightly improved the model's efficiency (to R^2 = 35.2%), compared to using only field and GIS data to explain the observed variation of the dependant variable (R^2 = 33%), Table 5.

Table 5. Description of models describing variation of rut depths and proportion of logging trails with ruts. Regressor subset (1) consisted of field and GIS data, regressor subset (2) consisted of field and GIS data including S-HYPE, after Mohtashami *et al.* (2022b).

Dependent variable	**Regressor subset**	**R^2**	**Fixed regressors**	**Random regressors**
Rut depths	1	18.8 %	Trail type*, ground protection*, DTM*, DTW	Logging sites
	2	19.3 %	Trail type*, ground protection*, DTM*, S-HYPE (sml_2)*	Logging sites nested within sub-basin areas
Proportion of logging trails with ruts, %	1	33.0 %	Trail type*, ground protection*, soil type, % logging site area with DTW< 1m	Logging sites
	2	35.2 %	Trail type*, ground protection*, soil type, S-HYPE (Rel-prec,Rel-srfd*, Rel-gwat*)	Logging sites nested within sub-basin areas

5.6 Clay content maps to predict risk for rutting (Paper VI)

The proportion of clay content was distributed differently over the logging sites included in this study. Almost all the area of logging site 1 was in the lowest clay content class, i.e., 0–4% (Figure 8), so the site was excluded from Figure 9 and Table 6.

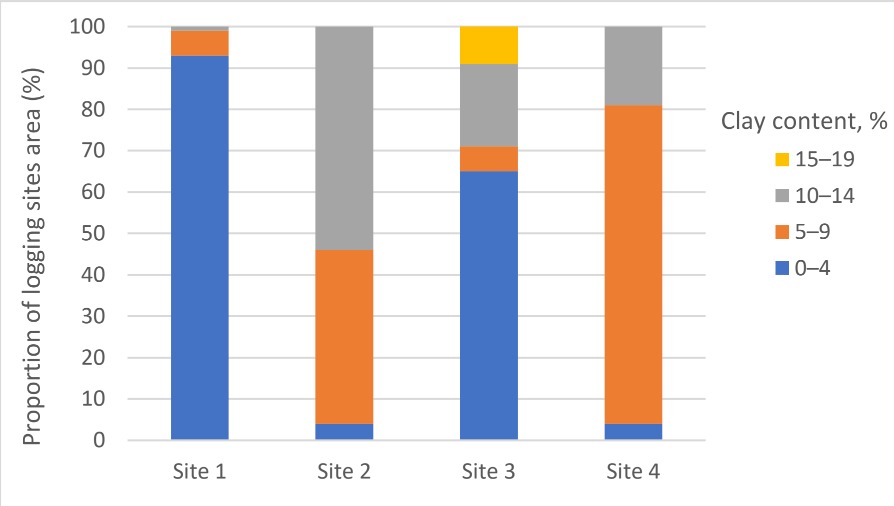

Figure 8. Proportion of logging sites area in the different clay content classes and logging sites, after Mohtashami *et al.* (2018).

As can be seen in Figure 9, base trails with medium traffic intensity (5-10 passages) had the highest number of ruts per hectare. Main base trails (with > 10 passages) had the lowest number of ruts because these trails are usually placed in more favourable parts of the terrain and protected with slash.

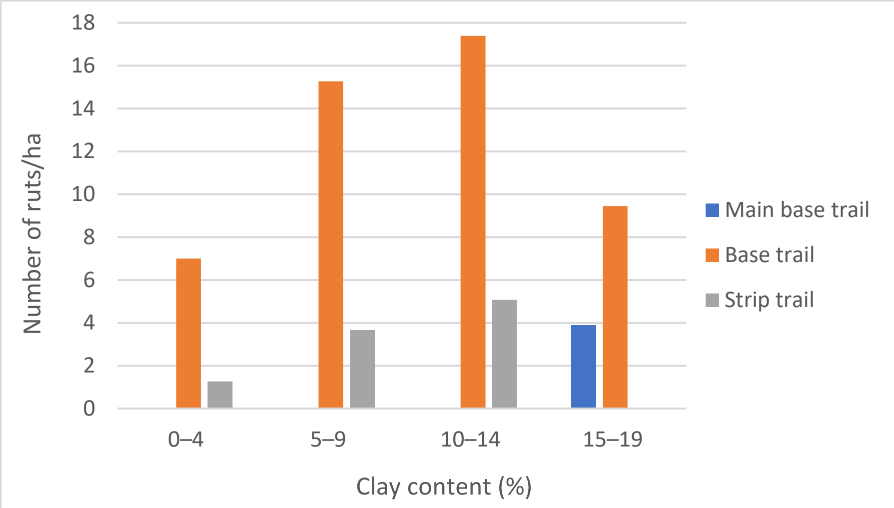

Figure 9. Number of ruts/ha in relation to clay content classes, after Mohtashami *et al.* (2018).

There was a tendency toward a smaller number of ruts in the 0–4% clay content class than in soils with higher clay content. Rut depth also tended to increase with increased clay content compared to clay content class 0–4% (Table 6), but this could not be verified due to the limited data.

Table 6. Average number of ruts per ha in relation to rut depth and clay content classes.

Rut depth (cm)	**Clay content (%)**			
	0–4	**5–9**	**10–14**	**15–19**
10–20	5.50	22.50	25.27	5.40
20–50	4.90	19.80	14.27	2.60
> 50	0.20	0.85	0.47	-

6. Discussion

Recent decades have seen a rapid development in the field of geographic information systems, GIS, which has made them available for practical applications. Most forestry machines in Sweden are now equipped with GIS and computers and have mobile web access through 4G technology. This technological development has facilitated the application of improved methods for planning logging operations and may help to minimise soil impacts. Using GIS-based decision support systems, like soil trafficability maps, forest planners and forest machine operators can obtain a more comprehensive image of the logging site and are thereby able to conduct more sustainable logging operations.

6.1 Results discussion

6.1.1 Soil trafficability map using GIS data and MCDA

Paper I described how a soil trafficability map and suggestions for possible forwarder trails can be created. This was done using existing GIS data layers and decision-making approaches like multi-criteria decision analysis. Such models may be further developed by integrating information sources that describe weather conditions and machine properties (Suvinen 2006a). A single map, covering several aspect of terrain trafficability, makes the planning of logging operations more effective by eliminating the need for individual users to gather and compile multi-GIS data. However, the quality of soil trafficability maps depends greatly on the quality of input data and the modelling technique applied for estimating different soil properties.

Multi-criteria decision analysis (MCDA) provides decision makers with a platform to create consensus among different and sometimes conflicting interests (Blagojević *et al.* 2019). Performing a sensitivity analysis on weighted factors in these analyses can provide extra insights on the effect of each factor on the final trafficability map (Saltelli 2002; Pamucar *et al.* 2017). This aspect was not evaluated in Paper I, due to considerable differences in quality of input data. Consequently, more studies with more accurate input data are needed to form a base for a soil trafficability decision support system (DSS) suitable for logging operations.

6.1.2 Soil trafficability maps in Europe

The study examining the status of trafficability maps in Northern and Central Europe (Paper II) indicated that most countries in Europe with large forestry sectors have access to digital elevation models with acceptable resolution. However, processing this dataset to generate different forms of soil trafficability decision support systems, like depth-to-water (DTW) maps, is demanding and costly. This may reduce the availability of these maps for large-scale implementation. It would be worthwhile if a central (state) authority could provide soil trafficability maps to forest stakeholders at reasonable costs, as is done for example in Sweden, Finland, and Norway. Access to mobile web networks with high data transmission standard in forestry machines also facilitates implementing soil trafficability maps available as web-based services. Developing dynamic soil moisture maps that incorporate actual weather and site conditions was identified as a next step in further development of soil trafficability maps.

6.1.3 Variations in rutting

The analysis of the risk for rutting using field and GIS data identified traffic intensity (Paper III & V), and soil type (Paper III) as significant factors. This is in line with results reported by (McNabb *et al.* 2001; Eliasson & Wästerlund 2007; Toivio *et al.* 2017), who showed that rutting increased by the accumulated effect of machine passages and was worse on soil with medium to fine texture. According to our soil bearing capacity classification in Paper III, all till soils were classed as medium bearing capacity. This classification is, however, very rough and does not reflect the actual variation in till soils. Till soils have high bearing capacity when they comprise medium to large soil particles, or when they contain a high proportion of stones and boulders. The bearing capacity diminishes in fine-grained till soils, especially in moist and wet conditions (Hillel 1998). The variation in particle sizes in till soils is not properly represented in the current Swedish soil type maps, reducing the applicability of such maps in detailed logging planning. High-resolution soil type maps, capable of separating fine and coarse grained till soils, are urgently needed to further develop soil trafficability maps.

In Paper III, reinforcement of logging trails with logging residues was not identified as significant, probably due to insufficient amount (Labelle & Jaeger 2012) or late application of these materials on logging trails. Similar inefficiency of logging residues for minimising soil impacts was reported by (McDonald & Seixas 1997; Han *et al*. 2006). In practical forestry, the slash reinforcement of the trails by the harvester is not always enough for the forwarder passages. As ruts appear during forwarder passages, the forwarder operators add more slash to the trail. Although this reduces or stops new ruts forming, the existing ruts remain on the trails and are included in the field-surveyed data.

In Paper V, logging residues were found to be a significant factor describing rut variations, probably due to their more efficient application. DTW maps had been used by machine operators to apply slash reinforcement on logging trails with low bearing capacity and high traffic intensity in the studied logging sites.

The results of Paper III also indicated that DTW maps alone cannot be used to predict the risk for rutting, as reported by (Ågren *et al*. 2015; Schönauer *et al*. 2021a). However, when combined with other type of data, like soil type and traffic intensity, DTW maps can be used to identify soil with low bearing capacity.

6.1.4 Effects of DEM resolution on DTW maps

Analysis of the performance of DTW maps in separating soil moisture classes in hilly/elevated areas indicated no improvements in the maps with increased resolution of the digital elevation models. This is probably because of the greater influence of large-scale topographic conditions on near-surface water movements than the influence of smaller-scale microtopography in hilly areas. The latter is improved in high-resolution DEMs (Murphy *et al.* 2009; Ågren *et al.* 2014).

The threshold limits in DTW maps need to be adjusted to actual soil type and weather conditions to make the maps dynamic and thereby more usable for planning of logging operations. As pointed out by (Campbell *et al*. 2013; White *et al*. 2013), another alternative is to adjust flow initiation (FIA) limits to weather conditions when creating DTW maps. This approach, however, was not addressed in this thesis.

6.1.5 Hydrological data to predict risk for rutting

The application of hydrological modelled data as a dynamic tool to predict risk for rutting has been examined in several studies (Jones & Arp 2017; Jones & Arp 2019). The functionality of such a model across larger spatial or temporal variation was evaluated in Paper V. The results indicated that the S-HYPE model contributed slightly to identifying areas with low bearing capacity at the spatial resolution required for planning of logging operations. Hydrological models are usually developed to function at watershed scales (700–1 000 hectares), and not logging site scales (2–10 hectares). For use in planning of logging operations, finer spatial resolution and locally validated models are needed.

With current spatial resolution, the S-HYPE model could be used to adjust the wet/dry threshold to weather condition in DTW maps. However, further studies are required to verify this application.

6.1.6 Clay content maps to predict risk for rutting

Clay content maps, estimated by digital soil mapping (DSM), were evaluated to analyse their usability for predicting the risk for rutting in logging operations (Paper VI). The results of this pilot study indicated tendencies toward a higher number of ruts per ha, and also deeper ruts, when clay content increased. However, the studied data (Paper VI) was too limited to enable more general conclusions.

Proper modelling techniques, developed specifically for forest landscapes, are required to make better prediction of clay content. This would enable their use in trafficability maps in logging operations. Future models also need to include the prediction of silt fraction of the forest soils, which is a very problematic particle size both in terrain transportation, optimal plantations, and forest road construction contexts. Such models need to be evaluated in decision support systems (DSS) over large forest areas, prior to implementation at large scales.

6.2 Methods discussion

6.2.1 Controlled versus uncontrolled study designs

Examining complex questions arising from human/nature interactions requires insights from several perspectives. These insights need to integrate both scientific facts, operational challenges, and realities. The survey studies of this thesis provided a realistic view on how nature, forestry machines, and operational methods interact and affect the risk for rutting in mechanised logging operations. Although not all factors could be analysed using practically available field and GIS data, the results indicated that planning of logging operation methods may be improved using GIS-based decision support systems. Performing a controlled study, on the other hand, enables analysis of variables of interest at the studied area, accentuating or reinforcing scientific facts. The results from such studies are site-specific and thereby challenging to extrapolate across areas with different conditions.

6.2.2 Statistical inferences

When collecting geospatial data for statistical inferences, it is important to account for the autocorrelative covariance structures that may characterise geographically confined areas (Wackernagel 1995). Autocorrelation introduces redundancy that reduces the dimensionality of the potential regressor matrix, which may lead to an overestimation of statistical power. To compensate for this effect, a sampling distance at scales well beyond the autocorrelation distance is required. This compensation was missing in Papers III & VI, probably leading to a somewhat overestimated prob-value used to identify significant factors. However, caution was applied to avoid this issue and manage autocorrelation in Papers IV and V.

To manage autocorrelative structures in Paper V, an empirical semivariogram was estimated using indicator kriging for ordinal data in ArcGIS 10.8. This was done by plotting the dissimilarities between observations of rut depths against the distance between observation points, which suggested an autocorrelative distance of approximately 114 m. However, assigning this distance to the collected data, resulted in uncomfortably large losses of data. This was managed by varying sample size as a function of autocorrelative distance using a scree diagram. This procedure resulted in selecting a minimum sample distance of 35 m for resampling the dataset.

When uncontrolled study designs are used to infer complex forestry processes, it is beneficial to rank the efficacy of explanatory variables while maintaining the estimated non-redundant dimensionality of the regressor matrix. This may be done using techniques like Partial Least Squares (PLS) analysis, where orthogonal linear combinations of regressor variables that describe the main variation of the explanatory variables are consecutively extracted. The individual variables that significantly contribute to these components are also identified. The PLS technique was used in Paper V, where the choice of hydrological data for describing rutting variations was particularly challenging.

The proportion of logging trails containing forestry ruts was inferred using general and generalised linear models (Olsson 2002) in Papers III and V respectively. The proportion of logging trails with ruts is a real number varying within the interval [0, 1], which does not follow a normal distribution as assumed in general linear models. Logit normal transformation was therefore used prior to analysis (in Paper III) in order to transform the data into the interval]-∞, +∞[and thereby allow the data to approximate a normal distribution. Using the SAS GENMOD procedure for generalised mixed logit-linked modelling (Paper V), on the other hand, provided a more direct method of treating non-normally distributed data. This procedure is more robust for inferring non-normal data, by not requiring direct transformation of input data and backward transformation of the results. Instead, data were implicitly transformed by using the logit transformation link.

6.2.3 Rutting measurements

To create a more standardised notion of rutting in logging operations, it is important to define rutting and how it is measured in the field. Definitions of rutting vary considerably among current forestry legislation and statutes. The threshold depth of tracks to be considered as ruts vary, which causes inconsistencies in assessments deriving from different sources. Using photogrammetry or LiDAR technologies to measure the ruts may improve the quality of field-measured data (Pierzchała *et al.* 2016; Nevalainen *et al.* 2017; Marra *et al.* 2018; Salmivaara *et al.* 2018). Harvester-mounted technical instruments, i.e., a controlling area network (CAN) bus device, can also be used to measure the rolling resistance of the soil, and provide live data regarding actual soil bearing capacity (Ala-Ilomäki *et al*., 2020; Salmivaara *et al*., 2020). Integrating these types of field-measured live data or frequently updated satellite-based soil moisture measurements (Schönauer *et al.* 2022) in GIS-based decision support systems may facilitate creation of a more dynamic prediction of risks for rutting.

6.2.4 Evaluation of soil trafficability maps

Trafficability maps are usually based on models that proxy soil properties relating to soil bearing capacity. To extract correct inferences from model evaluations, it is beneficial to (first) specifically study the model in direct relation to the variable it is designed for, as in Paper IV. This would facilitate understanding and identifying how much, and in which way, the model deviates from reality and thereby provides insights for further development. Model evaluations become more challenging when the model's results are assessed as one of the several factors affecting formation of a phenomenon like rutting (Papers III, V & VI). Comparing soil moisture or clay content maps with their actual values in the field, without coupling to rutting by forestry machines, for example, can produce more straightforward conclusions. Analysing hydrologically modelled data over the same study area(s) under different time intervals is another way to evaluate temporally and spatially variable soil properties, like moisture content.

A shortcoming in model evaluations in this thesis was exclusion of the effect of machines and machine configurations on rut formations. This was an effect of field data measurements after harvesting operations on the logging sites. The surveys provided large sets of field data, but the trade-off was that detailed data on number of machine passages, machine masses, and machine configurations could not be collected. However, the effect of machine passages in the surveys are in line with previous findings in controlled experiments (Eliasson & Wästerlund 2007; Toivio *et al.* 2017; Marra *et al.* 2018), so the effect of excluding these detailed data from field-measured data is probably not large.

6.3 Regulatory measures to minimise soil impacts

In addition to operational and planning decision support systems, global goals and national legislation/directives are required to manage exploitation of natural resources. The United Nations 2030 Agenda includes 17 global sustainability goals to promote, among other thing, sustainable use of natural resources and mitigate climate change (United Nations 2021). Minimising soil impacts in forestry logging operations by proper planning and decision support systems can contribute to the following global goals: clean water and sanitation (Goal 6), sustainable industry, forestry innovation, and resilient infrastructure (Goal 9), responsible consumption and production (Goal 12), climate action (Goal 13), preserving and sustainable use of life below water (Goal 14), and life on land (Goal 15).

The EU Water Directive aims to preserve "good water status" for surface and ground water in European countries (European Commission 2000). The EU Soil Strategy promotes restoration and protection of soil with concrete actions from 2030, to achieve healthy soils by 2050 (European Commission 2021). In the US, the Clean Water Act (1972) was established to protect surface waters from different pollutant sources and to regulate surface water quality standards. This act therefore sets the framework for timber harvesting activities in wood-production regions, as this is one of the contributors to erosion and sediment transport (Cristan *et al*. 2016).

According to the Swedish Forestry Act, forestry operations causing "serious soil impacts", like high levels of erosion and sediment transports to surface water, should be avoided (Anon 1994). Swedish environmental objectives, including quality objectives like "sustainable forest" and "thriving wetland", are pertinent for forestry operations.

When complemented by best management practices, regulatory tools can lead to minimised impacts on forests as natural resources and to sustainable use of the forests.

6.4 Implementation of results

Planning logging operations is a complex task, requiring integrated knowledge and experience from different domains. Minimising soil impacts is only one of several challenges forest machine operators need to manage during logging operations. Another is proper localisation of landing areas to collect harvested logs with minimised environmental and social (accidental risk) impacts and optimised profitability. Cultural heritage sites as well as areas with high conservation values in forest landscapes should be identified and managed during logging operations (Willén & Mohtashami 2017; Grönlund *et al.* 2020). Planning for this complex situation is particularly demanding during tough working conditions, when the Nordic forests are covered with snow or when darkness dominates the working hours in autumn and winter periods.

Easy and free access to GIS-based decision support systems can facilitate planning some parts of this complex situation, by visualising and suggesting sensitive areas on geospatial maps in the computer systems of the machines. High-quality input data in such systems increases the chances of making better predictions for soil trafficability. The high-quality data, however, need to enable proper correlation with risk for rutting to improve planning of logging operations.

High-quality input data on, e.g., soil moisture and soil texture, can also be used in planning of other forestry measures, such as planning of buffer zones around flow channels to preserve their functionality, planning of soil scarification, and reforestation (Ring *et al.* 2020). All these improvements create added value in the management of forest sites, and eventually improve sustainable use of the natural resources.

6.5 Recommendations and future research

Developing decision support systems to estimate soil trafficability and thereby minimise soil impacts requires accurate input data on a number of factors. These different data sources can be integrated to a soil trafficability map, which can be used in either scheduling harvesting time or planning the layout of machine operating trails.

Soil bearing capacity is a function of several factors and their interactions, which vary spatially and temporally across the forest landscape. Factors like soil texture, boulder, and stone fraction in the soils vary spatially, while soil moisture content and the armouring effect of tree root systems are factors which vary spatially and temporally.

Recommendations for further model developments, describing factors with only spatial variations, include:

- Application of new soil type mapping techniques to improve soil texture description, especially in till soils. Predicting the silt fraction of the forest soil could be an effective way to identify soil with low bearing capacity and a low level of natural recovery.

- Developing digital maps to estimate size, frequency and position of boulders and stones, with the aid of laser scanning, photogrammetry, or other scanning techniques.

Recommendations for further model developments, describing factors with both spatial and temporal variations, include:

- Supplementing soil trafficability models with live field data collection regarding soil moisture content during logging operations. This would enable modification of trafficability estimation and provide extensive field-measured data for future model developments.
- The tree root system strengthens the topsoil in forest landscapes, an effect that also varies temporally, depending on the site or stand age. Developing models to estimate this effect and evaluate how it may be used to reduce soil impacts, without causing root damage and thereby negative effects on future tree growth, could also improve soil trafficability estimations. Such a model could also be used to minimise the negative effect of machine passages on standing trees during thinning operations.

Recommendation for use of new computational method, include:

- Use of Artificial Intelligence (AI) could enable advanced prediction models of soil moisture content and soil texture. To achieve good results from such techniques, extensive and accurate sample data (ground truth data) are required to build training and validation datasets. Use of artificial intelligence can lead to further development of soil trafficability maps and minimise soil impacts in logging operations.

Recommendations for forestry practitioners, include:

- Soil trafficability maps should be regarded as decision support systems, to help forestry planners and machine operators identify soils with low bearing capacity prior to and during logging operations. It is important to use them as a guiding tool, and not regard them as reference maps for predicting rut positions.
- It is also important to build structural communication channels between researchers and practitioners in the forestry sector. This

would facilitate transfer of research results to practical operations and enable practical knowledge to be received and incorporated in further map developments.

- An important and effective measure to minimise the soil impacts in logging operations is to use logging residues, slash, to improve the soil bearing capacity on logging trails. Efficient models are required to use this material in the optimal way, for either bioenergy extraction or in-situ application to reduce soil impact.

7. Conclusions

The main findings of this thesis are:

- Soil trafficability maps can be created using various GIS data. Such maps can be used to identify soil with low bearing capacity, compare different layout options for logging trails, or to schedule logging operations.
- The trafficability maps can be developed by either merging different GIS data layers into a single new map or can be based on a single data layer such as a soil moisture or soil type map. Multi-criteria decision analysis can be used to merge different GIS data into a single trafficability map.
- Soil trafficability maps require high-quality input data.
- Easy and free access to soil trafficability maps based on high resolution digital elevation models facilitates their application in logging operations.
- DTW maps, together with other data, can be used to predict risk for rutting.
- A spatial resolution of 1–2 m was shown to be sufficient for reliable soil moisture predictions on DTW maps in hilly areas. Locally adapting the threshold values between wet and dry areas in DTW maps improves the identification of wet areas when evaluated in relation to field measurements of soil moisture.
- Temporal and spatial variation of soil moisture must be included in trafficability maps to improve their contribution to planning of logging operations. Knowledge about how the bearing capacity of a logging site is affected by prevailing weather conditions can help improve planning of logging trails and scheduling of logging operations.

- The use of data from the S-HYPE hydrological model only led to marginal improvements in predicting risk for rutting, compared to field-measured and other GIS data. Hydrological modelled data, with current resolution, may be used to adapt the wet/dry threshold limit in DTW maps to actual weather conditions. Data sources like satellite data or live field data measurements may improve predictions of temporal variation of soil moisture, and thereby improve functionality of soil trafficability maps.
- Clay content maps may improve prediction of soil strength and thereby improve functionality of soil trafficability maps. However, further studies are needed.

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Popular science summary

Timber harvesting operations in Swedish boreal forests are almost fully mechanised. Timber is harvested using the cut-to-length method. A single grip harvester is used for felling and processing and a forwarder for transport of the logs to roadside landings.

These heavy forestry machines may cause undesired soil impacts, such as rutting or compaction. Soil compaction disturbs soil porosity and pore connectivity, reducing air and water permeability. Rutting, in addition to being unaesthetic, implies a higher risk for soil erosion and transport of soil particles to surface waters, where sedimentation can affect the health of aquatic organisms. Soil impacts may also have other short- and long-term effects on tree health and reforestation success.

Consequently, there are many reasons to minimise soil impacts during logging operations. Forestry planners and machine operators require planning tools, like GIS-based decision support systems, to predict soil trafficability and minimise the risk for soil impacts before and during logging operations.

This thesis comprises six papers examining whether and how various Geographic Information System (GIS) data can be used to predict soil trafficability. A specific focus was on GIS maps describing or predicting soil moisture and soil type, and what can be done to facilitate their application in forestry operations is also discussed.

In Paper I, a soil trafficability map was created, using different GIS data layers and multi-criteria decision analysis. The map was used to evaluate different trail layouts for areas with restricted trafficability. Soil trafficability prediction was expected to improve with improved GIS data, like soil moisture and soil type maps. Paper II reviewed the status of soil trafficability maps in northern and central European countries. Paper III evaluated factors affecting risk for rutting in practical logging operations. Rutting surveyed on 17 logging sites was analysed in relation to existing GIS and field-measured data. Paper IV analysed whether depth-to-water (DTW) maps, created from high resolution digital elevation models, can improve soil moisture predictions in logging sites. Data regarding soil moisture content was surveyed across eight logging sites and compared with DTW maps with resolutions of 2, 1 and 0.5 m. Paper V examined whether inclusion of hydrologically modelled data can improve prediction of risk for rutting, compared to only GIS and field-measured data. Paper VI analysed whether or how clay content maps, created through digital soil mapping, can improve prediction of the risk for rutting. Clay content maps can be used as complements to existing soil type maps, particularly in areas where the latter are of low quality, due to either low spatial resolution or aggregated soil types.

The main conclusions from this thesis are:

- Soil trafficability maps can be created using GIS data.
- Soil trafficability maps can be used to delineate areas with low bearing capacity, schedule logging operations, or compare different logging trail layouts.
- DTW maps, together with other data, can be used to predict risk for rutting.
- Easy and free access to soil trafficability maps, such as DTW maps, facilitates their application in forestry operations.
- GIS data of high quality are required to create reliable soil trafficability maps.
- DTW maps based on a spatial resolution of 1–2 m is sufficient to predict soil moisture in hilly and elevated areas.
- Hydrologically modelled data and clay content maps may improve prediction of risk for rutting. Further studies are required to evaluate their application in forest landscapes.
- New data sources and data analysis techniques are required to predict spatial and temporal variation of soil trafficability.

Populärvetenskaplig sammanfattning

I Sverige är avverkning av boreal skog helt mekaniserad. Avverkningar utförs enligt kortvirkesmetoden, där en skördare avverkar och upparbetar trädet och en skotare lastar virket och transporterar det till ett avlägg vid väg.

Skogsmaskinerna är tunga och kan orsaka negativ markpåverkan som spårbildning och/eller markpackning. Markpackning kan skada markens porsystem, och leda till försämrat luft- och vattenflöde i marken. Spårbildning leder till högre risker för skador på trädens rötter, erosion och uttransport av markpartiklar jordpartiklar till ytvatten. Detta innebär att partiklarna kan sedimentera i vattenmiljöer och skada vattenlevande organismer. Negativ markpåverkan kan också ha andra kort- och långsiktiga konsekvenser på de kvarstående trädens hälsa och föryngringsresultatet efter avverkning.

Det finns därför många anledningar att minimera markskador vid avverkning. Skogliga planerare och maskinförare behöver bättre beslutsstöd för att bedöma markens bärighet och minimera risken för markskador, före och under avverkningarbetet. Dessa beslutsstöd bör vara GIS-baserade, exempelvis i form av körbarhetskartor.

Denna avhandling består av sex studier som utvärderat om och hur olika datakällor i ett geografiskt informationssystem (GIS) kan användas för att skatta markens bärighet. Fokus har varit på GIS-kartor som modellerar markfuktighet och jordart. De grundläggande kraven för att underlätta implementering av sådana kartor i praktiskt skogsbruk diskuteras också.

I artikel I utvecklades en körbarhetskarta baserad på olika GIS-kartor och multikriterieanalys. Körbarhetskartan användes för att utvärdera olika körvägsalternativ vid avverkning. Bedömning av markens körbarhet kan förbättras med bättre GIS-data, så väl markfuktighet- som jordartskartor. I artikel II undersöktes implementering av körbarhetskartor, framför allt

DTW-kartor (DTW=Depth-to-Water), i nordiska samt centraleuropeiska länder. Artikel III analyserade faktorer som påverkar risken för spårbildning i praktiskt utförda avverkningar. Körskador analyserats i förhållande till fält- och GIS-data som inventerats på 17 avverkningstrakter. Artikel IV utvärderade om en högre upplösning av DTW-kartor, baserade på högupplösta höjdmodeller, bidrar till bättre skattning av markfuktighet på avverkningstrakter. Fältdata om markfuktighet inventerades i fält längs avverkningsvägar på åtta trakter och jämfördes mot DTW-kartor med 2, 1, och 0,5 m upplösning. Artikel V utvärderade om skattningen av risken för spårbildning förbättras när man använder hydrologiska data tillsammans med fält- och GIS-data. I artikel VI studerades om och hur lerhaltskartor, baserade på fjärranalysmetoder, förbättrar skattningen av spårbildningsrisken. Lerhaltskartor kan anses som komplement till SGU:s befintliga jordartskartor, framför allt i områden där jordartskartorna har låg kvalité på grund av antingen låg rumslig upplösning eller aggregerade jordartsklasser.

Slutsatserna från denna avhandling är:

- Körbarhetskartor kan utvecklas med hjälp av GIS-data
- Körbarhetskartor kan användas för att avgränsa mark med låg bärighet, schemalägga avverkningar och/eller för att utvärdera olika körvägsalternativ.
- DTW-kartor kan tillsammans med annat data användas för att prediktera risken för spårbildning.
- Enkel och gratis tillgång till körbarhetskartor, exempelvis DTW-kartor, underlättar implementeringen vid skoglig planering.
- GIS-data av hög kvalité behövs för att utveckla välfungerande körbarhetskartor.
- DTW-kartor med en upplösning på 1–2 m är tillräckligt för att skatta markens fuktighet i kuperade områden.
- Hydrologiska data och lerhaltskartor kan bidra till att förbättra skattningen av spårbildningsrisken. Fler studier behövs för att utvärdera dess tillämpning i skogen.
- Nya datakällor och analysmetoder behövs för att bättre skatta både spatiala och temporala variationer i markens körbarhet.

Acknowledgements

I would like to begin by thanking my supervisor group at SLU and Skogforsk, for valuable teaching, coaching, and collaboration. Thank you, **Tomas Nordfjell**, for your high expectations of me, and for guiding me through the journey towards my doctoral degree. Thank you, **Lars Eliasson**, for always making yourself available to listen and discuss all my different questions and reflections at different stages of my journey. You helped me find my way back to the path when I was most confused, for which I am so grateful. Thank you, **Linnea Hansson**, for being a patient teacher of forest soil science, providing technical support, helping me with orientation in the field, and discussing many interesting research topics relating to my doctoral studies. Thank you, **Tomas Thierfelder**, for guiding me through the most challenging part of my studies, the statistics, with patience and passion. Thank you for answering all my questions and explaining things clearly and pedagogically. Thank you, **Johan Sonesson**, for interesting me in Swedish forestry challenges since my master's thesis study and was available for discussing new research questions. Thank you, **Carola Häggström**, for providing critical comments on my papers and thesis.

I would like to thank my employer, Skogforsk, where I started my career in Swedish forestry. Thank you, **Isabelle Bergkvist, Erik Willén, Lars Wilhelmsson, Maria Nordström, Magnus Thor** and **Charlotte Bengtsson** for supporting me at various times, prior to and during my doctoral studies at Skogforsk. I want to express my appreciations to my superiors in the Forest Management Programme at Skogforsk, **Erik Ling** and **Line Djupström**, who supported me at difficult times and understood me when I was experiencing the greatest workload when writing my thesis. Special thanks to **Eva Ring**, for valuable comments and discussions on my thesis and other studies, always full of insight and professional reflections. Many thanks to **Dag Fjeld** and **Marian Schönauer** for discussing and challenging my work. Special kind thanks to my colleagues for helping me with field data collections/managements in different studies: **Michael Krook, Martin Täljeblad, Hagos Lundström, Mikael Bergqvist, Linnea Hansson, Lars Eliasson, Karin Strömgren, Berit Gregorsson, Fredrik Johansson, Sven Tegelmo, Mikael Andersson,** and **Anders Rowell**. I would not have been able to collect my data without your help and support.

Many thanks to all other **colleagues**, **friends,** and **relatives** for enjoyable times and talks, both at Skogforsk and other establishments. Thank you for being kind listeners to all my research-related thoughts and challenges. Thank you **Karin Ågren**, **Johanna Enström**, **Rasmus Sørensen** and **Märtha Wallgren** for pleasant and supportive discussions and help in various critical situations. Thank you, **Leslie Walke**, for helping me with language review of all my papers and thesis.

I would like to thank my husband, **Soheil**, for all the support over many years, since our bachelor's degrees in Iran in 2002. Thank you for your patience and engagement, and for being a kind pappa (and mamma) to our kids when I was busiest with my studies. Thank you, my wonderful kids, **Armin**, **Ava**, and **Elsa**, for constantly reminding me of the joys and meaning of life, with those wonderful stars glittering in your eyes.

And last, but not least, I want to express my warmest thanks to my parents, **Mahboobeh** and **Mahmood**. You taught me not to give up at life's challenging situations, and unconditionally supported me in my university studies, both in Iran and in Sweden.

مامان و بابای خوبم

ممنون بابت همه زحمات بی دریغتون

دوستتون دارم

I

Original scietific paper – *Izvorni znanstveni rad*

A GIS Approach to Analyzing Off-Road Transportation: a Case Study in Sweden

Sima Mohtashami, Isabelle Bergkvist, Björn Löfgren, Staffan Berg

Abstract *– Nacrtak*

Off-road driving in logging operations began in Sweden in the 1960s. Those operations took place at final fellings during winter on prepared ice roads that protected the soil and mitigated possible soil damage. Today logging operations are fully mechanized and performed all year round. Thus forest strip roads may suffer severe impacts from off-road operations. Soil disturbances may have physical, chemical, biological, hydrological, and economic effects and affect the water quality. Similar problems are encountered in other regions, where driving occurs close to watercourses or vulnerable areas. The EU Water Directive has an impact on operations in forests, creating an incentive for improvements. Ongoing efforts in the design of vehicles and equipment are likely to improve operations. Soil damage can be avoided by applying GIS-based planning techniques, and by taking advantage of soil radar-scanned and ground laser-scanned data sets, which would facilitate safer off-road driving to a great extent. A case study in southern Sweden revealed that the use of digital planning for the improvement of strip roads in order to avoid vulnerable terrain made forwarding of timber more profitable. Using elevation, slope, aspect and soil type digital layers, a model has been created in 'model builder' environment of ArcGIS to build up a cost-index surface, which classifies the terrain suitability for driving into five different levels. Implementing distance analysis, the model designs the least costly roads connecting any desired destination to the landing point. The result of this study reveals that this kind of pre-planning tool can mitigate ecological damages to soil and water and at the same time it can also assist decision makers to evaluate different possible choices of road layouts regarding preserving sensitive regions in forest lands.

Keywords: GIS-based decision support system; Digital Terrain Model (DTM); ground damage; forest operations; forwarding; planning; rutting; soil

1. Introduction – *Uvod*

The mechanization of logging operations in Sweden and other countries began in the 1960s, and it led to off-road driving in order to bring timber to the landing. Those operations took place at final fellings during winter on prepared ice roads, thus protecting the soil and mitigating soil damage. Today, all logging operations are mechanized and performed throughout the year due to the all-year-round fresh timber demands of the pulp industry. Off-road driving is extensive on all forest lands during all seasons, even when the ground is vulnerable to soil disturbance. Any professional forester has to consider the great variety in the Swedish landscape in terms of topography, soil types and surface water.

In the 1970s, a terrain classification system was developed to aid the planning of off-road driving in conjunction with forest operations (Forskning stiftelsen Skogsarbeten 1969 and Skogforsk 1992). Recent guidelines (Ring et al. 2008) addressed the impacts of off-road driving from a water-quality perspective. Off-road driving close to surface water increases the surface water sediment load risk. Such sediments might be harmful to aquatic organisms (Skogforsk 2008). The guidelines allocate a 5–10 m zone bordering on lakes and streams in order to mitigate sediment release into water, avoiding driving on streams and wet areas, and utilizing technical devices in order to reduce physical soil disturbance at crossings. Planning is another important tool for reducing such negative impacts.

The aim of this paper is to;

⇒ elucidate the risky aspects of road driving in forest operations with respect to current forms of legislation.

⇒ investigate ways of mitigating soil damage by trying out a planning decision support system in a case study in South-Eastern Sweden. This decision support system facilitates routing in terrain considering soil, water and restricted areas. Proper route alignment for avoiding probable sliding of the loaded forwarders on steep slopes was considered as part of this method.

⇒ estimate possible financial gains by evaluating different route alternatives at a felling site.

1.1 Environmental and social significance *Okolišne i socijalne značajke*

Primary soil damage in conjunction with off-road driving may have secondary effects that cause physical, chemical, biological, hydrological, economic or aesthetic impacts. Although not specifically regulated in the environmental standards for forestry, the event of forest certification manifested in schemes like PEFC (2012) or FSC (2012) has stressed the importance of disturbance control in connection with off-road driving. One reason for this is the less permissive attitude to soil disturbance in Central Europe (Hauk 2001; Hildebrand and Schack Kirchner 2002). Off-road operations increase soil density down to 50 cm, and decrease soil aeration and thereby reduce root penetration (Eliasson and Wästerlund 2007). This impact varies with moisture content (Ziesak 2003; Yavuzcan et al. 2005). Rutting may result in compaction (Jamshidi et al. 2008) and adverse driving conditions, leading to costly interruptions and breakdowns, which eventually increase the energy use and related emissions. Reduction of soil disturbances at off-road operations can be beneficial both for the environment and for operational cost reduction. Physical soil disturbances may affect ecosystem pools of C and N in the soil (Finér et al. 2003). European environmental policies stipulate that processes in agriculture and forestry (e.g. draining, off-road driving and harvesting) which in general reduce C storage, should be avoided (Anon. 2004 and 2006). Increased nitrate leaching is commonly found after clear cutting and soil scarification (Ring et al. 2008). Logging tracks often induce similar disturbances to the soil and thus there is a risk of elevated N-mineralization and denitrification in these areas. Final fellings might result in the discharge of Hg and its consequent accumulation in fish (Bishop et al. 2009). This might be attributed to anoxic conditions in the soil caused by the raised water level in tracks.

Swedish environmental objectives (Swedish EPA 2011) regulate several impacts likely to be caused by soil damage in conjunction with forest operations and off-road driving. Under the EU Water Framework Directive (Anon. 2000), there is also a legal responsibility to maintain the water status. The generally anticipated process leading toward global warming (Peters 1990) is likely to affect the frequency of rainfall, droughts and what is nowadays called extreme weather, especially in Europe (Bolte et al. 2009). The authors believe that similar legal and consequent political pressure will affect forest planning and forest operations.

1.2 Technical means for mitigating ground damage – *Tehničke mjere za ublažavanje oštećivanja podloge*

Ground damage is caused when forces and pressures are exerted on the ground surface via the wheels or tracks of terrain vehicles. The resultant effect is compaction of the soil, skidding, and shearing of vegetation or soil layers. These effects can technically be avoided either by the design of the machine/vehicle or mitigated via operational skills, for example adjusting vehicle properties by reducing the impact of the load on the ground (Ziesak 2003; 2004) or the use of ancillary equipment (Staland & Larsson 2002) along planned routes to enable passages over brooks or other watercourses. Technical improvements in laser scanning have also provided quite precise data layers representing terrain surfaces in the form of Digital Terrain Models (DTM). These DTM layers, especially high resolution ones, have been quite attractive in supporting forestry operations in recent years since they provide thorough and detailed information about terrain topography (i.e. terrain elevation and steepness), which in turn are used to choose the best skidding system in complex forest fields (Lubello 2008; Vega et al. 2009). Krč and Košir (2008) have also used Digital Elevation Models (DEM) to develop a model for terrain classification based on the best predicted skidding direction on steep terrain. Benefiting from DEM along with other inventory information about the rockiness and stoniness of a terrain, Mihelič and Krč (2009) analyzed how to define new skidding systems or forwarding possibilities on different terrain classes in Slovenia.

High resolution DTMs are also used to define various soil wetness indexes like the Depth to Water Index, DTW (Murphy et al. 2008), and Compound Topographic Index (CTI) (Goetz 2010), to predict vegetation terrain types and ground bearing capacity in forest lands which are of great help for planning silvicultural activities.

1.3 Design of machines – *Konstrukcija strojeva*

Via machinery design, basic properties of a machine impact can be altered and adjusted to actual conditions. This can be done by adjusting the wheel pressure exerted on the soil through changing the tire pressure (wheel width) or using wider tires (Jonsson 2011). Tracks might be added in order to distribute forces more evenly over the ground surface, which itself will enhance the risk of shearing at turns. By adjusting the air pressure in the tires to the soil and the load or vice versa, the operator has the means of reducing ground damage (rut depths). Tests made with a CTI-system (Löfgren 1994) on a forwarder showed that the rut depth of 600 mm – wide tires with low pressure is the same as that of 800 mm – wide tires and high pressure. Basic machine properties have an impact on the ability to negotiate terrain. Positioning of the wheels before driving over obstacles using hydrostatic driving may be beneficial. The reduction and damping of vibrations has a similar effect (Baez 2008). Geometric design is the determining factor for a beneficial distribution of pressure on the wheels.

1.4 Supporting equipment – *Pomoćna oprema*

With the aid of different sorts of technical equipment, it is possible to reduce the damage to virtually nil; however, there is a cost and the issue is to have the required equipment on the right spot at the right occasion. The means for doing this are fixed or temporary bridges along the hauling route, or carrying prefabricated bridges for immediate use, for example when crossing a ditch. Other solutions are to work with ground cover rigs made of timber or tire mats. Moreover, the use of harvest residues and downgraded wood logs constitute other possible means. Residues or straw can be spread out along the hauling route in order to mitigate the ground damage when passing over sensitive spots (Eliasson 2007; Saunders and Ireland 2005). Consequently, it is important to plan the harvesting of residues, considering where the residues are needed to improve the bearing capacity of the ground, and where they could be harvested as forest fuel.

1.5 Planning – *Planiranje*

The issue of the right application of routes and ancillary equipment, as well as where the residues should be used on the forest road, is coordinated by planning. In order to plan the operations and utilize the ancillary equipment, updated maps are mandatory. Planning based on the Geographic Information System (GIS) is a great step forward compared to former methods as it is feasible to explore a variety of digital layers of information, extract the required relevant knowledge, evaluate possible alternatives and, finally, make appropriate decisions. A number of researchers have assessed the trafficability of terrain types for different goals with the aid of GIS. Initially, GIS was used for military off-road planning (Lubello 2008), and gradually it was introduced in the fields of agriculture and forestry. In most cases, GIS has been used for choosing the optimal routes out of a number of already-existing possible networks: Rongzu and Mikkonen (2004) used GIS to provide an optimized wood logistics GIS model based on a combined cost surface created from road transport costs and off-road transport cost surfaces. Pentek et al. (2005) used GIS to analyze the quality and quantity of an existing forest road network to determine potentials for planning future routes. Suvinen (2006) used a GIS-based simulation model to assess terrain tractability regarding two sets of constant and dynamic factors as well as machine characteristics to suggest a proper route layout for different load/terrain conditions. However, lateral inclination, which is an essential factor for properly guiding a machine on steep terrain, was neglected in that study.

2. Materials and methods – *Materijal i metode*

2.1 Study area and scenario definition – *Područje istraživanja i definiranje scenarija*

The study area under consideration was the property of Selesjö in Östergötland, located in South-Eastern Sweden, and it was mainly dominated by Norway spruce and Scots pine, Fig. 1. In the close vicinity of the harvesting site, with an area of 6.72 ha, a possible landing point was selected, where the harvested timbers were to be stored for further operations. This landing point was to be reached from 4 arbitrary destination points at the harvesting site. However, there was a wetland between the landing point and part of the stands, which needed to be protected against driving damage. This area as well as other existing sensitive parts, like ditches and streams, were called 'No Go' areas and were totally excluded for the purpose of locating the routes. Possible route alignment to reach the destination points with minimum disturbances to the surrounding environment was evaluated under two different scenarios: in Scenario 1, the routes were expected to go beyond the wetland and reach the landing point, while in Scenario 2 the possibility of building a corduroy road to pass the wetland was analyzed to see how the route layout would have to be adjusted to the new conditions and how much it could reduce the cost of transportation by providing shorter route stretches.

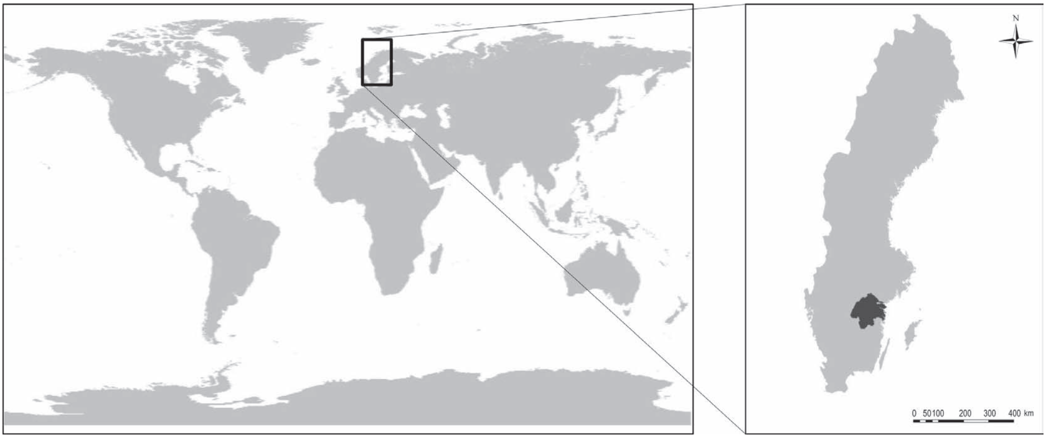

Fig. 1 Location of the study area on a map of the world (left) and in Sweden (right)
Slika 1. *Područje istraživanja na karti svijeta (lijevo) i u Švedskoj (desno)*

2.2 Input data and software – *Ulazni podaci i softver*

Data layers used in this model were as follows: a high resolution, 0.5 × 0.5 meter Digital Terrain Model (DTM), FORAN SingleTree® Laser Method, which are both the products of high density, 8–10 points/m^2, and laser scanning of the area using Foran Remote Sensing AB. The former layer was in raster format and the latter was in point format, containing information about tree species, crown diameter, stem diameter and the gross volume of stands. Slope and Aspect grid layers were extracted from the DTM and were used to evaluate the topography of the study area. All the grid materials were reclassified to a coarser resolution of 4 × 4 to be sure that each pixel can support the width of forwarders. Soil types, in polygon format, provided by the Swedish Geological Research Institute (SGU), represented different textures of the soil in the area. Environmentally-sensitive spots such as nature reserves, key biotopes and habitat-protected regions as well as historical values, were prepared by the Swedish Forest Agency, or Skogsstyrelsen (2011); these areas were to be set aside as protected. Separate shape layers localizing the landing point (source) and the destinations were other inputs in the model. In this study, the 10th version of the ArcGIS software packages provided by the Environmental Systems Research Institute, Inc. (ESRI 2012), including ArcMap, ArcCatalog were used for data preparation, data processing, information exploration, evaluation and, ultimately, for viewing the final results. The Slope, Aspect, Path Distance and Cost Path tools available from the Spatial Analysis and the 3D Analysis extensions were used to build up the desired model within the 'Model Builder' environment of ArcGIS.

2.3 Procedure of the analysis – *Postupak analize*

Planning sustainable forestry operations requires simultaneous consideration of the economic and ecological values in the forest. These two aspects do not always introduce similar approaches for forest managers in practice and consequently there is always an essential need to reach a consensus among all the stakeholders regarding evaluating and integrating various criteria and making the best decision. Eastman et al. (1998) defined it so simply: »decision is a choice between alternatives«, and Multi-Criteria Decision Analysis (MCDA) is a procedure that can unify several attributes and/or objectives as part of the decision-making process (Malczewski 2006). Therefore, this procedure formed the basis of the analysis for finding the optimal routes in this study. Weighted Linear Combination (WLC) was the rule applied in this process as it was compatible with the ArcGIS software.

Applying MCDA, elevation, slope and soil types were regarded as the most determining factors for estimating different levels of suitability of the area for driving. Since soil bearing capacity for supporting massive forest machinery has a direct relation with the degree of soil moisture, it has been assumed that the lower the elevation in an area, the higher the probability of having wetness in soil would be, and thus the worse the ground conditions for driving would be. Following this assumption, the elevation layer was used as

Table 1 Summary of data reclassification for cost-index surface preparation

Tablica 1. *Zbirni prikaz razredbe podataka za pripremu vrijednosnih indeksa površine*

Factors *Faktori*	*Factor classification – Razredba faktora*	
	Original values *Izvorne vrijednosti*	Cost-index values *Vrijednosti indeksa*
Elevation *Visina* (46–65 metres)	65–60	1
	60–55	2
	55–50	3
	50–46	5
Slope *Nagib* (0–90 degrees)	0–6	1
	6–11	2
	11–18	3
	18–27	4
	27–90	5
Soil classes *Tipovi tla*	Rocks-*outcrop*	1
	Till	3
	Silt	5

a simple model to identify the risky wet parts in the area. Slope layer was used to quantify the terrain steepness and to avoid driving on steep terrains (slope > 18 degrees). The soil type layer was used to find water courses, wetlands and similar sensitive parts in the area. These three layers were reclassified to a new scale of 1 to 5, called a cost index, in order to have a common scale for defining the suitability of the ground for terrain driving on all layers. The better the driving conditions, the lower the assigned cost index value to the corresponding class in each of the data layers was, Table 1.

For example the elevation values in this area ranged between 46 and 65, and therefore it was reclassified so that the values between 46 and 50 got the cost index (5), elevations between 50 and 55 got the cost index (3), elevations between 55 and 60 got the cost index (2), and the highest part with elevations between 60 and 65 got the minimum cost index (1). Finally, in order to integrate all these input layers into a single cost-index layer with 5 levels of suitability, different weights of importance were assigned to them based on ideas from a panel of 7 experts at the Forestry Research Institute of Sweden; Skogforsk. Elevation resulted in a weight gain of 50%, since in this case it had much better precision compared to the soil type layer for predicting where the moist soil texture could be located. Flat and low elevated areas are assumed to be wet and unsuitable for driving. The soil type layer gained 20% in terms of the weights and was used as a complementary layer to find the areas with the best bearing capacity, and finally Slope gained the remaining 30% in order to avoid technical problems under operational conditions. Later on, soil classes with unsuitable bearing conditions (such as wetlands, peat lands), as well as steep slopes (> 18 degrees) and ditches were regarded as constraints on the study area and were extracted from the cost-index surface by assigning »No Data« to their values and visualized with the darkest grey color in Fig. 2 and Figure 3. Afterwards, feeding the cost-index surface as a cost raster into the Path Distance tool together with the landing point layer, as the source, with DTM layer as the surface raster and Aspect as the horizontal factor into the Path Distance tool, the least accumulative cost of getting back to the landing point, raster distance, and also the proper direction of moving to the neighboring cell, backlink raster, was determined at this stage. A maximum inclination of 5 degrees with respect to the slope direction of the ground was meant to be achieved for the route layouts. This was implemented by applying the horizontal factor parameters in the Path Distance tool. The Aspect layer, defining the direction of the slope of the ground, was used as the input horizontal raster. The horizontal factor was set as a table type in ASCI format. This table consists of two columns; the first one is called the Horizontal Relative Moving Angle (HRMA) and defines the relationship of the moving direction with respect to the horizontal direction of the terrain, while the second column is called the Horizontal Factor (HF), and defines the difficulty of moving from one cell to another (ESRI 2011). In this case, all the HRMA between 5 and 175 degrees, which indicate uphill or downhill movement with too much tilting, were assigned very high HF (100), while for other HRMA ($0 \leq \text{HRMA} \leq 5$ degree or $175 \leq \text{HRMA} \leq 180$) that would not cause too much tilting on the terrain, the HF varied linearly between a value of 1 to 5; the smaller the tilting, the lower the assigned HF was.

The formula applied to calculate the values of the raster distance in Path Distance tool is (ESRI 2011):

⇒ For perpendicular movement:

Cost_distance = Cost_Surface * Surface_distance * {[Friction(a)* Horizontal_factor(a) + Friction(b) * Horizontal_factor(b)] / 2} * Vertical_factor

⇒ For diagonal movement:

Cost_distance = Cost_Surface * Surface_distance * 1.414214 * {[Friction(a) * Horizontal_factor(a) + Friction(b) * Horizontal_factor(b)] / 2} * Vertical_factor

The outcomes of this part aligned with the destination layer were inserted into the Cost Path tool to design the route layout in the harvesting site. As explained earlier, a wetland was located in the way of connecting the destinations within the site to the landing point, outside the harvesting border. In Scenario 1, the model was supposed to plan the routes by going beyond this restricted part, while in Scenario 2, a strip with the minimum cost-index (1) was added to the cost-index surface, over the wetland to a corduroy road that could be built on the wetland and contribute to a different route layout in the field.

3. Results – *Rezultati*

The model suggested the routes with the lowest cost index within the context of two different scenarios (Fig. 2 and Fig. 3). Both of these two route alignments are promising for reducing soil and water disturbances by suggesting the routes on the lowest cost-index values (i.e. the best driving conditions), while compensating for the surface distance and slope directions. Moreover, this model gives decision makers the opportunity of comparing the route alignments in two different scenarios, with or without a corduroy road, in order to find the most appropriate course of action. In this case, it was conceived that following the route design in Scenario 2 and building a corduroy road on the preserved wetland could contribute to a reduction of almost 700 m in the length of the routes to be passed from the destination points to the landing point. Using the FORAN SingleTree® Laser Method layer, the standing volume in the southern and central part of the area was measured as almost 2 526 m^3. This is actually the timber volume on the part that would be connected to the harvesting point through the corduroy road. The following table describes the equivalent volume in solid over bark and in tons, Table 2.

Thus, having almost 1 573 tons of timber at this site, and assuming the maximum possible load of large (PONSSE ElephantKing) forwarders to be 20 tons, the number of loaded forwarders required for collecting the timber is 79, which would result in 158 (79×2) passages of the mentioned forwarder over the terrain.

Fig. 2 Least costly routes suggested by the model for Scenario 1
Slika 2. *Izvozni pravci predloženi modelom za inačicu 1*

Fig. 3 Least costly routes suggested by the model for Scenario 2
Slika 3. *Izvozni pravci predloženi modelom za inačicu 2*

Table 2 Timber stands described as m^3 standing and volume solid over bark and mass as metric tons

Tablica 2. *Sastojinske značajke; drvo na panju u m^3, obujam s korom i masa u tonama*

m^3 standing *Drvo na panju u m^3*	m^3 solid over bark *Obujam s korom u m^3*	Tons *Masa u tonama*
2 526	2 097*	1 573**

* Conversion factor: m^3 solid over bark/m^3 standing = 0.83

** Conversion factor: tons/ m^3 solid over bark to = 0.75

Based on the experts' ideas at the Forestry Research Institute of Sweden, it has been assumed that the maximum velocity of a large forwarder is 0.8 m/s and its average operational cost is 85 Euro/hour. Thus, the second route layout over the corduroy road would result in a reduction of EUR 3,200 for the whole forwarding operation. The estimated cost of constructing the corduroy road was EUR 500, according to a panel of experts, which is less than the operational cost saving in Scenario 2 and therefore makes it more profitable.

4. Discussion and Conclusion – *Rasprava i zaključci*

Anticipated changes due to global warming and international agreements require well-considered planning of forest operations. The negative chemical, biological and physical consequence of soil damage is proven (e.g. Finér et al. 2003; Bishop et al. 2009). As a result of legislation and forest certification, it is important to show that operation managers have identified this aspect, and actions have been undertaken in order to remedy or improve deviations from the standards, which means that the operations must be close to best practices.

Means are available for mitigating damage, namely equipment for crossing water streams and wetlands, or tracks to mitigate rutting, but their successful use depends on access to relevant terrain information. Not just any equipment will be used when the right equipment is not available when needed. The advent of better pre-planning tools with the aid of GIS can facilitate that. High-resolution digital terrain models generated from laser scanning of the forest lands have improved the task of planning by providing comprehensive details about the terrain structure e.g. elevation, slope, etc. The digital maps in general use, with information about factors such as wetland areas or other objects of concern to be safeguarded, can ensure improved plans for achieving sustainable forestry in practice that are probably more economically rewarding and are likely to be asked for by planners, decision-makers or auditors from any certification agency. The case investigated in this study demonstrated that a practical application of available digital information and models for the planning and construction of alternative shorter and better routes in fact resulted in improved profitability of timber forwarding. Applied in a wider context, such improvements might result in substantial monetary savings and less disturbance to soil and water.

The impact any vehicle has on soils is influenced by its basic design, its wheels, and its load. The damage caused is a combination of the driving and planning applied. Improvements in machine properties will take a long time before they have an effect on the fleet of logging machines, and some will be more effective than others. Planning tools will have an immediate effect and will enable better allocation of logging machines to appropriate logging areas.

Acknowledgement – *Zahvala*

This research was performed at the Swedish Forestry Research Institute, Skogforsk, and the authors would like to thank the program managers Johan Sonesson and Magnus Thor for their valuable support. Dr. Wayne McCallum is also acknowledged for his help in checking the authors' English. The editor and reviewers are thanked for their comments and recommendations.

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Sažetak

Raščlamba terenskoga transporta uz pomoć GIS-a: primjer iz Švedske

Izvoženje drva pri njegovu pridobivanju započelo je u Švedskoj 1960-ih godina. Taj se oblik primarnoga transporta obavljao nakon dovršnih sječa tijekom zime na pripremljenim zaleđenim sekundarnim prometnicama, što je štitilo šumsko tlo i ublažavalo njegovo moguće oštećivanje. Današnji šumski radovi u potpunosti su mehanizirani i provode se cijele godine. Zbog toga su sekundarne šumske prometnice (vlake i putovi) pod značajnim utjecajem radova koji se provode u šumskom bespuću. Oštećivanje tla izaziva mehaničke, kemijske, biološke (smanjen prirast), hidrološke i ekonomske promjene i narušava kakvoću podzemnih i površinskh voda zbog prekomjernoga otpuštanja zagađivača, kao što je metil-živa koja nastaje od anorganske žive u anaerobnim uvjetima u jezerima ili rijekama (http://en.wikipedia.org/wiki/Anaerobic_organism). Slični problemi pojavljuju se i u drugim regijama, gdje se privlačenje drva izvodi u blizini vodotoka ili u područjima podložnim oštećenju tijekom toplijih godišnjih razdoblja. Direktiva Europske unije o vodama utječe na šumske radove tako što stvara poticajno okruženje za ublažavanje i otklanjanje tih problema. Trenutačni napori u konstrukciji vozila i pripadajuće opreme vjerojatno će poboljšati provedbu šumskih radova. Oštećivanje tla može se izbjeći primjenom privremenih prijelaza preko ugroženoga područja ili pomoćne opreme, ali i upotrebom nove generacije tehnika i tehnologija laserskoga skeniranja u šumama, s 8–10 lokacija po kvadratnom kilometru, koje pruža prilično precizne podatke o sastojinskim i terenskim značajkama.

Ta je vrsta sustava za pomoć pri donošenju odluka o određivanju izvoznih pravaca s manjim posljedicama za okoliš bila izrađena i testirana u pokusnom području smještenom u jugoistočnoj Švedskoj. Različiti digitalizirani slojevi, na primjer nadmorska visina i nagib, izlučeni su iz digitalnoga modela reljefa visoke razlučivosti (0,5 m × 0,5 m) radi pronalaženja najpovoljnijih područja za vožnju izbjegavajući pri tome tehničke probleme koji se javljaju na strmim terenima. Ti su slojevi bili združeni sa slojevima tipova tla i zaštićenih područja da bi se dobila osnovna karta vrijednosnoga indeksa područja. Ta karta dijeli područje u pet razina prikladnosti za vožnju primjenom razredbe koja se zove vrijednosni indeks. Niži indeks označuje pogodniji teren s obzirom na nosivost tla. U sljedećem koraku pomoću navedenoga indeksa vrijednosti površine model pronalazi najkraće putove najmanjega kumulativnoga vrijednosnoga indeksa spajajući bilo koje željeno odredište u sječini s odabranom lokacijom pomoćnoga stovarišta. Svakako, u tom *je studijskom području močvara, koja je trebala biti izuzeta od vožnje, bila locirana uz pomoćno stovarište, što je zahtijevalo da se pri planiranju procijene dva različita pristupa izradi izvoznih pravaca za prikupljanje drva, 1) vožnjom iza močvare i dosegom odredišta u sječini za utovar drva, ili 2) izgrađivanjem prijelaza preko močvare radi dolaska do pomoćnoga stovarišta. Rezultati su pokazali smanjenje udaljenosti vožnje dobivene prelaskom preko izgrađenoga mosta uz smanjenje operativnih troškova, ali i povećanje troškova zbog izgradnje mosta, do čega se došlo uz pomoć opisanoga modela za planiranje izvoznih putova.*

Ključne riječi: sustav GIS za pomoć pri odlučivanju, digitalni model reljefa, oštećivanje tla, šumski radovi, izvoženje drva, planiranje, gaženje, tlo

Received (*Primljeno*): February 17, 2012
Accepted (*Prihvaćeno*): April 30, 2012

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II

Current Forestry Reports
https://doi.org/10.1007/s40725-021-00153-8

FOREST ENGINEERING (R PICCHIO, SECTION EDITOR)

Trafficability Prediction Using Depth-to-Water Maps: the Status of Application in Northern and Central European Forestry

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Accepted: 9 December 2021

Abstract

Purpose of Review Mechanized logging operations with ground-based equipment commonly represent European production forestry but are well-known to potentially cause soil impacts through various forms of soil disturbances, especially on wet soils with low bearing capacity. In times of changing climate, with shorter periods of frozen soils, heavy rain fall events in spring and autumn and frequent needs for salvage logging, forestry stakeholders face increasingly unfavourable conditions to conduct low-impact operations. Thus, more than ever, planning tools such as trafficability maps are required to ensure efficient forest operations at reduced environmental impact. This paper aims to describe the status quo of existence and implementation of such tools applied in forest operations across Europe. In addition, focus is given to the availability and accessibility of data relevant for such predictions.

Recent Findings A commonly identified method to support the planning and execution of machine-based operations is given by the prediction of areas with low bearing capacity due to wet soil conditions. Both the topographic wetness index (TWI) and the depth-to-water algorithm (DTW) are used to identify wet areas and to produce trafficability maps, based on spatial information.

Summary The required input data is commonly available among governmental institutions and in some countries already further processed to have topography-derived trafficability maps and respective enabling technologies at hand. Particularly the Nordic countries are ahead within this process and currently pave the way to further transfer static trafficability maps into dynamic ones, including additional site-specific information received from detailed forest inventories. Yet, it is hoped that a broader adoption of these information by forest managers throughout Europe will take place to enhance sustainable forest operations.

Keywords Depth-to-water · Remote sensing · Digital terrain models · European forestry · Precision forestry · Trafficability prediction

Introduction

In Central and Northern European countries, ground-based harvesting equipment accounts for the vast majority of commercially supplied roundwood. These predominantly cut-to-length operations are usually performed by harvester-forwarder systems unavoidably impacting the soil ecosystems due to high machine and payload weight transported over sensitive forest grounds [1]. Such impacts occur in various forms and include soil deformations such as ruts [2, 3], or soil compaction, which increases bulk density due to a decreasing pore space [4, 5], restricting the permeability of the soil [6]. The occurring degree of damage is a function of the traffic experienced, site conditions such as soil type, climate variables and machine operator skills [1, 7].

Historically, the primary timber logging season was scheduled for the winter periods when the soils are frozen [8, 9], making them relatively resilient to impacts due to

This article is part of the Topical Collection on *Forest Engineering*

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their increased bearing strength [10]. Yet, the high ownership costs of modern logging equipment and involving supply chains require these machines to work year-round with the capability to increase their loads for cost reduction in an increasingly complex business environment with global competition [11]. Moreover, time periods of favourable operational conditions, in terms of frozen and thus stable soils, are getting shorter and less frequent [5, 12]. On the other hand, periods of freeze and thaw cycles with wet or even water-saturated soil conditions are likely to be extended, resulting in vulnerable soils with restricted trafficability [13]. This leads to a more significant potential for lasting site damages caused by heavy machinery in the form of soil rutting or compaction [14] and is thus a major concern during sustainable impact assessment of forest operations and timber supply chains [15].

The occurrence of severe soil impacts can be associated with several negative effects, including both economic and ecological aspects. For instance, more machine power is required when machines are driving on soft grounds, resulting in increased fuel consumption, machine wear and technical failures [16•, 17]. Moreover, ongoing operations need to be stopped if the occurring rut depth exceeds degrees or extents defined in contracts made between entrepreneurs and forest owners, resulting in high costs due to machine relocations and downtime.

In addition to economic drawbacks, various traffic-induced environmental consequences are of concern. The compaction of soil in a continuous linear pattern, such as a wheel track, restricts the soil's permeability and alters hydrological conditions [18]. On steeper slopes, ruts can result in channelling with increasing erosional energy, fortifying the loss of valuable topsoil [19]. When exceeding a specific soil bulk density, negative effects on plant available water [20] and plant growth [21, 22] can occur. Beylich et al. [23] report negative effects on various soil faunal groups related to the reduced macropore volume and the altered hydrological conditions. In addition, soil disturbance through rutting has also been suspected of mobilizing heavy metals, e.g. methyl-mercury, although the direct effect of soil disturbance alone has not been quantified [24–26].

In consequence, it is critically noted that forestry machines have increased in total weight over the last decades [27]. However, the pressure exerted by heavy forwarders on the ground did not increase, as a result of likewise increased contact area between machine and soil [28]. Along with wider and optionally low inflatable tyres [29], numerous technological solutions aim to mitigate traffic-induced site impact. Hereby, a focus is set on increasing machine flotation, traction and contact area, as for example through bogie tracks [30], long-tracked bogie axles [31], triple-bogie axles [32], auxiliary axles [33], rubber-tracked bogie axles with support rollers [34], large radial tyres with alternative treads [35], the utilization of traction-assist winches [36], brush mats [37] and innovative steering concepts [38].

However, an efficient utilization of technical soil prevention measures relies upon the information of soil state in advance of scheduled operations. This enables the selection of adequate equipment and sites to be operated in actual instructions for machine drivers, as well as a sufficient support during the off-road navigation in forest stands. The potential avoidance of areas and sites possessing a currently high vulnerability to machine impact implies the spatial prediction of risks to severe damages—both, among extensive off-road traffic during clear-cut operations, as common in Nordic countries, but also among single-selection silviculture systems commonly practiced in Central Europe, where machine traffic is often confined to permanent machine operation trails. There, next to the reduction of soil impacts in general, the technical functionality and consequent permanent accessibility into forest stands can be maintained if machine operators know which segments of a machine operating trail to avoid at a given time of operation. Field testing equipment such as penetrologger, penetrometer or vane testers are easy to handle tools, generating established indices about soil strength [39]. However, assessing an entire operation site with these tools is time consuming and represents only the current situation at time of measurement. Thus, there is an increasing role for planning software solutions with predictive power for different conditions expected and demanded in harvesting preparations [40–42].

A number of rut risk prediction tools have been developed in the last decades: A simplified model was suggested by O'Sullivan et al. [43], in which contact areas between soil and tires, soil type, initial bulk density and water content profiles are considered for the selection of an appropriately equipped machine. A similar approach was invented by Canillas and Salokhe [44], who added external variables like travel speed, axle loads and number of passes to tire and soil variables, to develop a decision support system, providing recommendations for soil management practices on agricultural areas. Still, a regular application of such systems in day-to-day forestry operations is pending. It can be assumed that a reason for a lacking implementation of predictive systems into forest management can be found in the high demand of required input data, or time-intensive efforts for related in-field measurements [39]. Consequently, topical research emphasizes the utilization of openly accessible data, as for example shown by the work of Lidberg et al. [45•], who generated wet area maps based on data from national inventories, fused with topographical information, including the topographic wetness index (TWI) and depth-to-water (DTW) maps. Salmivaara et al. [46••] developed an integrative tool to predict trafficability, using a spatial hydrological model, inventory data, a wide range of spatial information and data derived from the operating machine.

The increasingly available ALS (airborne laser scanning)-derived digital terrain models (DTM) have been verified by the plethora of their various applications, both for practical and scientific purposes. Perhaps one of the most significant applications of ALS-derived DTMs in forest operations has been in facilitating the mapping of areas of anticipated high moisture and therewith potentially high vulnerability to soil damage by vehicle passes. The nowadays wide availability of high-resolution DTMs (i.e. 0.5–2 m grid cell size) allows for precise application of spatial parameters useful to determine soil trafficability sensitivity, such as the TWI developed by Beven and Kirkby [47]. This index quantifies the influence of topography on hydrological processes based on slope and upstream contributing area. Researchers have evaluated TWI's successfulness in predicting the groundwater table [48], the effect of DTM resolution on its prediction [49] and how it performs in comparison to a dynamic model [50]. There are several possible methods to calculate the contributing area, flow channels and slope out of a DTM for the TWI index, partly with local alterations.

The cartographic DTW algorithm, developed by Murphy et al. [51, 52], has proven to be powerful in the prediction of soil state across different landscapes [52, 53]. This algorithm was evaluated to be more independent from the scale of the DTM provided, as compared to other topography-derived algorithms, such as the TWI [54]. This allows for reliable results even when the calculations are based on input grid cells of different resolutions, thus having an asset over the TWI.

Due to the rising interest in the DTW-based trafficability assessment by researchers and industry, our paper aims to give an overview and synthesizing the readiness level for the implementation of national terrain simulations, applying the DTW algorithm. Relevant forestry countries in Northern and Central Europe have been selected to review the status of available terrain data derived from state-of-the-art airborne laser scanning (ALS) technologies—a fundamental prerequisite to produce DTW maps. Further, already existing applications of the DTW algorithm or other means of spatial trafficability prediction to reduce the impact of ground-based logging systems are presented among the selected countries, too. Hence, this paper provides an assessment of the status and the potential integration of such tools to support sustainable forest management by improved operational planning and execution.

Literature Review

Review articles are commonly based on the screening of scientific publications, identified through a search string of selected keywords in combination with Boolean operators applied to a publication database such as the Web of Science. Although this review approach facilitates a logical identification of publications assigned to a specific topic, it also often leads to hundreds of selections which are not relevant for the review's objective and need to be manually eliminated through a time-consuming initial examination of at least the title or the abstract.

This review on the DTW algorithm in the context of trafficability mapping follows the snowball approach, where the bibliography of a known recent key publication, in this case Salmivaara et al. [46••], is used as a starting point to identify further publications. Subsequently, selected publications were reviewed and those bibliographies used to identify additional publications until no more new references of relevance appeared. A priority was given to publications of the last decade (2011–2021), following the wider promotion of forest soil moisture modelling for operational purposes in 2011 by Murphy et al. [52]. This approach was selected since in contrast to a purely keyword focused database search, the snowball system considers all relevant references, including non-peer-reviewed early-stage research, as well as institutional and industry reports. Moreover, the authoring team consists of experts on the topic, being involved in the two multiyear EU projects TECH4EFFECT (grant number 720757) and EFFORTE (grant number 720712), which conducted intensive research in the field of trafficability prediction. Thus, additionally to the relevant state-of-the-art publications, latest findings from ongoing research and technical implementation on national level could be incorporated into the review process. Through this rather open approach, 56 peer-reviewed publications, 14 web resources and 8 institutional reports of relevance directly involving or related to forest site trafficability prediction with the DTW algorithm could be identified and reviewed for the period of interest.

Conception of the Depth-to-Water Algorithm and Its Application for Trafficability Mapping

DTW uses flow lines derived from a DTM-based flow accumulation, to calculate the anticipated vertical distance between any given grid cell of a DTM to a modelled water layer [55]. Each grid cell's accumulated flow value is computed based on the size of the area, converging from the adjacent cells. The accumulated area size is then used to initiate a flow line, depending on a defined threshold. This threshold of area size defines the flow initiation area (FIA, m^2). For example, if the FIA was set to 2,500 m^2, an accumulated value of 2,500 m^2 was sufficient to start a flow line, which continues until leaving the area of interest. If a large FIA is used to initiate a simulated flow line, a low level of soil moisture is represented in return. Contrarily, a small FIA can be used to represent very wet or sensitive soil conditions, as the network of flow lines expands.

The flow lines created in this way are added as a dichotomous value to the respective DTM. The combination of both flow lines and DTM can be used to compute the vertical difference between each grid cell and the nearest flow line—defining the DTW index. Therefore, a least cost function is applied to estimate the least slope gradients between the grid cells and the flow lines, minimizing Eq. (1):

$$DTW[\mathrm{m}] = \left[\sum \frac{dz_i}{dx_i} a \right] x_c \tag{1}$$

where $\frac{dz_i}{dx_i}$ is the slope between a cell i and adjacent cells, a is 1 in case of parallel drainage and $\sqrt{2}$ in case of diagonal drainage and x_c is the grid cell size (m).

For enhanced utilization of the DTW concept, the procedure was described in detail and made openly available by Schönauer and Maack [56]. The DTW index can be interpreted as a relative measure of soil drainage condition, which approximates the tendency of a saturated landscape point. Cells with a small DTW value show a trend of surface water or water containing layers in the soil [51]. In return, high values of DTW are assumed to indicate dryer soils (Fig. 1).

Since the susceptibility of soils to deformations is deeply attributed to the soil moisture content [57], DTW maps are increasingly used to assess the risk of causing machine traffic-induced rutting and compaction [39, 58]. DTW maps can be adopted by the forest industry to plan operations and guide machine traffic. Such a planning approach can be used for instance to identify and avoid potential wet areas, streams which are not visible due to a snow cover, or to optimize the delineation of a machine operating trail across forest stands. An integrated on-board navigation system in harvester and forwarders could then be used to identify and warn operators when approaching sensitive areas within a harvesting unit. Zimbelman and Keefe [59] demonstrated the use of geofencing tools to notify workers of high hazard zones in forestry activities. Similar activities could be developed that integrate the mapping of soft soils and actively inform the operator when they approach those areas. However, it would also require additional training to ensure that the operators can quickly implement this information to improve forest management's sustainability.

Recent studies reveal a possible fusion of DTW maps with further data sources, including openly accessible spatial information and hydrological modelling, to be used for the prediction of forest soil's trafficability [45•, 46••] and improve the off-road navigation of forest machines [60•, 61]. Such approaches profit vastly from open and cross-border availability of spatial data [62]. In particular, the European Community INSPIRE Directive implemented public availability of manifold data sets [63]. Through the INSPIRE programme, 34 spatial data themes needed for environmental applications, such as elevation, are compiled and organized in a standardized infrastructure for sharing among public organizations, but also providing public access on a European scale, aiming towards an enhanced land-use policy-making across boundaries [64].

Country Overview and Readiness for DTW

Countries are collecting spatial data from regional to national level, characterized by differences in survey technology, processing and provision to users (Table 1). In consequence, this determines the DTW readiness for operational purposes within a specific country. Therefore, a detailed overview of national ALS mapping campaigns and derived DTM accessibility shall be given for selected key forestry

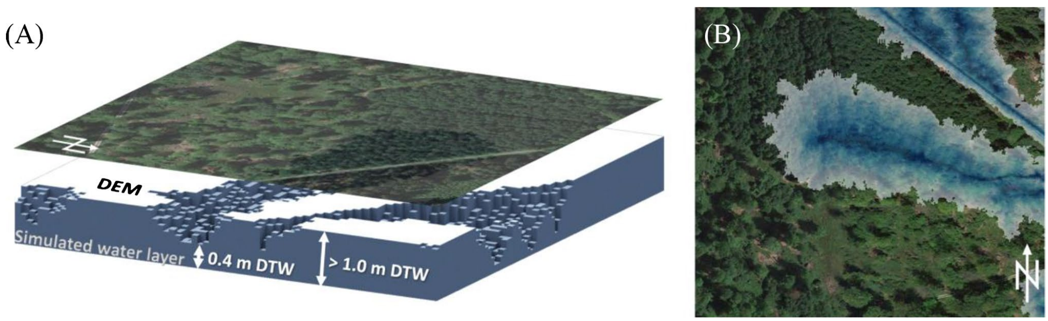

Fig. 1 The depth-to-water index (DTW) indicates the vertical proximity to the nearest simulated water layer, which is based on flow lines or areas saturated by water. Particularly, this metric index is calculated for each cell of a digital terrain model (DTM). **A** Values less than 1 m indicate wet areas with high susceptibility for soil deformations, whereas values greater than 1 m should possess sufficient trafficability for heavy forest machines. **B** Thus, areas with a high risk for soil damage can be shown on maps, as indicated by the blue colouring

Table 1 Overview of the availability and quality of digital terrain models in selected European countries

Country	Grid cell size	Data acquisition	Year of national campaign	ALS resolution	Source	Costs
Austria	10 m	National ALS campaign	2013	4 pts/m^2	www.data.gv.at	Open access
	1 m (0.5 m)	State-individual ALS campaigns	Varying between states			
Finland	2 m	National ALS campaign	Accomplished 2020	0.5 to 1 pts/m^2	www.paituli.csc.fi	Open access
France	National ALS campaign in progress					
	25, 75 and 250 m	Various sources according to regional acquisition approaches		Not applicable		Open access down to 75 m, 25 m with costs
Germany	200 m	Various sources according to regional acquisition approaches	Update based on regional data provision	Diverse	www.bkg.bund.de and www.geoportal.de	Open access
	5 m					Individualized licensing scheme
	1 m		Varying between states			
Latvia	20 m	National ALS campaign	2013–2019	4 pts/m^2	www.lgia.gov.lv	Open access
Norway	10 m (national level, locally higher)	National ALS campaign and regional orthophotos	Updating campaign 2016–2022	Min. 2 pts/m^2 (locally higher)	www.hoydedata.no	Open access
Poland	0.5 m (1 m)	National ALS campaign	Since 2011–2014	4, 6 and 12 pts/m^2	www.gugik.gov.pl	Open access
Sweden	2 m	National ALS campaign	2009–2016 (new campaign since 2018)	0.5–1 pts/m^2	www.lantmateriet.se and www.geodata.se	Free access for research and education, yearly subscription fee for commercial applications
	50 m	Various sources according to regional acquisition approaches		Not applicable		Open access

countries. Namely, the Nordic countries Finland and Sweden were selected due to its high degree of mechanized operations with heavy logging equipment, as well as a considerable share of sensitive operation sites such as peatlands. Norway, with its more mountainous landscapes, completes the boreal forest biome of the Nordic countries. In Central Europe, Germany and France are representing diverse temperate forest regions of major timber-producing countries, applying a wide range of silvicultural and operational systems. Austria, following similar forestry approaches, is included to represent the high mountain regions of Central Europe. East-Central Europe is represented by Poland as an important timber producer with vast forest areas shaped by continental climate conditions. Furthermore, Latvia was added to represent the specific Baltic conditions with seasonally waterlogged plains.

Next to the acquisition and provision of terrain data, the current availability or implementation of DTW maps and non-DTW-based trafficability prediction in the selected countries is surveyed within this review.

State of Operational Moisture-Driven Trafficability Modelling

Finland

Forest owners in Finland can estimate forest soil trafficability with two alternative methods: with the DTW maps or with the static trafficability maps developed by Arbonaut Oy.

The DTW maps are based on 2 m DTMs practically available for the whole country. Various stream networks are calculated by using 0.5 ha, 1 ha, 4 ha and 10 ha threshold on the flow accumulation raster. The DTW is finally calculated based on these stream networks and slope with cost accumulation per watershed, which is conducted by Luke, and the maps are available in the national spatial data download service (www.paituli.csc.fi).

The static trafficability map presents the classification of forests in 6 different trafficability classes. The map product, developed by Arbonaut Oy, combines classic topographic DTW information to tree volume and soil type (peatland or mineral soil). The trafficability classes are based on seasonal changes in bearing capacity of forest floor in Finland. The map provides information about the season when harvesting operations may take place with standard logging machinery (i.e. a harvester and a forwarder) without causing substantial damages on forest soil. The mapping unit is a pixel of 16 m size compatible with the forest resource information provided by the Finnish Forest Centre. Each pixel is classified in one of the following classes: 1, operations possible in all seasons; 2, operations possible in summer, mineral soils; 3, operations possible in summer during dry season, mineral soils; 4, operations possible in summer, peatlands; 5, operations possible in summer during dry season, peatlands; and 6, operations possible only during frost or thick layer of snow [65].

The trafficability maps are available for the whole country. The data is distributed as open access data by the Finnish Forest Centre. The data can be accessed via a map application and a web map service WMS. Also, the raster maps can be downloaded from the Finnish Forest Centre's www site (https://aineistot.metsaan.fi/avoinmetsatieto/Korjuukelpoisuus) as tif files. In addition, forest owners can access the data in www.metsaan.fi service portal. Metsaan.fi is a service for forest owner to easily access the information of their own forest and to use digital forest services. The trafficability maps are today widely used in Finnish forestry by forest operation managers and forest machine operators [66].

Sweden

The Swedish Mapping, Cadastral and Land Registration Authority, Lantmäteriet, scanned the entire country with high-resolution ALS technology between 2009 and 2016 to provide detailed terrain model required for climate change adaptation programmes and other environmental programmes [67]. The scanning was performed from airplanes at an altitude of 1,700–2,300 and up to 3,500 m in the mountains, on areas of 25 × 50 km, and collect data in the form of point clouds. The point intensity in scanning varies between 0.5 and 1 per m^2. It has an average error of 25 cm planar direction in the reference system SWEREF 99 TM and 5 cm in elevation in the reference system RH 2000. Using triangular irregular network (TIN) interpolation, the point data is transformed to a 2-m elevation grid with a precision that is better than 10 cm in height and 30 cm in planar [67]. The data set is freely available for research and education but requires subscription fee for commercial application. Elevation data, grid 50, is another terrain model available at the Swedish Mapping, Cadastral and Land Registration Authority. This model is built based on either the (1) national terrain model or (2) the elevation data bank (from the 1980s) and are used in more general applications, e.g. height contours generations and correction of satellite images.

A new nationwide LiDAR campaign with higher point density (1–2 pts/m^2) has just started in spring 2018, mainly to update the forest estimations, e.g. tree volume, height, average diameter and biomass. The product will be prepared for areas of 2.5 × 2.5 km [67] and produces DTMs with 1 m resolution.

DTW maps were prepared by the Swedish forest agency over the whole country since 2014 and were freely available through their online map services. The maps had been used by majority of forestry companies since about 5 years and contributed to improve planning of different forest operations [66].

A new version of soil moisture maps has been developed at the Swedish University of Agricultural Sciences (SLU) and is available at online map services of the Swedish forestry agency since beginning of 2021. There, Artificial Intelligence (AI) information from various (24) data layers, e.g. soil type, topography and climate, is combined to estimate a moisture index representing a yearly average of soil moisture in raster layers of 2 × 2 m resolution [45•].

Norway

The Norwegian Mapping Authority (Kartverket), in conjunction with partner organizations, collects, systemizes, processes, manages and disseminates national geographical information. In 2016, a national programme was started to generate a new detailed terrain model based on ALS, for areas with vegetation/forest cover, and image matching for mountain areas with little to no vegetation. The new terrain model is scheduled to be completed for the whole country (325,000 km^2) by 2022 [68]. Private vendors were awarded project wise to conduct the scanning campaigns with a coverage of at least 2 pts/m^2, delivering classified point clouds to the Norwegian Mapping Authority. Classes vary between ALS projects but always include the class "ground points". In addition to the contracted deliveries, existing regional ALS data of higher quality, but also photogrammetric image matching for high mountain plateaus, is used by the Norwegian Mapping Authority to generate the latest national DTM. The density of the point cloud behind the updated national DTM can therefor regionally differ but is constantly updated if higher quality data is available. The latest data sets can be visualized with a variety of web map services at the portal "hoydedata.no". Both the ALS point cloud data and a 1 m resolution DTM can freely be downloaded. A second acquisition of a national ALS data set at a later point in time is not planned so far. The digital elevation data will be updated using photogrammetry based on aerial images that are acquired in regular intervals (5–10 years) [69].

Based on the DTM availability, two DTW maps (Markfuktighetskart) presenting the soil moisture in a grid either as classes or in centimetre towards the soil surface are openly available on national level (www.kilden.nibio.no). The DTW maps are to varying degree used by foresters in the planning of forest operations in Norway. Further developments of the DTW maps will include a dynamic approach for trafficability mapping that combines weather data and DTW maps to predict trafficability, which will also lead to a better seasonal classification of operational sites.

France

In 2021, the first national French ALS campaign was initiated by the National Institute of Geographic and Forest Information (IGN = public administrative establishment placed under the joint authority of the Ministries in charge of ecology and forestry). In the course of this campaign, 10 pts/m^2 based products will progressively be published as open data by 2025, starting from the Mediterranean region and upward [70]. Although no starting date finalized so far, it is supposed to be implemented with countrywide coverage over a period of 5 years. Yet, sub-regions are identified as priorities for EU CAP monitoring purpose and are expected to be accomplished by 2023. The scanning campaign is envisaged to be conducted with a coverage of 10 pts/m^2, and the data will be used to produce DTMs and DSMs, after completion openly available through the national geoportal (https://www.geoportail.gouv.fr/). Additionally, an initiative from the Ministry of Agriculture intends to update the spatial data on 3-year intervals through 25 cm IR photography. But currently, the BD Alti, based on various regional data acquisition techniques, is the only nationwide available DTM, with highest resolution of 25 m grids, only.

For forest soil trafficability assessment, a model developed for agriculture (SoilFlex; developed by Keller et al. [71]) was also tested on two French forest sites. The purpose of the model was to predict compaction risks and rutting from a set of accessible parameters to practitioners for either agriculture or forestry. Results were, for the most part, successful. The exception occurred for the inclusion of the surface organic layer. This organic layer includes a high organic carbon and moisture and a smaller deformation than predicted by the model [72]. During the last decade, experimental plots were instrumented and monitored to document hydric transfer phenomena and forest soil reaction after compaction. Such fundamental research has been limited to few plots established on state-owned forest (two sites in Lorraine region) or via the network F-ORE-T with two sites partially focused on and instrumented for these topics. Monitoring of experimental sites for the long-term productivity shows that after two of the routing cycles of a forwarder, the sensitive forest soils are quickly degraded, and their restoration takes longer than 7 years [73]. Moreover, active restoration through e.g. mechanical loosening or ecological engineering practices such as exudation and providing substrates to promote biotic processes of soil recovery following soil compaction is difficult [74].

Germany

Owing to the federal organization in Germany, generation and provision of geodata is administered at different regional scales. The 16 individually organized state surveying offices of Germany are responsible for their respective data acquisition, including ALS campaigns to create terrain models. Although the resultant DTMs possess a high variability in terms of technology used and updating, they are available in all states with a grid cell size of 1 m, since the completion of the state Saxony in 2020 [75]. Access and retail fees depend on individual policies, ranging from open data DTMs, as provided via a web coverage service for the area of North Rhine-Westphalia [76] to commercial products as available for the area of Lower Saxony [77].

The Federal Agency for Cartography and Geodesy, BKG (Bundesamt für Kartographie and Geodäsie), in fulfillment of the Federal Geo-data Reference Act (BGeoRG), maintains geodetic reference systems and collects and provides data for utilization by other national authorities and to fulfil its international obligations [78]. The BKG delineates and updates countrywide DTMs as soon as new data is submitted by one of the 16 state surveying offices. The state-wide DTMs are merged to countrywide DTMs with a grid cell size ranging from 5 to 1,000 m. A countrywide DTM with a grid cell size of 200 m is openly accessible as part of the INSPIRE programme [64], same applies to the digital CORINE land cover map "LCL5", providing land-use classification at 5 ha resolution. DTMs with a higher resolution, covering the whole area of Germany, are retailed as commercial products by the BKG. Among these, the "DGM5" (5 m grid cell size) has the highest resolution, with prices dependent on area size and type of utilization.

Despite of the availability of DTMs, trafficability of forest management units in Germany is currently rather statically and non DTW-based evaluated, besides at a current regional research activity in North Rhine-Westphalia [79]. Site information and terrain slope classifications, in combination with the local forest manager's experience on trafficability, are a common way to select appropriate machine systems and schedule the most suited time of the forest operation. However, soil mapping has been conducted intensively in Germany, and digital soil maps are available, although highly varying between states [80]. Based on such soil maps, regional solutions were developed to support the common practice for mechanized forest operations. For instance, the state forest enterprise of Lower Saxony introduced trafficability risk maps, consisting of four risk levels [81] and made available for forestry stakeholders through an internal online GIS (geographic information system). Another approach was developed to evaluate operational systems according to technical limitations by the site classification, and in addition to observed stand development phases and weather conditions during the scheduled harvesting period [82]. Going a step further, the State Office for Environment, Agriculture, and Geology in the state of Saxony (LFULG) already provides a digital map showing soil's sensitivity to compaction at a scale of 1:50,000 [83]. It is based on the governmental digital soil map "digBK50", interfaced with monthly climatic water balance values recorded from 1993 onwards, and allows to consider soil compaction sensitivity according to various soil features during the seasons for large area planning, such as agricultural or construction operations. Although this is one of the first attempts of a soil moisture-driven trafficability modelling, the scale is too large to suit individual forestry operations.

Austria

Based on the INSPIRE programme of the European Parliament [63], and legally ratified through [84], a DTM with a grid cell size of 10 m is openly accessible for the whole area of Austria. This DTM has been retrieved from the first cycle of scan flights by ALS, in 2013. Due to the country's federalism, the geospatial data are managed individually by the nine states. A second and third cycle was performed by each state independently. The data density for the first cycle, in general, was 4 pts/m^2, while the intended value for ongoing measurements was 8–16 pts/m^2.

Austria has an open geodata portal, operated by the governmental provider [85]. The availability of geospatial data varies between the states: For instance, in Upper Austria, all the data are made freely available by the state office and contain DTMs with a grid cell size of 0.5 m or 1 m for each municipality. A guidance for merging and processing the XYZ tiles, using open tools, is provided too [86]. In line with this data organization, several Austrian states openly provide DTMs with a grid cell size of 1 m. However, for the area of Burgenland, Tyrol or Lower Austria, freely accessible DTMs show a lower grid cell size (5 m, or 10 m). For the area of Vorarlberg, contour lines are available only, either as a shapefile or rasterized.

Although the DTMs available for a large area of Austria are sufficient and the country declared a mandatory conservation of soils [87, 88], an implementation of machine-induced impacts through trafficability predictions is pending so far. Still, soil mappings and additional geospatial data for various topics such as forest, natural hazards, nature conservation, flood, and aerial images are offered partially.

Poland

In Poland, the data covering now whole country and first large acquisition is from one ALS campaign completed between 2011 and 2014. It was completed to fulfil obligations imposed on EU countries by the Directive 2007/60/EC of the European Parliament and the Council on the Assessment and Management of Flood Risks (23 October 2007) [89]. To assess flood risk, the Polish Government decided to start the project entitled "IT System for the Country's Protection Against Extraordinary Threats" (in Polish: ISOK – "Informatyczny System Osłony Kraju przed nadzwyczajnymi zagrożeniami"). Under this project, 92% of the total area was covered with ALS data, and based on DTM generated from ALS data, the flood risk assessment was determined. Before this period, there were obtained ALS data just from single projects and covered relatively small areas. The area scanned under the ISOK project was 288,806 km^2, from which 267,403 km^2 was completed with density of 4 pts/m^2; 8,148 km^2 with 6 pts/m^2, priority areas; and 13,769 km^2 with 12 pts/m^2, cities [89]. The derived DTMs are available with a grid cell size of 0.5 and 1 m. After 2014, new campaigns of ALS data acquisition were carried out, and now almost whole Poland is covered at least with one ALS data set.

The authority which hosts the national data is the Department of Photogrammetry at the Geodesic and Cartographic Documentation Centre in Warsaw. All data are freely available for any purpose. But currently the data has not been used to implement a DTW or other spatial approach to predict forest trafficability. However, on a pilot site, DTW maps have recently been applied for trafficability prediction on research level [79].

Latvia

In Latvia, 50.1% of the territory is covered by forests; agricultural land is covering 22.8%, grasslands 15.9%, wetlands 6.2% and settlements 4.8% [90]. One-time coverage of ALS data is provided for the whole territory of the country, and data collection has been organized by the Latvian Geospatial Information Agency (LGIA) by hiring foreign companies. ALS surveys were performed in the period from 2013 to 2019. The Leica ALS70, Riegl LMS-Q680i and Riegl LMS-Q780i scanners were used for scanning. ALS scanning was performed on both the leaf-on and leaf-off periods. The total point density is at least 4 points per square meter, while the density of ground points is at least 1.5 points per square meter. The ALS point cloud is automatically classified by ground points, as well as low, medium and high vegetation classes, but infrastructure and other objects are manually classified. The data is freely available on the LGIA website, as well as a generated DTM of 20 m resolution. Negotiations are underway for a second ALS campaign.

At the beginning of 2021, ALS data in Latvia were used to generate DTW maps nationwide in 5 m horizontal resolution, and individual map sheets can be downloaded from the LSFRI Silava website (http://www.silava.lv/produkti/Kartografiskie-materiali.aspx). In parallel, work is underway to develop a wet area map for the entire country according to the methodology described by Ivanovs and Lupikis [91]. Wet area mapping uses various indices obtained by processing DTM, such as depression maps, normalized elevation index, slope, TWI, DTW and other indices. These maps are planned to be popularized in forestry industry seminars and put into practice in forest management planning.

Discussion

This review indicated that there is a potential to mitigate impacts from ground-based harvesting by improved planning aided by DTW-derived predictions of sensitive soil conditions. The review of the country-wise status of trafficability predictions illustrated that basic requirements for applications in forestry industry are expanding throughout Northern and Central Europe with the increasing availability of highly accurate ALS-derived DTMs (Fig. 2A). However, it is merely in the Nordic countries that national DTW maps are publicly available with close to national coverage (Fig. 2B).

Since most European countries have initiated national ALS flight campaigns, country- or state-wide DTMs are available, enabling the creation of DTW maps for practical and scientific purposes. The creation of countrywide DTW

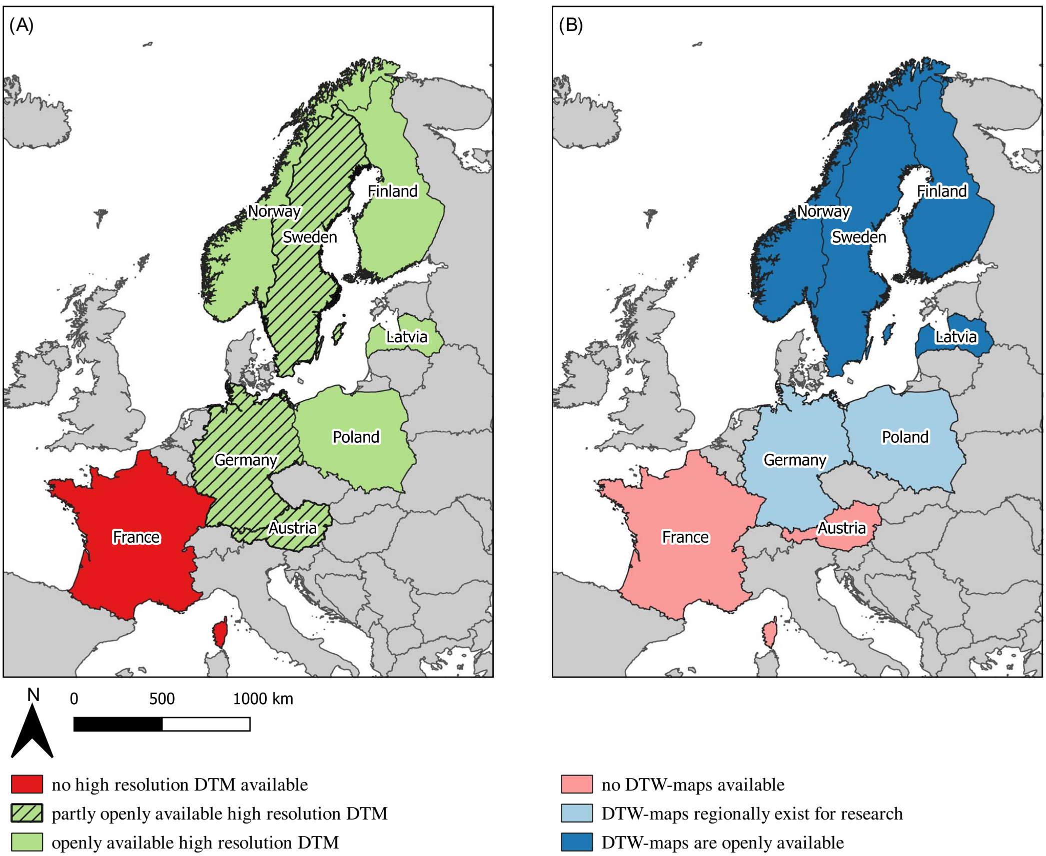

Fig. 2 Availability and accessibility of **A** high-resolution digital terrain models (DTM) and **B** depth-to-water (DTW) maps among the European countries included in the review about current state of trafficability prediction

maps has already been facilitated by specific public or private institutions in the Nordic countries such as Sweden, Norway, Finland, and Latvia. In order to actually enable the widespread use of high-resolution DTW maps in forest operations, the maps will very likely have to be produced by a central organization as it seems unrealistic that small- and medium-sized individual organizations are able to execute the acquisition of openly available data or the commercial purchase of DTMs from governmental providers. The availability of DTMs ranges between openly accessible DTMs with a grid cell size of 0.5 m to complex hybrid business models requiring the purchase of DTMs with such a high spatial resolution. For instance, in the case of large areas of Austria and Germany, a fee is required for high-resolution DTMs. There, only DTMs with a grid cell size of 5 m, 10 m or 200 m, respectively, are made openly accessible according to the INSPIRE programme [64]. Although the application of the DTW algorithm is generally robust to DTMs of different size [54], best results are achieved with DTM resolutions not exceeding 5–10 m, and ideally be even less than 5 m [92]. Thus, DTW modelling is technically also possible on DTMs with a low resolution of e.g. 200 m, but the resulting DTW map would not be practical for operational implementation to determine machine trafficability on a logging site [54].

Generally, it can be stated that the availability and accessibility of high-resolution DTMs is not a major limitation for the creation of DTW maps anymore. All surveyed countries already provide DTMs with a sufficient resolution, or as in the case of France, are on the way to facilitate national ALS campaigns. The more fundamental bottleneck might be the actual calculation of the DTW algorithm for the application of such maps as tools to increase soil conservation. Currently, DTW maps in most countries are produced by researchers and individual authorities [54] for an intended user, who covers the costs or possesses specific project funds. For a widespread practical application, supporting day-to-day forest operations, the maps should be generated on behalf of forestry stakeholders by dedicated experts, since entrepreneurs might not have the capability to create DTW maps. Although not solely DTW-based, the currently available static trafficability maps in Finland are a good example how information about trafficability can be made openly accessible and support sustainable forest operations at small scale [65]. Another big asset of the Finish maps is also the classification according to seasonal recommendations for the execution of operations [65]. Such a feature current DTW maps are generally lacking, since they just define an area as "wet" or "dry" [45•], although attempts to further classifications into various wetness categories are in progress [66]. Therefore, it would be a worthwhile endeavour to governmentally provide comprehensive trafficability maps, covering European forests. In addition, the open accessibility to DTMs with a sufficient resolution as well as to remaining geospatial data would support and promote both practical applications and purposes, as confirmed by Melander et al. [17].

Regardless of the origin of DTW maps, an enhanced soil conservation through cartographic material requires a user-specific interface. Modern forest machines are capable to read and display geospatial grids, such as DTW maps. Apart from that, the "TECH4EFFECT Mapping App" [93] is a good example following the open geospatial information philosophy, by providing such an interface through a no-cost Android OS mobile application. The app is conceived primarily as a visualization tool for machine operators to be able to adopt their path of travel in accordance with the geo-referenced location and displayed DTW maps. Additionally, such apps usually allow for incorporating further spatial information about additional "no-go areas", such as protected areas, with the option to prompt the user with a signal when approaching these.

Displaying DTW maps by machine's on-board computers, integrated into mobile GIS applications, can provide the operator with site-specific information to choose the extraction route that combines consideration for both benefits for soil conservation and operational efficiency. The latest GNSS (Global Navigation Satellite System) receivers are standard features on state-of-the-art logging equipment, setting the basis for such an approach. Yet, precise machine positioning, as through RTK (real-time kinematic) support [94], and in-field access to DTW maps, which could be provided as web map service, require mobile networks with high data transmission standards, also in remote forest areas [95]. But in many European regions, the mobile network infrastructure does not meet these requirements yet [96]. It is therefore the responsibility of the relevant government agencies of the individual countries to build up the demanded standards. Until then, standalone applications, functioning in off-line modes, will be the focus of intermediate solutions [95].

Besides technical and administrative challenges, a full-range implementation of DTW-based trafficability maps would require a dynamic approach, accounting for seasonal variation of soil moisture [92, 97, 98]. Research activities currently address this issue, for example by sequential combination of DTW maps and additional, freely accessible weather data. This led to a recently conducted dynamic approach, integrating information about topography, soil and vegetation [99], used for trafficability prediction on pilot sites in Finland, creating suitable outputs with a grid cell size of 16 m [46••]. Including real-time weather forecasts in the trafficability models would further enhance prediction quality at a dynamic level [92, 97, 98].

Further to dynamic information about moisture-driven trafficability, operational information is required to optimize quasi-instantaneous planning, the actual most efficient routing of forestry equipment to ensure productive operations with minimal impact. The "BestWay" decision support system [60•] shows on a case study level in Sweden how DTW maps, in combination with further detailed information on operational site features, can be used for optimized routing. Detailed information on forest volume, its density and concentration, position of landings and areas for natural conservation, as well as known unavoidable crossings in the terrain, are used in complementing the DTW maps. By this, the least cost extraction route with lowest expectable soil damage can be identified. Despite its promising results, evaluated under scientific settings, the "BestWay" system is too complex and processing capacity demanding for practical applications [45•]. However, principles of the "BestWay" decision system have been adapted to develop the more basic but operational commercial planning tool "Timbertrail", which is well acknowledged by first user experiences [100]. This pinpoints on the relevance to further implement additional spatial and site-specific information to reach sufficient trafficability prediction systems.

Site-specific information, such as information derived from forest inventories or soil mapping, are commonly gathered by national institutions, but not always openly accessible for every forestry stakeholder. National forest inventories were initiated in Europe already a century ago, providing detailed information on the forest condition and other related parameters for decision support, collected through sample plots, but also remote sensing approaches, continuously improving on the fine resolution of this data [101]. In addition, soil mapping on national level has a long tradition in Europe too, and initiatives are in place to merge national attempts to a digital and thematic soil map database—yet this is a long-term process, and the resulting spatial information will only be available at a coarse resolution [102]. The accessibility to various geospatial data gathered by national authorities and consequently the ability to integrate such data in topical trafficability predictions should be improved by open access databases.

Current research demonstrated already how openly available geospatial and temporal data can be used to improve predictions of soil moisture and trafficability. Recent findings of Schönauer et al. [103] showed a method how information of different origins and spatial resolutions was fused, in order to achieve a spatiotemporal prediction of soil moisture on different forest sites in Europe. Moreover, spatial predictive systems can be merged with operation-specific information, captured in real-time through forestry machine-based sensors itself [17, 45•, 46••]. Fully mechanized harvesting operations are eminently suitable for such an approach, since the forwarder extraction is invariably consecutive to the harvester traffic, allowing forwarder routing to be adapted based on the previously captured data. The international forest machine standard StanForD compiles operational data for various components of forest machines and can be used to determine the felled and loaded timber on each machine; thus, the pile volumes can be constantly updated as well as the gross weight of the vehicle. In addition, the CAN-bus (controller area network) system captures data from the engine and drive train, which are valuable for trafficability purposes, too. As soon as telecommunication infrastructure will allow for improvements of accurate RTK-supported positional data from the GNSS, wheel slip can potentially be computed [104], based on machine internal CAN-bus recordings [16•]. The CAN-bus data therefore can contribute to computationally producing a mobility map for optimal routing of the forwarder, as rut formation after a harvester pass has been a good predictor of the rut formation in forwarding, both on mineral and on peatland soils [41, 105]. In addition, forest machine-mounted LiDAR (light detecting and ranging) proved to be able to measure rut development during forwarder operations and can be used as another potential component to be integrated in an active routing system of a forwarder [17, 45•, 46••, 106].

With GIS expertise nowadays in place in forestry institutional and corporate settings, and the DTW algorithm available through open access data repositories [56], the corresponding maps can be easily created for regional applications, as long as access to a sufficient DTM is granted. Thus, the required economic resources can be considered moderate in comparison to the benefits of improved operational planning and increased efficiency during timber harvesting. Moreover, since static DTW maps once created can easily be used on mobile devices or standard forest machine map interfaces, no further running costs can be expected. Yet, further developments towards a dynamic approach could demand additional services and system infrastructure related to the more intensive data input, which can add new costs to the use of such systems. However, any potential additional expenses should always be offset against the multiple environmental benefits associated to higher consideration of soil conservation along the timber supply chain. Further, it is also worth mentioning that DTW maps can support multiple other application areas in forestry. DTW maps were reported as being promising tools in enhancing water protection through a better spatial knowledge of perennial and intermittent streams, an important asset for the implementation of riparian buffer zones as best management practice among sustainable forest operations [107]. Even in winter months, when the surface was covered by snow, and streams were invisible, such maps helped to avoid machine passes in these sensitive areas [108, 109]. Further, Bartels et al. [110] used DTW maps to relate bryophyte assemblages to wet forest areas, indicating the potential use of the algorithm to select between harvest areas and sites relevant for biodiversity conservation within a landscape management approach. In addition, DTW maps were recently used to monitor site indices. A variation in productivity was adequately portrayed in a survey by Bjelanovic et al. [111], who reported a potential application to model forest growth and yield. Finally, a combination of DTW maps with data of annual precipitation was used to delineate drought-prone areas during periods of low moisture conditions [108, 109, 112].

Conclusions

DTW maps are eligible to support forest management towards a mitigation of traffic-induced soil impacts, by identifying sensitive areas that should be avoided during mechanized operations. It is therefore supportive during the planning phase, but also during the execution of operations. The creation of practicable DTW maps relies on the availability of high-resolution DTMs. Most of the European countries have programmes to capture ALS data and produce high-resolution DTMs with increasing data quality or are on the way to do so. However, the DTMs and other spatial information is not always openly available, or just in lower resolutions. In order to generate and apply DTW-based trafficability maps to aim for sustainable forest operations on a wider range, the already proceeding European open access policy for spatial data should be further intensified and be more consolidated across the continent. This should not only cover spatial terrain data, but also forest inventory, soil mapping, climatic conditions and other relevant information currently envisaged to further improve upon the potential of dynamic trafficability mapping and post-harvest impact monitoring. Furthermore, additional work is needed to integrate this information through consistent applications and interfaces to enable a full usage of such systems by forest planners and machine operators. Despite all that, DTW maps already found their way into forest operations and first attempts to make them dynamic are in place. The Nordic countries, in particular Sweden, adopt a forerunner position, but the other reviewed countries initiate similar approaches, and it can be expected that in foreseeable time, dynamic trafficability maps will become a standard tool to support sustainable forest operation practices.

Funding Open access funding provided by Norwegian Institute of Bioeconomy Research. This research was funded by the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation programme, TECH4EFFECT Knowledge and Technologies for Effective Wood Procurement—project (grant number 720757) and EFFORTE Efficient forestry by precision planning and management for sustainable environment and cost-competitive bio-based industry—project (grant number 720712). The contributions from the University of Göttingen were further financially supported by the Eva Mayr-Stihl Stiftung.

Declarations

Conflict of Interest Stephan Hoffmann, Marian Schönauer, Joachim Heppelmann, Antti Asikainen, Emmanuel Cacot, Benno Eberhard, Hubert Hasenauer, Janis Ivanovs, Dirk Jaeger, Andis Lazdins, Sima Mohtashami, Tadeusz Moskalik, Tomas Nordfjell, Krzysztof Stereńczak, Bruce Talbot, Jori Uusitalo, Morgan Vuillermoz and Rasmus Astrup declare that there are no conflicts of interest to declare.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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• Of importance
•• Of major importance

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Silva Fennica vol. 51 no. 5 article id 2018
Category: research article
https://doi.org/10.14214/sf.2018

SILVA FENNICA

http://www.silvafennica.fi

ISSN-L 0037-5330 | ISSN 2242-4075 (Online)
The Finnish Society of Forest Science

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Influence of soil type, cartographic depth-to-water, road reinforcement and traffic intensity on rut formation in logging operations: a survey study in Sweden

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 vol. 51 no. 5 article id 2018. 14 p. https://doi.org/10.14214/sf.2018

Highlights

- Soil type and traffic intensity had significant effects on rut formation.
- Further studies are required to identify all factors affecting rut formation, especially on soils with medium bearing capacity.
- The cartographic depth-to-water index (DTW) alone did not predict rut formation, but used in combination with other information, e.g. soil type, could be an interesting tool for delineating soil areas that are potentially vulnerable to rut formation in logging operations.

Abstract

Rut formation caused by logging operations has been recognised as a challenge for Swedish forestry. Frequent traffic with heavy machines on extraction roads, together with a warmer climate, is one of the factors that increases the risk of rut formation in forests. One possible way to control this impact of logging operations is to design and apply decision support tools that enable operators to take sensitive areas into account when planning extraction roads. In this study, 16 different logging sites in south-eastern Sweden were surveyed after clear-cut. Information was collected about extraction roads (i.e. traffic intensity, whether the roads had been reinforced with slash) and ruts. Digital maps such as cartographic depth-to-water (DTW) index and soil type were also examined for any connection to rut positions. Soil type and traffic intensity were found to be significant factors in rut formation, while DTW and slash reinforcement were not. However, the DTW map combined with other information, such as soil type, could contribute to decision support tools that improve planning of extraction roads.

Keywords forestry; forwarder; soil disturbance; decision support tool
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Received 16 January 2017 **Revised** 10 November 2017 **Accepted** 16 November 2017

1 Introduction

Forest harvesting takes place all year round in Sweden, as forest industries need fresh wood to produce high-quality sawn goods and to reduce the need for chemicals in pulping. Modern timber harvesting machinery is costly, but high annual utilisation rates help reduce harvesting costs and provide operators with full-time employment throughout the year, which could compensate for the investment cost. Operating heavy forest machinery all year round poses many challenges, not least negative environmental impact on the physical and chemical properties of soil.

Depending on ground bearing capacity, rut formation and soil compaction may occur in forest soil during ground-based logging operations with heavy machines (Kozlowski 1999; Williamson and Neilsen 2000; Eliasson 2005; Horn et al. 2007). Soil compaction occurs when applied load on soil exceeds the ground bearing capacity, destroying air-filled pores among the soil particles (McNabb 2001). This increases the soil strength and may reduce root penetration (Taylor 1971), and disturbs water drainage and air infiltration, which promotes anaerobic conditions in the soil and affects site fertility (Kozlowski 1999; Cambi et al. 2015).

The level of soil compaction resulting from forestry operations depends on several factors, including machine-applied pressure, soil texture and its organic matter and water content (Ampoorter et al. 2010). Ground bearing capacity of a specific site may even vary significantly between seasons, depending on variability in flow discharge amounts and soil wetness (Ågren et al. 2015). When moisture content of the soil increases beyond a critical level, extra pressure would cause soil displacement at the site of machine tracks, contributing to rut formation after vehicle passages (Cambi et al. 2015). Consequently, degree of rut occurrence also depends on site-specific factors such as soil texture and moisture content, vehicle specifications and driving behaviour e.g. velocity and turning radius (Braunak et al. 1993; Liu et al. 2010). Rut formation may imply higher bulk density and lower hydraulic conductivity at the tracks that, in turn, leads to higher risk of surface run-off and erosion (Shack-Krichner et al. 2007) and could be followed by higher loads of sediments (Ågren et al. 2015), nutrients and accumulated mercury in soils of Swedish boreal forests to water environments (Futter et al. 2016). Field studies, however, have shown both positive and negative effects of soil disturbance on forest growth (Wronski and Murphy 1994), and effects can change over time (Passauer et al. 2013).

According to Swedish forestry legislation, "severe ruts" are ruts that may affect soil and water status negatively, disturb accessibility of pathways, reduce aesthetic values of the forest, or damage cultural heritage sites. Severe ruts should be avoided in forestry operations (Swedish Forest Agency 2015). Protecting water bodies by leaving trees in 8–10 m buffer zones and avoiding driving heavy machinery across flow channels and ditches are examples of preventive actions suggested in a handbook provided for forest machine operators in Sweden (Ring et al. 2008).

A commonly used method to reduce soil disturbance is to use tops and branches from harvested trees, slash, to strengthen the ground on extraction roads where the soil is moist, i.e. more susceptible to rut formation, or where the extraction roads are expected to be trafficked more intensively. Eliasson and Wästerlund (2007) showed that application of slash on extraction roads reduces soil compaction on the upper parts of the soil, but soil compaction tends to increase with the number of passages, even on reinforced extraction roads. Slash has an economic value as biomass for energy production, so it is only used to reinforce extraction roads where necessary. The extraction of biomass for fuel therefore competes with the application of slash as a reinforcement element in improving the soil bearing capacity (Labelle and Jaeger 2012).

Other methods are used to reduce ground impact. Planning or decision support tools have been developed as a function of topography and soil type (Mohtashami et al. 2012) or combined with other factors like vehicle wheel specifications (Suvinen 2006) to predict terrain trafficability.

These planning tools could be regarded as possible best-management practices to minimise soil disturbances, and their performance could improve if the models predict soil hydrological characteristics in the terrain more dynamically. LiDAR (light detection and ranging) extracted digital terrain models (DTM) have been used to map different soil moisture indexes that capture the paths of water flows on terrain surfaces, considering both surface topography and gravitational differentiation as driving forces for water drainage (Seibert and McGlynn 2007; Grabs et al. 2009; Qin et al. 2009). In the 1970s, Beven and Kirkby (1979) introduced the topographic wetness index (TWI), which is based on local upslope area draining through a certain point, divided by the gradient at that point.

A variety of methods are used to calculate TWI. Sørensen et al. (2006) studied different versions of TWI, applying different approaches to calculate catchment area and slope, and evaluated them against field-measured variables such as vegetation, soil chemistry and hydrology in boreal forests in northern Sweden. Beven and Kirkby's TWI was seen to be site-specific and dependent on the type of variable it was to estimate; different versions might perform better than others, so local verification would be needed to achieve optimum results. In general, a modified Tarboton et al. (1991) method for calculating flow distribution resulted in improved matches for ground water level estimations.

Murphy et al. (2006) developed a cartographic depth-to-water (DTW) index based on topographic conditions and hydrographic data. DTW is also defined as the "tendency of the soil to be saturated" (Murphy et al. 2007). The model is mathematically described in Eq. 1:

$$\text{DTW (m)} = \left[\sum\left(\left(dzi / dxi\right)a\right)\right]Xc \quad (1)$$

where dzi/dxi is the smallest elevation path between cells of the landscape and nearest surface water with highest probability for hydrological connectivity to that cell; a is a constant parameter adjusting for direction of movement from cell to cell, and is equal to 1 when the path is parallel to the cell edge and 1.414214 when it passes the cells diagonally; Xc is the grid cell size (m) (Murphy et al. 2009).

Murphy et al. (2009) also compared the wet areas captured by DTW and those of the TWI with field-mapped soil wet areas for a 193-ha watershed in Alberta, Canada. Results showed that DTW had a better conformance, probably because it accounted for the local downslope topography and hydrological conditions, while omitting the effect of overdependence on convergent flow accumulation in TWI. However, in areas with different climatic and topographic conditions, field verification would be required to attain better DTW conformance. Ågren et al. (2014) compared several wetness indexes, e.g. Tarboton's TWI, and Murphy's DTW, in a Swedish landscape to evaluate which had the best capability for capturing the watersheds. TWI and DTW were identified as best matches; TWI is scale-sensitive while DTW is not. It was also shown that the optimal threshold for flow channel initiation in the DTW model needed to be adjusted to the surrounding soil type.

Most studies of the effect of specific factors on rut formation have applied controlled study designs to avoid confounding factors. However, a major factor influencing rut formation during logging operations is decisions taken by the machine operators, such as where to locate extraction roads, where to reinforce them, and which areas to avoid. Furthermore there are areas close to landings, where all logs are collected for final transportation, where driving cannot be avoided. This complexity of site conditions, operator decisions and interaction of influential factors are difficult to capture in controlled studies, so a survey study of several logging sites is needed in order to describe rut formation during practical harvesting conditions.

This study aims to evaluate whether cartographic soil moisture (DTW index), slash reinforcement of extraction roads, traffic intensity presented as number of machine passages, and expected bearing capacity of different soil type influence the risk for rut formation in commercial harvesting operations. Another aim was to evaluate whether a DTM-based soil wetness index would contribute to a decision support tool that could help logging planners and forest operators detect sensitive parts of the forest soil prior to logging operations, thereby enabling them to make better decisions regarding protection of moist soil.

2 Materials and methods

Sixteen logging sites, totalling 171 ha, were surveyed by two field technicians in summer 2013 to collect information on extraction roads and ruts in practical operating conditions. The logging sites belonged to Bergvik Skog AB and were located in Österbybruk, south-eastern Sweden. The logging operations involved mechanised cut-to-length (CTL) systems consisting of a single grip harvester and a forwarder. Operators and logging machines varied from site to site. To prevent rut formation, harvester operators reinforced extraction roads with slash where it was deemed necessary according to instructions given by the company responsible for harvesting operations in Bergvik Skog's forest lands, Stora Enso. The sites were harvested between October 2011 and March 2013, and logs were forwarded immediately after felling. The surveyed data was collected using Arcpad software installed on a Yuma Trimble field computer.

2.1 Field data collection on extraction roads

All extraction roads, strip and base, used by forwarders were surveyed and described in line shapefiles with field-related attributes: (1) whether they had been reinforced with slash, and (2) traffic intensity, expressed as road class. Road classification – small strip roads, strip roads, base roads – was based on an estimated number of forwarder passages and the position of the extraction road on the logging site. Little-used peripheral road segments were combined into roads with more passages, and an intensively used road segment cannot become less trafficked as it approaches the landing. This might introduce some bias in the data, but the two field technicians agreed on the classification system applied to the surveyed roads (Table 1). All the extraction roads had been trafficked once by the harvester prior to forwarding, but this passage was not included in the classification procedure, since harvesters cause much less soil disturbance than a laden forwarder.

2.2 Field data collection on ruts

Ruts were defined as parts of a road surface where the soil had been disturbed by being pushed downwards or sideways due to machine passage. They were visually detectable, with depths greater than 10 cm in the deepest part of the cross-section of the tracks measured from adjacent ground level.

Table 1. Classification of extraction roads based on the estimated number of forwarder passages.

Road class	Number of passages
(1) Small strip road	1–2
(2) Strip road	3–5
(3) Base road	6–10
(4) Main base road	>10

Table 2. Soil bearing capacity classification based on soil type.

Soil bearing capacity class	Soil type
(1) High bearing capacity	Bedrock, stony soils, gravely till soils
(2) Medium bearing capacity	Sand and gravel sediments, sandy till soils
(3) Low bearing capacity	Peat soils, clay and silt sediments, clayey silt and silty till soils

The ruts of each site were surveyed and collected in either point or line shapefiles. The surveyed ruts were described by the following attributes: (1) length and width, (2) the road class on which they were located, and (3) whether they were located on slash-reinforced/non-reinforced segments of the roads. If severe ruts appeared in both tracks of the roads, they were measured separately but were given a single GPS-positioned point. Shape and raster files were processed in ArcMap 10.1.

2.3 Extracted data from digital maps

In addition to field-collected attributes, information about soil type and wetness condition was retrieved from soil and DTW maps for all surveyed roads and ruts. As the soil type classification in the maps is imprecise, they were grouped into three bearing capacity classes to simplify the analysis (Table 2).

A DTW index map with 1-ha flow initiation, was prepared for the logging areas by the Forestry and Watershed Department at the University of New Brunswick. The saturated areas captured by the DTW index were classified in two main groups: areas where the depth to the nearest surface water was equal to or less than 1 m (DTW ≤ 1 m), and areas where the depth to the nearest surface water was more than 1 m (DTW > 1 m).

GPS-positioned roads and ruts were projected onto the maps to extract corresponding soil and moisture classes to the field data and to measure the length of road segments in corresponding classes on each map. Fig. 1 illustrates one of the logging sites, surveyed roads and ruts on the DTW map and the soil map.

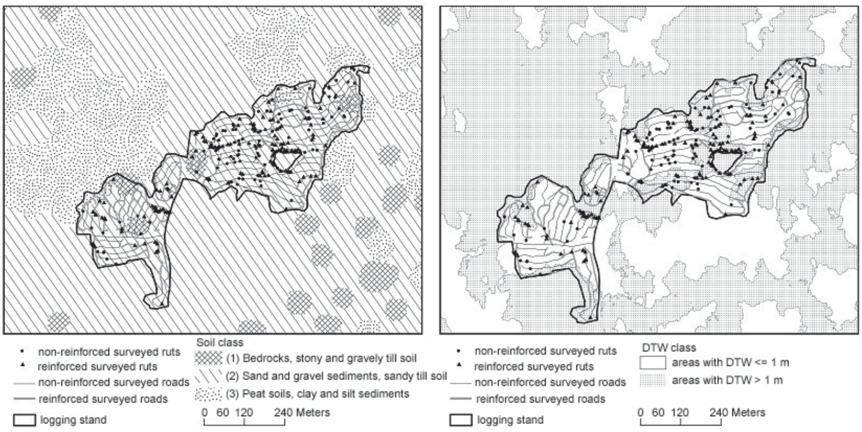


Fig 1. One of the 16 logging sites with surveyed roads and ruts over soil map (left), and the reclassified cartographic depth-to-water (DTW) map (right).

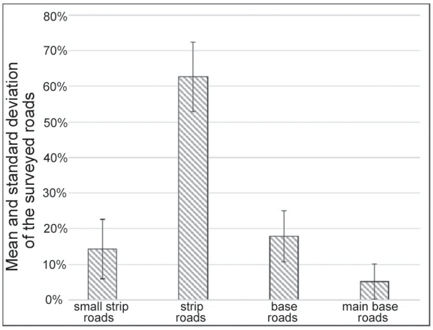
Table 3. Summary of the surveyed sites and extraction roads trafficked by forwarders. Areas with depth-to-water (DTW) <= 1 m were supposed to be more vulnerable for rut formations at trafficking.

Object no	Area, (ha)	Share of area with soil type of different bearing capacity, (%)			Share of area with DTW <= 1 m, (%)	Total length of roads, (m)	Share of roads with ruts deeper than 10 cm, (%)
		low	medium	high			
1	39.27	13	73	14	14	23062	28
2	20.15	7	86	7	7	12210	8
3	4.87	11	65	25	25	3392	28
4	2.97	1	52	48	48	1641	20
5	1.86	0	64	36	36	1038	25
6	2.65	0	88	12	12	1624	18
7	15.61	2	71	27	27	8900	21
8	0.85	12	88	0	0	410	5
9	5.92	2	75	22	22	3300	7
10	3.94	0	65	35	35	2249	6
11	18.15	4	79	17	17	10042	7
12	7.99	0	79	21	21	4258	2
13	18.38	5	70	25	25	9833	1
14	7.08	0	97	3	3	4171	0
15	16.26	19	77	4	4	8811	2
16	12.19	0	98	2	2	4836	3

A summary of variations in size of logging sites, soil bearing capacity, share of saturated areas in the logging sites, and total length of extraction roads is presented in Table 3.

2.4 Data processing and evaluation

Where a point-registered rut involved ruts in both tracks, the lengths of these segments were summed to give the total length of the rut at that point. In areas where the ruts had been collected in line shapefiles, the length of the lines was doubled if there were ruts in both tracks. The same procedure was applied to measure the length of the extraction roads: GPS-recorded roads were measured in ArcGIS and their length was multiplied by two to account for both tracks of a single



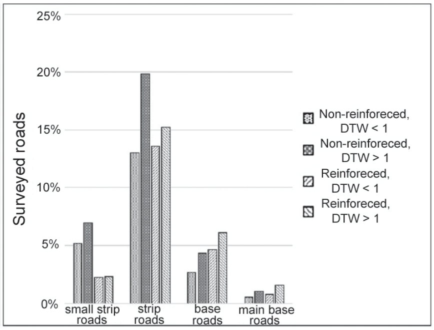


Fig 2. Mean value and standard deviation of the surveyed roads on 16 logging sites by road class: (1) small strip road with 1–2 passages, (2) strip road with 3–5 passages, (3) base road with 6–10 passages and (4) main base road with >10 passages (left); Distribution of surveyed roads by road class and the cartographic depth-to-water (DTW), (right).

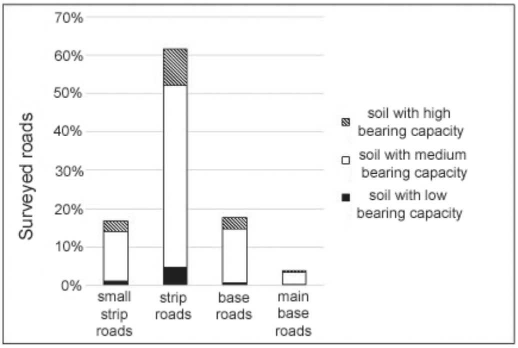


Fig 3. Distribution of the surveyed roads by road class and soil type.

machine. The share of roads with ruts deeper than 10 cm was calculated by dividing the total length of ruts, either as point or line, by the doubled length of the lines representing the road segments in each road class, soil class, reinforcement and DTW class. Collected data was evaluated to: illustrate how mean value and standard deviation of the extraction roads looked like by road class in the surveyed sites (Fig. 2, left), how the extraction roads were distributed in terms of slash reinforcement and correspondent DTW index (Fig. 2, right), and how they were distributed over road class and soil type (Fig. 3).

2.5 Statistical analysis

All the statistical analysis involved shares of ruts on road segments in the defined classes of road class, soil type, slash reinforcement and DTW. The mixed linear model in Eq. 2 describes the statistical model used to analyse the data. Since the share of roads with ruts was not normally distributed, the share of ruts was logit transformed to (y_{ijklm}) before analysis to fulfil the normal distribution requirement of the mixed model analysis. The logit transformation was necessary since it transforms the primary range of shares $s_m \in [0, 1]$ onto the interval [-∞, ∞] assumed by the normal distribution (Olsson 2002).

$$y_{ijklm} = \mu + a_i + b_j + c_k + d_l + ab_{ij} + ac_{ik} + ad_{il} + bc_{jk} + bd_{jl} + cd_{kl} + s_m + e_{ijkml} \quad (2)$$

where

y_{ijklm} is the logit value of the response variable for observation *ijklm*,

μ is the overall mean,

a_i is the fixed effect of road class *i* (where *i* is small strip road, strip road, base road or main base road),

b_j is the fixed effect of DTW class *j* (where *j* is DTW≤1 or DTW>1),

c_k is the fixed effect of slash class *k* (where *k* is reinforced or non-reinforced with slash),

d_l is the fixed effect of soil class *l* (where *l* is high, medium or low bearing capacity),

s_m is the random effect of site *m* (where *m* is stand 1, 2, …, 16); where we assume $s_m \sim N(0,\sigma_s^2)$,

ab_{ij}, ac_{ik}, ad_{il}, bc_{jk}, bd_{jl}, cd_{kl} are interaction effects, and

e_{ijklm} is the random residual of observation *ijklm;* where we assume $e_{ijklm} \sim N(0,\sigma_e^2)$.

Sites were regarded as a random factor in the analysis, since they had been chosen randomly from the landowners' stand databases for logging operations. A level of $p<0.05$ was chosen to distinguish significant factors. The analyses were carried out using the Proc MIXED procedure in the SAS® statistical software (Ver 9.4 SAS Institute Inc.).

Since site has a large influence in the joint analysis above, the GLM (General Linear Model) in Eq. 3 was used to analyse which factors had a significant effect within each site.

$$y_{ijklm} = \mu + a_i + b_j + c_k + d_l + ab_{ij} + ac_{ik} + ad_{il} + bc_{jk} + bd_{jl} + cd_{kl} + e_{ijkml} \quad (3)$$

3 Results

Distribution of the surveyed extraction roads by road class varied from site to site. Analysis of the mean value of the road lengths among the studied sites showed that the most common road class was strip roads with 3 to 5 passages (Fig. 2, left). Non-reinforced roads constituted almost 54% of the roads in surveyed sites. In total, 21% of the surveyed roads were non-reinforced and were located on saturated areas with DTW ≤ 1 m, while a further 33% of the roads were non-reinforced with slash but situated on drier soils with DTW > 1 m (Fig. 2, right). The surveyed extraction roads were distributed differently on soil with low, medium and high bearing capacity types; 7%, 77%, 16% respectively. Fig. 3 shows shares of soil type over road class; the biggest share of soil type in each road class had medium bearing capacity.

The share of roads with ruts varied considerably among the logging sites (Table 3). In a statistical analysis of the share of roads with ruts deeper than 10 cm, using the variables road class, DTW, slash reinforcement, soil class and their interactions, both soil class and road class had significant effect on the share of rutted roads (Table 4). The variance between sites was 42% of residual variance. Analysis of the share of roads with ruts deeper than 10 cm in relation to soil class showed that soil types with medium bearing capacity had the largest share of ruts compared to the other two classes, and that share of ruts in all road classes clearly increased with the number of machine passages (Fig. 4).

The site wise analyses showed that more factors can have a significant influence on rut formation in an individual site than those that proved to be significant in the general mixed model. The two factors that most commonly had a significant or near significant influence on rut formation

Table 4. Statistical analysis of share of roads with ruts, and explanatory variables: road class, cartographic depth-to-water index (DTW), slash reinforcement, soil classes and their interactions. A level of $p < 0.05$ was chosen to distinguish significant factors.

Variable	Degrees of freedom	F-value	p-value
Road class	3	13.29	<0.0001
DTW	1	1.68	0.1960
Slash reinforcement	1	0.43	0.5144
Soil class	2	12.18	<0.0001
Road class × DTW	3	0.39	0.7613
Road class × Slash reinforcement	3	0.64	0.5887
Road class × Soil class	6	1.37	0.2266
DTW × Slash reinforcement	1	0.88	0.3488
DTW × Soil class	2	0.92	0.3986
Slash reinforcement × Soil class	2	0.00	0.9977

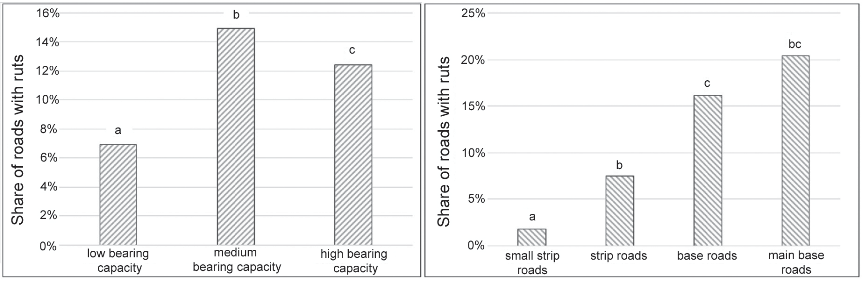


Fig. 4. Share of roads with ruts deeper than 10 cm by soil class (left) and road class (right) in all surveyed sites. Bars with different letters are statistically significant from each other according to the Tukey test.

were, as expected from the mixed model, road class (traffic intensity) in 8 of 16 stands and soil type (soil bearing capacity) in 9 of 16 stands. The DTW index was influential in 8 of 16 stands, but this was almost always in interaction with another factor (Table 5).

4 Discussion

Several factors determine the severity of rut formation during logging operations. Soil bearing capacity, wetness of the ground, intensity of traffic on logging roads, and applied mitigating measures such as reinforcement of the extraction roads with slash are among the factors that can affect the level of soil disturbance in forest operational activities.

Some parameters such as road class (traffic intensity) and soil bearing capacity influenced the share of ruts mainly in the expected way, i.e. the share of ruts increases with traffic intensity, which corresponds with the findings of others (Ezzati et al. 2012; Agherkakli et al. 2010) and decreases for soils with high bearing capacity. One important finding of this study is that the main trafficked soil type with the greatest share of rut occurrence on the surveyed sites is soils of medium bearing capacity. There have been far more controlled experimental studies on soil with a low bearing capacity (Eliasson 2005; Eliasson and Wästerlund 2007; Bygdén et al. 2004), so there is a need for controlled experiments on factors affecting rut formation on soils of medium bearing capacity.

DTW had no significant influence on predicting rut frequency in the analyses of the total survey data. However, when the data was separated by site, DTW had an impact on the frequency of ruts in some sites, often in interaction with other parameters. This is logical, as soil moisture could be expected to have a larger effect on the probability of rut formation on weak (fine grained) soils than soils with high bearing capacity or on bedrock. Furthermore, the calculated DTW is a continuous variable, so the boundary between the two DTW classes used in this study does not mean that $DTW > 1$ equals dry soil and $DTW \leq 1$ equals wet soil, but rather that the former is probably drier then the latter. Our findings support those of Ågren et al. (2015), who showed that DTW maps alone cannot be used as a tool for predicting rut locations, but can delineate saturated areas connected to main flow channels where rut occurrence may increase the risk for sediment transportation.

The cartographic depth-to-water index, DTW, when used together with other site-specific information such as soil type and topography (Mohtashami et al. 2012), could be used as a planning tool that can help detect sensitive areas in logging sites. Such a tool can assist planners and

Table 5. Analysis of the influence of road class, cartographic depth-to-water (DTW) index class, soil class and slash reinforcement on the share of roads with ruts in the different sites, *p*-values from the 16 stand-based ANOVAS. A level of $p < 0.05$ was chosen to distinguish significant factors, cells with * indicate a significant influence and cells ** with are the ones with a near significant influence.

Stand	Road class	DTW	Slash reinforcement	Soil class	Road class × DTW	Road class × Slash	Road class × Soil class	DTW × Slash reinforcement	DTW × Soil class	Slash reinforcement × Soil class
1	0.0215*	0.03*	0.0002*	0.0197*	0.9748	0.0026*	0.2036	0.9905	0.572	0.0828**
2	0.0964**	0.165	0.9365	0.001*	0.4871	0.5493	0.3164	0.3892	0.0183*	0.3962
3	0.001*	0.2934	0.3274	0.0537*	0.4494	0.6837	0.0089*	0.4046	0.4716	0.5252
4	0.04*	0.2958	0.9687	0.4161	0.1479	0.9619	0.2917	0.8235	0.455	0.9128
5	0.0044*	0.6441	0.2259	0.2571						
6	0.5042	0.495	0.7857	0.7572	0.5648	0.6788	0.3797	0.5098		0.7765
7	0.0322*	0.4084	0.0879**	0.0205*	0.2025	0.6711	0.1634	0.4945	0.8165	0.1111
8	0.3764	0.4226	0.8608	0.3453						
9	0.0119*	0.1102	0.097**	0.0015*	0.1057	0.0019*	0.1448	0.7727	0.3545	0.0003*
10	0.0354*	0.1911	0.7014	0.419	0.6164	0.2061	0.701	0.041*	0.8409	0.1424
11	0.101	0.6993	0.2517	0.0004*	0.0819**	0.3958	0.2811	0.6566	0.1238	0.1942
12	0.0893**	0.5333	0.9812	0.1362	0.3472	0.4568	0.9896	0.7221	0.317	0.942
13	0.0185*	0.1037	0.0683**	0.0129*	0.1339	0.3667	0.2057	0.4966	0.0567**	0.568
14	0.5771	0.4427	0.006*	0.1794						
15	0.0571**	0.3014	0.0064*	0.0172*	0.2202	0.0311*	0.3344	0.0352*	0.4112	0.0665**
16	0.1307	0.0536*	0.2513	0.0068*	0.0363*	0.2383	0.6492	0.1621	0.6386	

machine operators in making decisions about where to locate roads and where slash reinforcement is necessary. In the surveyed sites, neither planners nor operators had information about the cartographic soil moisture and soil type maps prior to logging operations. A comparison with a complementary survey study where a decision support tool had been applied at the time of road planning, is necessary before a conclusion can be drawn on how much the DTW index and soil type information could help to reduce rut frequency.

Slash reinforcement had no effect in the surveyed sites. This is probably an effect of the harvester operators reinforcing the roads they expect to be vulnerable to rut formation, and forwarder operators placing extra slash at the road surface where they observe rut development during the forwarding operation. Consequently, ruts observed in reinforced roads is not a true measure of the probability of rut formation on a road reinforced with slash by the harvester; instead, it is a combination of that probability with the probability that a road is first reinforced with slash by the forwarder when rut formation has begun. In the first case, slash reinforcement was probably not sufficient to cope with the amount of traffic. This could be the result of machine operators underestimating the amount of slash required, since there were no specific guidelines defining how much slash was needed. Similar results were found in cases where a small amount of slash was not effective in reducing ground damage when the ground was moist (Han et al. 2006; McDonald and Seixas 1997). Wood et al. (2003) also linked the failure of slash-covered roads to terrain conditions, especially water content.

Since the study was a field survey, road class had to be estimated. This may induce some subjectivity in the collected data, as it not is easy to estimate the exact number of passages. There is always a risk that the number of passages is overestimated on a rutted section of the road, but as this would then also influence the classification on the next section without ruts, the bias in road classification should be small.

A common challenge of survey studies like this is that, unlike a designed experiment, not all possible factors affecting the occurrence of ruts could be controlled or measured. For instance, it was not possible to account for the season in which the logging operation was performed, so meteorological factors, and consequently variations in soil bearing capacity caused by temperature and precipitation, were excluded.

Another important issue is that, in practice, roads are planned by the machine operators. They try to avoid causing ruts, since ruts are considered to be a negative impact on soil and have undesired effects on forwarding operation. Consequently, operators actively choose to locate roads in areas that they perceive as having sufficient bearing capacity where passage is unavoidable, and try to reinforce the road surface. In other words, they are motivated to select appropriate road locations and reinforce them if they assume the road segment will be used by more traffic. This behaviour will influence the results of the survey and must be considered when interpreting the results.

5 Concluding remarks

Further studies are required to identify the effects of all factors included in this survey on rut formation, especially on soils with medium bearing capacity. The cartographic depth-to-water index (DTW) could be an interesting tool for delineating wet soils that are potentially vulnerable to rut formation during logging operations when combined with other information, e.g. soil type. Decision support tools that incorporate these variables could help forestry operators plan extraction roads in areas with best bearing capacity, or give an indication of where the soil bearing capacity needs to be improved by, for example, slash reinforcement.

Acknowledgements

The authors wish to thank Bergvik Skog AB for allowing us to perform this study on their logging sites. The authors wish also to thank Professor Tomas Nordfjell for his valuable comments on the manuscript, and Michael Krook and Gustav Friberg for conducting the field work.

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Total of 37 references.

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International Journal of Applied Earth Observations and Geoinformation 108 (2022) 102728

Contents lists available at ScienceDirect

International Journal of Applied Earth Observations and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Evaluating the effect of DEM resolution on performance of cartographic depth-to-water maps, for planning logging operations

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ARTICLE INFO

Keywords:
Soil moisture maps
DTW
Digital Elevation Model
Forestry
Soil disturbance

ABSTRACT

Reliable and accurate soil moisture maps are needed to minimise the risk of soil disturbance during logging operations. Depth-to-water (DTW) maps extracted from digital elevation models have shown potential for identifying water flow paths and associated wet and moist areas, based on surface topography. We have examined whether DEMs from airborne LiDAR data with varying point density can improve performance of DTW maps in planning logging operations. Soil moisture content was estimated on eight sites after logging operations and compared to DTW maps created from DEMs with resolutions of 2 m, 1 m, and 0.5 m. Different threshold values for wet soil (1 m and 1.5 m depth to water) were also tested. The map performances, measured by accuracy (ACC) and Matthews Correlation Coefficient (MCC), changed slightly (79%, 81% and 82% and 0.33, 0.26 and 0.30 respectively) when DEM resolutions varied from 2 m to 1 m, and 0.5 m. The corresponding values when the DTW threshold value for wet/dry soil changed from 1 m to 1.5 m were 70%, 72%, 71% and 0.38, 0.41 and 0.39. LiDAR-based DEM resolutions of 1–2 m were found to be sufficient for extraction of DTW maps during planning of logging operations, when knowledge about soil hydrological features, associated wet and moist areas, and their connectivity is beneficial.

1. Introduction

Utilising forestry machines in combination with a warming climate requires extra efforts to avoid possible soil disturbances during logging operations in forests (Uusitalo et al., 2020). Reliable and accurate soil moisture maps, based on high resolution digital elevation models (DEM), are among tools that improve planning and execution of logging operations (Hoffmann et al., 2022). Capturing topographic details of ground surface from point clouds collected by airborne Light Detection and Ranging (LiDAR) has contributed to DEM extractions with improved resolution and information contents (Wehr & Lohr, 1999). Which point density LiDAR data and corresponding DEM resolution to use is an important question for practical forestry, as the DEMs are used for creating different kinds of trafficability maps. For example, soil moisture maps are used in most heavy forestry machines in Sweden today (Ring et al., 2020; Ågren et al., 2021;).

Logging operations in Swedish forestry have developed considerably since the 1940s. Human and horse muscles were first replaced with chain-saws and modified farm tractors, which gradually developed to the current use of forest machines. Improved productivity, cost-efficiency, ergonomics and work safety of the operations and higher demands for wood-based-products from forests were the main drivers of this development (Nordfjell et al., 2019). Simultaneously, forest machines have become bigger and heavier, weighing approximately 15–40 Mg, which implies a higher risk of soil disturbances, i.e. rutting, compaction, runoff, and erosion (Cambi et al., 2015). The risk for soil disturbances intensifies when forest soils are wet and moist (Toivio et al., 2017). In the boreal forest of Nordic regions, periods with frozen soils and improved bearing capacity are likely to diminish due to anticipated warmer climate conditions (Lehtonen et al., 2019), underlining the need for improved planning of logging operations in sensitive areas. Soil moisture content, together with soil texture, are important factors for determining soil bearing capacity (Susnjar et al., 2006; Wästerlund, 2020), i.e., the ability of soil to withstand external forces without undergoing detrimental changes. Deep ruts develop more easily on fine-grained soils (Eliasson & Wästerlund, 2007; Sirén et al., 2019)

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https://doi.org/10.1016/j.jag.2022.102728
Received 22 December 2021; Received in revised form 1 February 2022; Accepted 17 February 2022
Available online 4 March 2022

and peatlands (Uusitalo & Ala-Ilomäki, 2013) with high moisture content. Ruts can cause water ponding on flat terrain due to compaction and reduced hydraulic conductivity in machine tracks, leading to increased runoff and sediment transport to nearby watercourses (Hansson et al., 2018). Erosion rate may increase after machine passages in steep terrain (Labelle et al., 2021; Najafi et al., 2009), creating extra obstacles to the natural recovery of soils for decades after off-road transportations (DeArmond et al., 2021).

The spatial variation of soil moisture content is influenced by soil texture, topography (measured as slope and elevation), and vegetation, and varies temporally according to meteorological condition, i.e., temperature and precipitation (Huisman et al., 2002; Lunt et al., 2005). Knowledge about the location of sensitive soils with high moisture content is therefore necessary to minimise negative impact caused by off-road transportation (Campbell et al., 2013; Jones & Arp, 2019; Murphy et al., 2009). Measuring soil moisture content using in-situ techniques like time domain reflectometry (TDR) or ground penetrating radar (GPR) to measure soil moisture content over large areas (hectares) are time- and labour-intensive (Lekshmi et al., 2014), making these methods non-practical for operational forestry planning. Soil moisture prediction models, using digital elevation models (DEM) based on increasingly available LiDAR technology, or photogrammetry-based DEMs, have therefore been used to improve the mapping of soil hydrological features.

The topographic wetness index (TWI) (Beven & Kirkby, 1979) was among pioneer wetness models that used topography to model water flow paths in landscape. The index is calculated by relating upslope catchment area at each DEM cell to a calculated slope in that cell. TWI was shown to be more sensitive to proper estimation of upslope areas than the calculated local slope at different resolutions (Hjerdt et al., 2004). This property makes the index sensitive to underlying DEM resolution and reduces the accuracy of soil moisture estimation in less elevated areas, where local slope does not reflect the hydraulic gradient efficiently (Grabs et al., 2009). TWI was shown to function properly for large-scale landscape planning, but to lose its robustness at high DEM resolutions (Sørensen & Seibert, 2007; Ågren et al., 2014).

Depth-to-water (DTW) index is another DEM-based soil wetness index that calculates least elevation difference between surface flow channels and nearby landscape areas (Murphy et al., 2007; Murphy et al., 2008). The surface flow channels, extracted from DEMs, are regarded as reference ground water level by DTW index. DTW values are defined as zero at surface flow channels. Moving upwards from flow channels in the landscape implies increased depth to water values, indicating reduced soil wetness away from surface waters. Soil moisture maps based on the DTW index therefore need assigning two thresholds: 1) flow initiation area (FIA), i.e., a catchment area required to form flow channels, 2) a DTW threshold value for when soils are wet, i.e., a high soil moisture content on a time-averaged basis. Ågren et al. (2014) compared DTW maps of different FIA values, TWI, and seven other DEM-derived indexes (at resolutions ranging from 2 to 100 m) to measure soil moisture classes in the field in a Swedish boreal forest catchment area. They reported DTW as the most numerically robust index to predict soil moisture classes. Identification and connectivity of smaller wetlands areas (<1 ha) and riparian zones extracted from 10-m photogrammetry-based DEM were improved using the DTW index, compared to aerial photo interpretations (Murphy et al., 2007). Much longer stream flow channels could also be mapped in Sweden, both at watershed (Ågren et al., 2015) and national scales (Ågren & Lidberg, 2019), using the DTW index. The stream flow channels were extracted from 2-m DEMs and compared to aerial photo-based flow channels shown on topographic maps (scale of 1: 12 500) created by the Swedish Mapping, Cadastral and Land Registration Authority.

DTW maps can help logging planners decide the proper time to perform logging operations on logging sites with large areas of moist and wet soils. Logging operations in these areas can be scheduled during winter periods when the soil is frozen and has greater strength for machine passages (Mattila & Tokola 2019; Susnjar et al., 2006). When DTW maps are used to identify moist and wet areas in logging sites, the risk for rutting may be reduced if machine operating trails do not cross such areas (Arp, 2009; White et al., 2013). Leaving logging residues on machine operating trails (Labelle et al., 2021) improves soil bearing capacity in these areas, prior to necessary machine passages. The planning measures become extra important when logging sites are in the vicinity of groundwater discharge hotspots with high ecological values (Kuglerová et al., 2014). DTW maps were found to be an effective tool for minimising severe rutting in areas close to surface waters (Friberg & Bergkvist, 2016), although they cannot predict rut locations in logging operations (Mohtashami et al., 2017; Schönauer et al., 2021a; Ågren et al., 2015).

DTW maps can also be used to develop soil trafficability models. In a case study in Canada, Campbell et al. (2013) related cone penetration index to rut depth, DEM-derived elevation, slope, and DTW index (at 2-m resolution), creating projected rut-depth maps for an all-terrain vehicle navigation in forest. The model was further improved by including hydrologically predicted soil moisture content and meteorological data to adjust the model for actual weather conditions (Jones & Arp, 2019). Despite indicating promising applications in the study areas, the authors stated that further evaluation in different terrain conditions was required.

Soil moisture maps are also important in forestry for identifying suitable locations for necessary stream crossings (Ring et al., 2020). Soil moisture maps could be used for designing optimal and functional forest buffers/riparian zones around permanent or temporal stream flow networks with important ecological values (Kuglerová et al., 2017; Kuglerová et al., 2014). They could also be used to improve planning of site preparation and fertilisation adjacent to surface waters (Ring et al., 2020; Ågren et al., 2015). Reliable and accurate soil moisture maps could therefore lead to essential improvements in planning of logging operations.

Creating DTW maps that capture temporal and spatial variations of stream networks and associated wet areas at both small and large scales is challenging. To improve the map performance and customise them to local and temporal conditions, the FIA threshold can be adjusted to local physiographic properties (Murphy et al., 2009; Ågren & Lidberg, 2019) and seasonal changes (Schönauer et al., 2021b; Ågren et al., 2015). The DTW threshold value for separating wet/dry soil also needs to be adjusted to soil drainage properties, topography, and local weather conditions (Ågren et al., 2021). DTW values of 1 m (Ågren et al., 2014, Murphy et al., 2011) or 1.5–1.7 m (Murphy et al., 2009) have traditionally been used for this purpose in different studies. How the change of threshold may affect the performance of DTW maps in the same areas has not been specifically reported in previous studies.

Resolution and information content of DEMs are important factors affecting extraction of hydrological features (MacMillan et al., 2014). A comparison between the performance of DTW index and soil wetness index (SWI) using LiDAR-based DEM (1-m resolution) and photogrammetry-based DEM (10-m resolution) indicated that a higher DEM resolution resulted in improved conformance for both moisture models (Murphy et al., 2009). Lidberg et al. (2017) evaluated different pre-processing methods on LiDAR DEMs with resolutions of 16 m, 8 m 4 m and 2 m, and showed that higher DEM resolution leads to more accurate stream network extractions. Stream-road crossings identified in DEMs were compared with field recorded culvert positions in this study. Previous studies have not addressed how an even higher resolution than 1 or 2 m of DEMs created from higher point density LiDAR data can affect the performance of the DTW maps to identify wet and moist areas and the potential to improve the maps for planning forest operations.

The objective of this study is therefore to evaluate the effect of high-resolution DEM (2 m, 1 m, 0.5 m), based on airborne LiDAR data, hereafter LiDAR data, with different point density (0.5–1-point m^{-2}, 1–2-point m^{-2}, and 24-point m^{-2}), on soil moisture prediction using a cartographic depth-to-water (DTW) index, and an empirical approach.

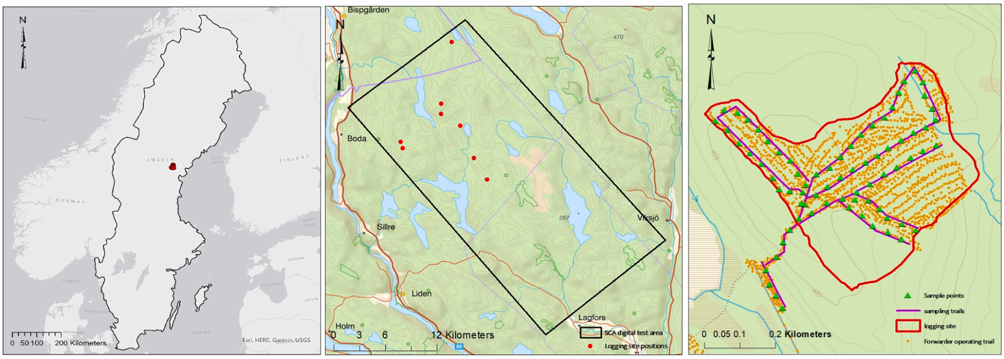


Fig. 1. Left: Overview of the logging sites, in mid-eastern Sweden. Centre: Distribution of the logging sites within the SCA digital test. Right: One of the studied logging sites over the topographic map. Data about soil moisture points were collected in geopositioned sample points (green triangles) along pre-marked sampling paths (purple), selected on the basis of forwarder time logged operating trails (small orange dots).

Table 1
Description of surveyed logging sites with information on logging site area (ha), main soil type according to Quaternary Deposits maps, and number of collected sample points.

Site No.	Area (ha)	Main soil type	No. of collected sample points
1	7.2	Till	36
2	5.2	Till	26
3	23.6	Till	70
4	17.8	Till	44
5	6.5	Peat	43
6	17.8	Till, bedrock	66
7	15.8	Till	59
8	10.2	Bedrock, Peat	41

This is done by point-to-point comparison of field estimated soil moisture with DTW-based soil moisture predictions with resolutions of 2 m, 1 m, and 0.5 m on eight logging sites in mid-eastern Sweden, after logging operations. Another objective was to test whether the results would change when the threshold value for wet soil was changed from 1 m to 1.5 m DTW.

2. Materials and methods

2.1. Study areas

The study included eight logging sites selected from 24 recent final fellings in the SCA forest company's digital test site (17°2′47″E, 62°49′46″N) in mid-eastern Sweden (Fig. 1). The sites were selected to ensure a variation of estimated soil texture and soil moisture according to available digital maps. The logging sites varied in size and topographic condition (elevation, slope), and were situated mainly on mineral till soils according to Quaternary Deposits maps (1: 25000–1:100 000 Geological Survey of Sweden). The dominating tree species were Norway spruce (Picea abies (L.) Karst.) and Scot's pine (Pinus sylvestris L.). The logging sites were clear-cut during spring-summer 2020, applying a cut-to length (CTL) mechanised system, using harvester models Komatsu 951 and JD 1470 G (27–30 Mg) and forwarders, Komatsu 895, and JD 1910 G models (50–52 Mg when fully loaded). A general description of the logging sites is provided in Table 1.

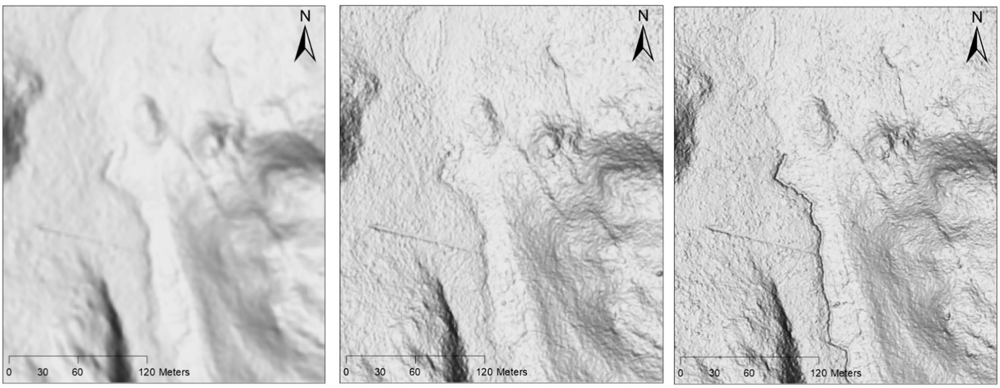


Fig. 2. Digital elevation models (DEM) with resolutions of 2 m (left), 1 m (middle) and 0.5 m (right) presented by multiple hillshade effect. Illustration of surface detail improves when DEMs are illuminated with light from six different directions, i.e., multiple hillshading. A man-made ditch (black line) is captured more clearly by 0.5 m DEM.

Table 2
Technical description of airborne LiDAR data used in terms of point density, laser scanner model, manufacturer, and LiDAR accuracy. DEM extraction algorithm and provider of each data source are also specified.

DEM resolution (m)	LiDAR data point density (point m^{-2})	Laser scanner model, manufacturer	LiDAR Accuracy	DEM extraction algorithm	Data Provider
2	0.5–1	ALS 60, Leica	XY accuracy < 0.3 Vertical accuracy = 0.1 m	Triangular Irregular Network (TIN) interpolation	Swedish mapping, cadastral and land registration authority (Anon, 2020)
1	1–2	LS1A, Leitech	XY accuracy < 0.3 Vertical accuracy < 0.1 m	Gridding with adaptive triangulation	Swedish mapping, cadastral and land registration authority (Anon, 2021)
0.5	24	VQ-1560i DW, RIEGL	XY accuracy = 0.02 m Vertical accuracy = 0.02 m	Streaming Triangular Irregular Network interpolation	SCA forest company (Anon, 2022)

Table 3
Mean value and standard deviation of elevation and slope within the studied logging sites, extracted from 2 m DEM.

Logging site No.	Elevation (m)		Slope (degrees)	
	Mean	Standard deviation	Mean	Standard deviation
1	366.11	3.48	6.68	4.05
2	364.50	4.06	8.90	7.35
3	419.54	8.19	7.02	3.74
4	340.70	6.63	9.77	6.70
5	373.35	5.22	11.16	7.05
6	367.03	9.56	12.25	8.05
7	387.07	9.9	7.09	3.86
8	341.14	12.98	11.54	6.63
Average	369.93	7.50	9.30	5.93

2.2. Field data collection

Soil moisture was estimated in the field during September-November 2020. The sampling paths were pre-marked on digital topographic maps along the time-logged forwarder operating trails to make data inventory practical (Fig. 1). Soil moisture in the field was estimated and classified as: 1) wet, 2) moist, 3) mesic-moist, 4) mesic, and 5) dry according to National Swedish Forest Inventory Instructions (Anon, 2013). To facilitate soil moisture classification in the field, humus layer thickness was measured at sample points using a soil probe and a field ruler. Full definition and characteristics of moisture classes are provided in Table A1. Field data was collected in geopositioned sample points using ESRI application Survey123 (version 3.9) in an iPad Air 2 (8th generation). iPad Airs are equipped with Global Navigation Satellite-based System (GNSS) receivers which uses satellites from the American Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS). Sample data were collected in the World Geodetic System (WGS-1984) in the field and were later projected with SWEREF99 Transverse Mercator when used in ArcMap. The positioning accuracy achieved by iPad Airs in forest with different tree densities is around 2.5–5 m and improves to 2.5–3 m in clear-cut sites (Hannrup et al., 2020). The first sampling points were randomly selected along the first 50 m of trail on the cut area. A uniform distance of 50 m was then assigned between sampling points, to prevent autocorrelation among observations. A total of 385 sample points were collected in the field.

2.3. LiDAR data and DEM description

Digital elevation models with resolutions of 2 m, 1 m and 0.5 m were created from airbirne LiDAR data with a point density of 0.5–1, 1–2 and 24-point m^{-2}, Fig. 2. Elevation models with resolutions of 2 m and 0.5 m were provided as ready to use raster (TIFF) layers, by the Swedish Mapping, Cadastral and Land Registration Authority and the SCA forest company, respectively. The 1-m resolution DEM was extracted from LiDAR data with 1–2 point m^{-2} (by authors) using Quick Terrain Modeler (INTL, x64), v8.0.4.1 software. Technical specifications of the LiDAR data and DEM extraction algorithms are described in Table 2. In this study, the analysis did not include the measurement errors inherent in each of the LiDAR acquisition techniques, filtering methods and DEM production algorithms, nor how they may affect the accuracy of generated DEMs.

2.4. DTW map production

DTW maps with resolutions corresponding to the DEMs used were created in ArcMap 10.8. Each DEM was first processed to create elevation models with no depressions using a fill function (Tarboton, 1997). The preferential water path from each cell was calculated using a flow direction tool. Flow channels were extracted from DEMs with a deterministic 8 (D8) flow accumulation tool (O'Callaghan and Mark, 1984), using a FIA value of 1 ha. Selecting a 1-ha FIA value allowed us to keep the GIS processing of high-resolution DEMs practical and to produce DTW maps comparable to maps that have been available to the Swedish forestry sector since 2015. It also improved delineation of small temporal flow channels which are mainly activated during high runoff periods, i.e., when snow starts to melt in early spring and/or when rain is the dominant form of precipitation in early autumn (Murphy et al., 2011; Ågren et al., 2015).

The least elevation differences between each surface cell and nearest flow channel, i.e., DTW indexes, were calculated using digital elevation models, slope, and flow channel data layers according to Eq. (1), (Murphy et al., 2007; Murphy et al., 2008):

$$DTW(m) = \left[\sum ((dzi/dxi)a)\right]Xc \quad (1)$$

$DTW(m)$: Estimated depth to ground water table
dzi/dxi: The least cumulative elevation difference from each cell to the nearest surface water (e.g., the flow channel, or other known watercourses).
a: 1 when movement direction is parallel to the cell edge and 1.414214 when cells are passed diagonally
Xc: resolution of the elevation model, m

2.5. Topographic and DTW index variations of logging sites

The studied logging sites were located on relatively hilly areas, and varied in topographic conditions, i.e., elevation and slope. Mean elevation and slope values, extracted from 2-m DEM, varied between 340.70–419.54 m and 6.68–12.25°respectively among the logging sites, Table 3.

Depth-to-water values <1 m are conventionally considered as potential 'moist' and 'wet' areas for DTW soil moisture mapping in the Swedish landscape (Ågren et al, 2014). These areas were classed in ranges of 0–0.25, 0.26–0.50, 0.51–0.75 and 0.76–1 m and marked in shaded colours in all three variants of the DTW maps over the studied

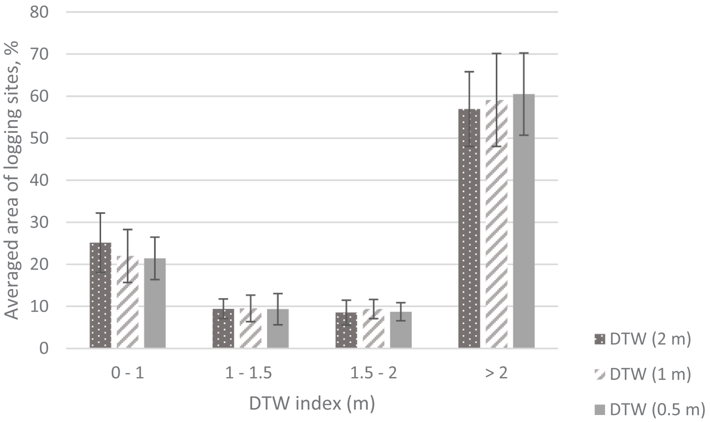


Fig. 3. Distribution of averaged area of logging sites over classes of DTW index. Error bars indicate standard deviation of each DTW index class.

Table 4
Reclassification of DTW maps and field estimated soil moisture classes to binary values, applying conventional DTW threshold value of 1 m to separate wet/dry soils on maps and corresponding soil moisture classes in the field.

DTW reclassification		Field soil moisture reclassification	
Old values	New values	Old values	New values
DTW $\leq$ 1 m	Wet	Wet, moist	Wet
DTW > 1 m	Dry	Mesic-moist, mesic, dry	Dry

logging sites (Table 2A). The averaged area of all logging sites, distributed over the DTW values (0–1, 1–1.5 m, 1.5–2, and > 2 m) on the three resolution maps, are illustrated in Fig. 3. Soils with a DTW index > 2 m made up the major fraction (57–60%) of the areas of all logging sites regardless of DTW map resolutions. Soil moisture condition is considered as 'dry' at these areas, when maps are consulted.

2.6. *Data analysis*

The average values of the depth-to-water indexes, with a 95% confidence interval, over all the field estimated soil moisture classes were plotted, to evaluate any difference among DTW maps in separating field estimated moisture classes.

In a general linear model, field estimated moisture classes were analysed against DTW index values (from the three map variants, i.e., 2 m, 1 m, and 0.5 m) for all the sample points, to evaluate possible correlations in the soil estimation methods, i.e., field- vs. DTW index estimations. The statistical inferences were performed in Dell Statistica 13.0.

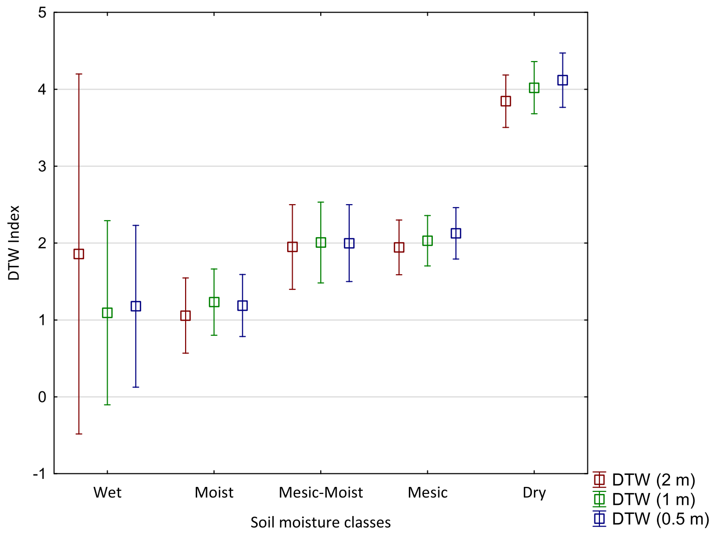


Fig. 4. 95% interval of averaged DTW index values over field estimated soil moisture classes (Anon, 2013), in DTW maps of resolution 2 m, 1 m and 0.5 m.

Table 5
The results of general regression models, where DTW index values were regressed against field estimated soil moisture classes, reporting adjusted R^2, sum of square (SS), degree of freedom (df), F-value and P-value for the models. All three DTW map variants were almost equally effective for distinguishing soil moisture classes in the field.

Dependant variable	Adjusted R^2	SS model	df model	MS model	F	p
DTW (2 m)	0.20	492.92	4	123.23	24.66	< 0.001
DTW (1 m)	0.20	466.56	4	116.64	24.84	< 0.001
DTW (0.5 m)	0.18	426.19	4	106.55	21.65	< 0.001

Table 6
Distribution of True Positive (TP), True Negative (TN), False Positive (FP), False Negative (FN) of DTW maps and corresponding accuracy (ACC, %) and Matthews correlation coefficient (MCC) in DTW maps of resolution 2 m, 1 m and 0.5 m. A DTW threshold value (DTW $\leq$ 1 m) separates wet/dry soil in the maps. Field estimated soil moisture classes wet, and moist are considered as 'Wet'. Number of sample points (n) = 385.

	TP	TN	FP	FN	ACC, %	MCC
DTW (2 m)	25	281	67	12	79	0.33
DTW (1 m)	19	292	56	18	81	0.26
DTW (0.5 m)	21	293	55	16	82	0.30

Table 7
Distribution of True Positive (TP), True Negative (TN), False Positive (FP), False Negative (FN) of DTW maps and corresponding accuracy (ACC, %) and Matthews correlation coefficient (MCC) in DTW maps of resolution 2 m, 1 m and 0.5 m. A new DTW threshold value (DTW $\leq$ 1.5 m) separates wet/dry soil in the maps. Field estimated soil moisture classes wet, moist, mesic-moist, and mesic are considered as 'Wet'. Number of sample points (n) = 385.

	TP	TN	FP	FN	ACC, %	MCC
DTW (2 m)	92	178	71	74	70	0.38
DTW (1 m)	88	188	31	78	72	0.41
DTW (0.5 m)	87	186	33	79	71	0.39

2.7. DTW maps: Performance evaluation

In a more general comparison, DTW values and field estimated moisture values were reclassified to binary values: Wet and Dry. A DTW threshold value of 1 m was used for map reclassification, i.e., all areas with DTW $\leq$ 1 m were reclassed to 'Wet' while areas with DTW > 1 m were reclassed to 'Dry'. The field estimated moisture classes 'wet' and 'moist' were merged to 'Wet' while 'mesic', 'mesic-moist' and 'dry' were merged to the 'Dry' class, Table 4. The averaged area of all logging sites classified as 'Wet' according to this limit in the DTW map reclassification is presented in Fig. 3.

To evaluate the overall conformance of wet areas captured by DTW maps and field-identified wet areas in the new binary classification, accuracy (ACC), and Matthews correlation coefficient (MCC) (Matthews, 1975) were calculated according to Eqs. (2) and (3):

$$ACC = \frac{TP + TN}{TP + TN + FP + FN} \tag{2}$$

$$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}} \tag{3}$$

where TP, TN, FP, FN are components of a confusion matrix and are defined as:

True Positive (TP): when both DTW maps and field estimated soil moisture classify the sample as 'Wet'.
True Negative (TN): when both DTW maps and field estimated soil moisture classify the sample as 'Dry'.
False Positive (FP) or type I error: when DTW map reclasses the sample as 'Wet', while soil moisture in field is estimated 'Dry', and
False Negative (FN) or type II error: when DTW map reclasses the sample as 'Dry', while soil moisture in field is estimated 'Wet'.

Finally, the reclassification of soil moisture estimations was iterated with new limits in both DTW maps and field estimations to evaluate possible effects on calculated ACC and MCC in the new classification system. A threshold DTW value of 1.5 m, previously 1 m, was now used to separate 'Wet' and 'Dry' areas in DTW maps, while field estimated soil moisture classes, including 'wet', 'moist', 'mesic-moist', and 'mesic', were reclassified to 'Wet' areas this time.

3. Results

3.1. DTW index value ranges in field estimated soil moisture classes

A comparison between the distribution of DTW indexes and soil moisture classes on each of the DTW maps indicated that all three variants had equivalent performance on separating soil moisture classes estimated in the field. The averaged DTW values were approx. 1.2 m in field moisture class 'wet' and 'moist', approx. 2 m in field moisture class 'mesic-moist' and 'mesic', and approx. 4 m in field moisture class 'dry', Fig. 4. The larger confidence interval for the 2-m resolution DTW index in soil moisture class 'wet' is an effect of one outlier observation being classified as 'wet' in the field while having a DTW value of 4.9 m on the 2-m resolution DTW map.

The averaged DTW index values in the classes 'wet' and 'moist' overlap the values in the classes 'mesic-moist' and 'moist', indicating that DTW maps do not distinguish these soil moisture classes in the field effectively. However, the DTW index in the moisture class 'dry' is efficiently distinguished from other classes.

3.2. Soil moisture prediction by DTW maps

In the general regression models, DTW indexes from all three map variants were regressed against field estimated soil moisture classes. The model resulted in F-values ranging from 21.65 to 24.84 and 24.66 and adjusted R^2-values ranging from 0.18 to 0.20 in the DTW maps with 0.5 m, 1 m, and 2 m resolutions, indicating no improvement in performance of the maps when resolution was improved from 2 m to 1 m and 0.5 m, Table 5.

3.3. Wet and dry soil classification by DTW maps

The accuracy of the binary reclassified ACC of DTW maps in reclassifying the logging sites to 'Wet' and 'Dry' areas increased slightly, from 79% to 81% and 82% in DTW maps with resolutions of 2 m, 1 m, and 0.5 m. The MCC values, however, changed non-uniformly from 0.33 to 0.26 and 0.30 over the studied resolutions respectively (Table 6).

Using the 1.5-m DTW threshold value between wet and dry soil when binary reclassifying DTW maps and field estimated moisture classes, 'wet, moist, mesic-moist and mesic' as the new 'Wet' class, resulted in slightly lower accuracy for all three DTW maps compared to maps with DTW $\leq$ 1 m as the limit between wet and dry areas. The accuracy varied from 70% to 72% and 71% when the resolution of DTW maps was changed from 2 m to 1 m and 0.5 m. Compared to DTW maps with a 1-m limit, the MCC values for these new reclassified DTW maps improved to 0.38, 0.41, and 0.39 (Table 7).

4. Discussion

In this study, we have evaluated how the spatial resolution of the digital elevation models based on different point densities of LiDAR data can affect soil moisture predictions using the DTW soil moisture index.

The pattern and extent of wet and moist areas in maps changed marginally at the studied resolutions and logging sites. The 95% interval of DTW indexes from the spatial resolutions over the field estimated wetness classes showed equivalent distribution of DTW indexes in all three DTW maps. This implies that increased resolution of DEMs at the studied scale, 2 m, 1 m, and 0.5 m, did not affect the performance of the DTW maps in capturing the stream networks and associated wet areas. The higher point density of LiDAR data means more accurate DEMs, with detailed information about surface topography, thereby minimising the need for surface interpolation between the scanning points. This detailed image of the landscape includes small-scale surface features like boulders or stumps, which do not affect the overall pattern of where water would flow in the landscape. DTW maps are created by accounting for differences in gravitational potential energy derived from elevation difference between flow streams and adjacent parts of the landscape. The difference is less affected by changes in microtopography when DEM resolution is increased from 2 m down to 0.5 m, in elevated and hilly areas like the studied logging sites. Large-scale topography is the main controlling factor of water movements in these areas, while detailed surface topography has the main effect in near-surface areas in flat terrains, where DTW maps perform best (Murphy et al., 2009; Schönauer et al., 2021b).

The differences in our DTW maps are not of the same magnitude as that found when 10-m photogrammetry-based DEM were compared to 1-metre LiDAR-based DEMs (Murphy et al., 2008; Murphy et al., 2009). They were not improved in the same way as when (Lidberg et al., 2017) compared resolutions of 2 m, 4 m, 8 m, and 16 m when mapping flow stream networks from hydrologically-corrected LiDAR-based DEMs. Sørensen and Seibert (2007) also reported that higher resolution and information content in 5-m LiDAR-based DEM affected the pattern and distribution of soil moisture estimations by TWI index, compared to 10 m, 25 m, and 50 m LiDAR DEMs. At high resolution DEMs, upslope areas became smaller, contributing to formation of more irregular water flow paths. However, the authors recommended choosing optimum resolution based on the importance of studying topographic features and the soil moisture modelling application.

At higher resolution DEMs, anthropogenic features of landscapes like road banks, railways and ditches may have greater impact on the accuracy of DEMs, so the need to pre-process these models and hydrological modification is more pronounced (Lindsay & Dhun, 2015). Breaching was found to be an optimum algorithm for performing hydrological corrections in DEMs prior to soil moisture modelling (Lidberg et al., 2017). However, we applied “filling” in our DTW map productions, to keep their conformance to DTW-maps available for the whole of Sweden. Slight variations in captured patterns of flow channels and associated wet areas at studied resolutions might therefore be explained by different sensitivity of these DEMs to artefacts like road banks close to the logging sites (Table A2, logging sites 1, 2, 4, 6 and 7). However, the differences were quite minimal and did not result in considerable variation in the soil moisture maps created here at the studied scales.

The comparison of DTW indexes and field estimated soil moisture classes also indicated that DTW maps were more effective in distinguishing dry areas, with DTW $\geq$ 4 m from the other moisture classes (Fig. 4). DTW values in the wet and moist soil moisture classes (0.02 m $<$ DTW $<$ 2 m) and mesic-moist and mesic (1.5 m $<$ DTW $<$ 2.5 m) overlap to a great extent, making the index ineffective in separating these soil moisture classes. This was also confirmed by results from the general linear model, where DTW index values regressed by field estimated soil moisture classes produced low adjusted R^2 values for all resolutions. However, this might partly be an effect of the resolution of the field classification of soil moisture, where many of the recognition signs are related to an area surrounding the sample point and not just the sample point itself. Furthermore, as soil moisture is a continuous variable, the transitions between classes will be gradual and not well defined at specific boundaries.

The accuracy (ACC) of DTW maps slightly improved, from 79% to 80% and 81% respectively, regarding reclassifying the soil moisture to the binary values of ‘Wet’ and ‘Dry’ in maps and the field, when resolution was increased from 2 m to 1 m and 0.5 m. This was mainly due to the increased number of observations in the True Negative and True Positive classes, i.e., correctly classified field sample points in moisture classes ‘Dry’ and ‘Wet’ by the DTW maps. However, the MCC value did not improve. When the resolution was changed from 2 m to 1 m and 0.5 m, MCC was reduced from 0.33 to 0.26 and increased to 0.30, contrasting with the marginal improvement of accuracy (ACC). The records are not far from values reported in two areas with similar soil deposits, i.e., till and peat studied by Ågren et al. (2014), with ACC = 83.9% and 77.5% and MCC = 0.39 and 0.34.

Modifying the applied threshold for reclassification of DTW index and field estimated soil moisture classes, i.e., DTW $\leq$ 0 1.5 and field classes as wet, moist, moist-mesic, and mesic, resulted in reduced ACC but improved MCC for all resolutions of DTW maps, compared with the previous classification trial. The best MCC improvement was found for DTW (1 m), from 0.26 to 0.41. This would indicate that applying a DTW threshold value $\leq$ 1 m is not always the best practice to identify sensitive areas around flow channels, and the limit needs to be adjusted to local topographic conditions (Ågren et al., 2021).

Mesic-moist and mesic soil moisture classes indicate more temporal variations during a year, having least bearing capacity (more wet and moist areas) during early spring and late autumn. Soils of these moisture classes may have higher bearing capacity when the soil is drier during summer. Therefore, including actual meteorological data, like field measured or hydrologically modelled soil temperature and moisture content, could be a possible approach to generate more dynamic DTW maps (Jones & Arp, 2019). Real time data about actual soil strength by automatic indirect measuring methods, such as harvesters’ CAN-BUS measurements of rolling resistance (Ala-Ilomäki et al., 2020) prior to forwarding operations, can also be used as a complement to static soil moisture models. Real time measurement of soil strength, together with spatial data and hydrological modelling, can also provide dynamic soil trafficability maps (Salmivaara et al., 2020). These types of maps are increasingly demanded by forestry to minimise the negative impacts of machinery operations on soils in more fluctuating weather conditions.

Identifying optimal FIA values for different scales of application has been recognised as challenging, due to spatial and temporal variations in soil moisture content (Lidberg et al., 2020). In a study by Schönauer et al. (2021b), field-measured soil moisture content and soil strength in time series under different weather conditions in boreal and temperate forest sites in Germany, Poland, and Finland were compared to DTW maps with varying FIA values. DTW performance in predicting soil moisture condition was best at FIA = 4 ha. The map performance, however, did not improve overall with site- and condition-adjusted FIA values.

The somewhat low conformance of the maps to field estimated moisture classes found in this study may also be because we applied a constant flow initiation threshold of 1 ha for extraction of the flow channels over all studied logging sites, without making any modifications based on local topographic and temporal condition. This FIA may result in DTW maps overestimating wet areas in steep terrain conditions or in soils with high drainage properties (Lidberg et al., 2020; Murphy et al., 2009). This effect is more pronounced in DTW maps with 2-m resolution, with higher False Positive values (FP = 67) compared to FP = 56 and FP = 55 at 1 m and 0.5 m resolutions (with DTW ≤ 1 m as threshold value for wet/dry soils). When mapping small stream networks (<6 m wide) at a national scale in Sweden, a FIA value of 2 ha is recommended (Ågren & Lidberg, 2019). However, much smaller, seasonally activated, water flow paths at logging site scales may not be captured at this FIA value.

New techniques, such as machine learning, enable inclusion of more site- and time-specific information like hydrological measurements or multiple topographic wetness index. This improves the development of regionally adjusted wet area maps at local and national scales (Lidberg et al., 2020; Ågren et al., 2021).

A higher spatial resolution of the DEMs did not effectively change the accuracy of DTW maps in identifying wet and moist areas in forest soil in elevated and hilly topography. However, DTW maps based on extracted flow channels from LiDAR-based DEMs have greatly improved mapping of flow-channels and associated wet areas compared to conventional methods using aerial photography. Capturing integrated flow channels based on detailed DEMs can improve planning of logging operations, by identifying possible wet areas near surface waters and applying modified log extraction methods in these areas. Developing dynamic DTW maps through inclusion of hydrological and weather data may also improve scheduling of logging operations in these areas to periods with improved soil strength.

5. Conclusion

The results of our study confirm that higher resolution of digital elevation models (considering 2-m, 1-m, and 0.5-m resolutions) based on high-density airborne LiDAR data does not imply improvement in identifying wet and moist areas in forest soils in relatively elevated and hilly terrain using the DTW soil moisture index. The overall pattern of subsurface water movement is mainly influenced by large-scale topography over these types of terrains, and not by detailed surface topography, as on flat areas. DEM resolution of 1–2 m can therefore be considered as sufficient for application in planning of logging or other forestry operations in terrains with similar properties, where knowledge about soil hydrological features, and associated wet and moist areas and their connectivity, is beneficial.

CRediT authorship contribution statement

Sima Mohtashami: Conceptualization, Data curation, Formal analysis, Investigation, Resources, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Lars Eliasson:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Linnea Hansson:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Erik Willén:** Conceptualization, Writing – review & editing, Project administration. **Tomas Thierfelder:** Conceptualization, Formal analysis, Methodology, Supervision, Software, Writing – review & editing. **Tomas Nordfjell:** Conceptualization, Formal analysis, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors thank the Research Foundation Nils & Dorthi Troedssons for financing the project, SCA for hosting and providing us with logging sites and high-resolution LiDAR data, and Greensway for helping us with data collection on logging sites during Oct-Nov 2020.

Appendix A

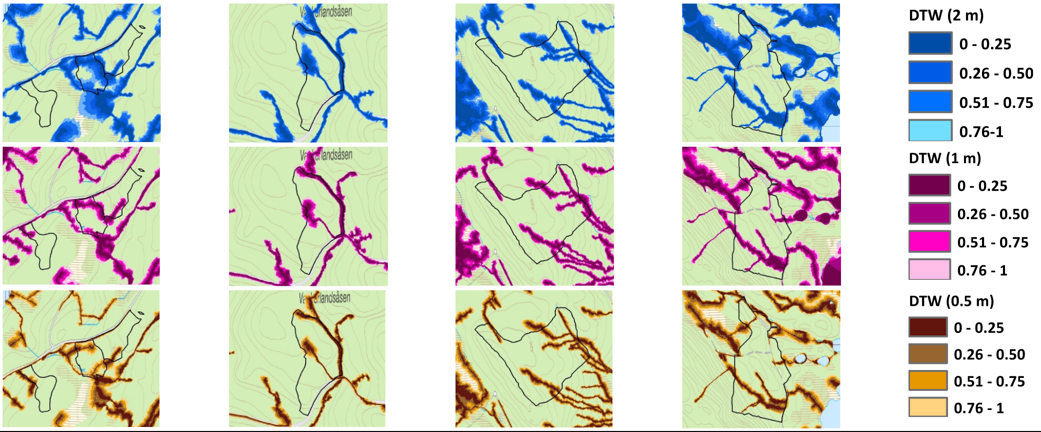
See Tables A1 and A2.

Table A1
Definition of soil moisture classes with recognition signs in forest, according to National Swedish Forest Inventory Instructions (Anon, 2013).

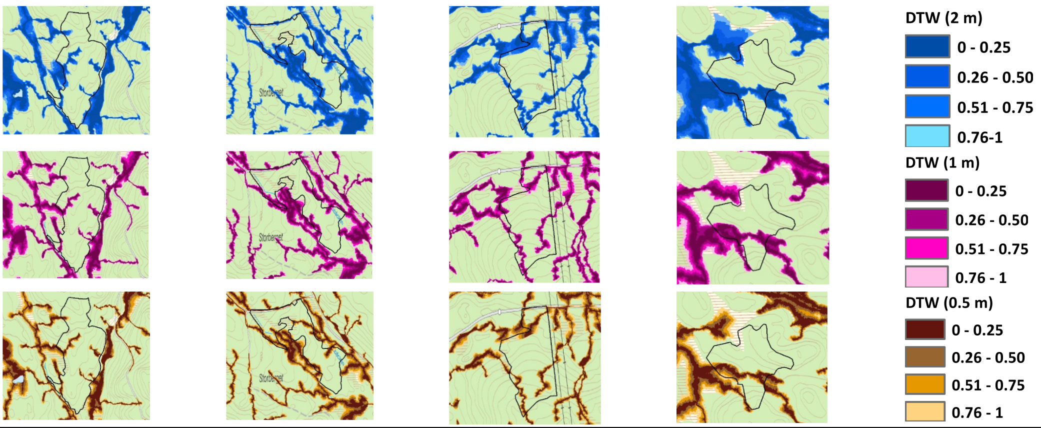
Soil moisture classes	Groundwater Level (GWL)	Recognition signs in forest
Wet soils	GWL at soil surface	(1) Organic soils (often fens). (2) Conifers occur only occasionally. (3) Frequent permanent water pools. (4) One cannot walk dry footed in low shoes.
Moist soils	GWL $<$ 1 m depth	(1) Soils range from organic (generally fens) to mineral (generally humus-podsol). (2) Wetland mosses dominate local depressions (pits), and trees often show a coarse root system above ground. (3) One can walk dry footed in low shoes, provided one can step on tussocks in the wetter parts. (4) Ditches are common.
Mesic-moist soils	GWL $<$ 1 m depth	(1) Soils are podzolic (humo-ferric to humic podsols) (2) The mineral soil is covered by a thick peaty mor (thicker than mesic soils) (3) Wetland mosses are common (4) Trees show a coarse root system above ground (germination point above soil) (5) One can walk dry footed in low shoes over the entire vegetation area, expect after heavy rain or snowmelt.
Mesic soils	1 m $<$ GWL $< 2\ m$	(1) Ferric podsols with a thin humus layer (mor) are common. (2) The bleached horizon is grey-white and well delineated against the rust yellow, rust-red or brownish rust-red B-horizon (the darker the colour, the wetter the soil). (3) The bottom layer consists mainly of dryland mosses. (4) One can walk dry-footed in low shoes over the area even after heavy rains/snowmelt.
Dry soils	GWL $> 2\ m$	(1) Usually found on eskers, hills, marked crowns and ridge crests (2) Soils tend to be coarse in texture and include lithosol, boulder soil and iron podsol formations, generally covered with a thin humus blanket on a thin bleached horizon. (3) Significant bedrock exposure.

Table A2
Comparison of DTW maps over eight logging sites, presented on topographic map of Sweden. DTW maps with resolutions of 2 m, 1 m, and 0.5 m, are extracted from DEMs with corresponding resolution. Wet areas with DTW index values 0–0.25, 0.26–0.50, 0.51–0.75 and 0.76–1 m are shaded on the DTW maps. Flow initiation area (FIA) was defined as 1 ha for all DTW maps.

Logging site 1	Logging site 2	Logging site 3	Logging site 4



Logging site 5	**Logging site 6**	**Logging site 7**	**Logging site 8**



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Use of Hydrological Models to Predict Risk for Rutting in Logging Operations

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Abstract: Using hydrological models with a high temporal resolution to predict risk for rutting may be a possible method to improve planning of forwarder trails or to schedule logging operations in sites with low bearing capacity to periods when soil moisture content is at a minimum. We have studied whether descriptions of rut variations, collected in 27 logging sites, can be improved by using hydrological data, modeled by Swedish HYdrological Prediction for Environment (S-HYPE). Other explanatory variables, such as field-surveyed data and spatial data, were also used to describe rut variations within and across logging sites. The results indicated that inclusion of S-HYPE data led to only marginal improvement in explaining the observed variations of the ruts in terms of both "rut depths" within the logging sites and "proportion of forwarder trails with ruts" across the logging sites. However, application of S-HYPE data for adapting depth-to-water (DTW) maps to temporal changes of soil moisture content may be a way to develop more dynamic soil moisture maps for forestry applications.

Keywords: rut formation; forestry operations; hydrological data

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Citation: Mohtashami, S.; Thierfelder, T.; Eliasson, L.; Lindström, G.; Sonesson, J. Use of Hydrological Models to Predict Risk for Rutting in Logging Operations. *Forests* **2022**, *13*, 901. https://doi.org/10.3390/f13060901

Academic Editor: Enrico Marchi

Received: 4 May 2022
Accepted: 4 June 2022
Published: 9 June 2022

1. Introduction

Increasing sustainable forest production to substitute non-renewable energy-intensive material and services is an effective way to reduce human-induced greenhouse gas emissions [1,2]. However, increased forest production in Sweden implies more intensive logging operations, utilizing heavy machinery all year round, to deliver saw logs, pulpwood, and other products with a continuous flow from forest to industry. Data from official Swedish statistics shows an increase in annual fellings, from 49.3 to 85.3 million cubic meters, between 1956 and 2016 in terms of five-year averages [3].

Fully mechanized cut-to-length (CTL) logging operations with heavy machines may cause soil compaction or rutting in forest soils [4]. Soil compaction implies reduced pore volume and pore connectivity between the soil particles, and a resultant negative impact on air infiltration and water drainage in soil layers [5,6]. Increased bulk density in compacted soil may increase root penetration resistance and reduce tree and seedling growth in extreme conditions [7–9]. Oxygen deficiency and increased rates of water retention in compacted layers may also increase mobilization of total mercury/methyl mercury from the forest soil to nearby water streams, posing a threat to aquatic organisms [10]. Rutting occurs when machines apply compression or shear forces to sensitive soils, which may cause displacement of the soil to the sides or to the middle of the tracks [11]. The extent of soil compaction and rutting depends on factors such as axle load, ground pressure, number of machine passages, and ground bearing capacity [4,12,13]. In turn, ground bearing capacity is determined mainly by soil texture and moisture content [12,14], and thereby varies spatially and temporally in forest landscapes. It is also influenced by factors such as the armoring effect of roots and aboveground biomass [15]. Soils with fine-grained texture and high moisture content are more prone to developing deep ruts during logging operations [16]. Soil moisture content has been shown to be an important factor for predicting soil resistance to penetration and the associated risk for rut formation in conjunction with logging operations in fine-grained soils [17].

Various technical and planning measures are used in Swedish forestry to reduce the risk for rutting. Important planning measures include scheduling of logging to avoid sensitive sites in wet conditions and trafficability prediction models to decide where to drive and where strip trails need to be reinforced with slash [18,19]. Sites with low bearing capacity can be scheduled for harvesting in dry periods when soil moisture content and, consequently, wet areas are at minimum, or in frozen periods. Sites with stronger bearing capacity may be planned for harvesting during thaw or rainy conditions. Forest companies in Sweden usually sort their sites to plan harvesting seasons based on rough estimations of bearing capacity. However, soils with the best bearing conditions constitute only 5.2% of forest land in Sweden [20], while 45.2% of forest land comprises soil in the second-highest bearing class. Sites in the second-highest soil class can be harvested during most of the year if operational adjustment for soil moisture and thawing is taken into account [21]. Planning tools are required for more precise prediction of risk for rutting, both for scheduling logging operation and for planning machine operating trails during logging operations in the second-highest soil class.

This is especially important, since indicators of climate change in Nordic regions with implications for forestry operations include a reduced number of winter days with snow cover, from 120 days in 1950 to 100 days in 2020 [22], as well as higher average winter temperatures, from approximately −4 °C in 1900 compared to approximately −2 °C in 2020 in Sweden [23]. The indicators are calculated as ten-year averages for the whole country, thereby covering variations from south to north. In Finland, projections of probable climate scenarios indicate that the duration of winter periods with suitable bearing capacity in peatlands, e.g., with 20 cm frost depth or 40 cm snow cover, will shorten by the end of the 21st century [24].

In the past decade, topography-based soil moisture models, such as depth-to-water (DTW) maps, have been used as trafficability prediction models by most Swedish forest companies [19]. The DTW maps provided by the Swedish Forest Agency are available as spatial data layers covering the entire country. DTW maps estimate soil wetness by calculating the least elevation differences between the land's surface and the nearest open water surface, e.g., flow channels or lakes, based on digital elevation models [25]. DTW maps do not include precipitation and therefore provide temporally static descriptions of wet areas. Changing the threshold value for upstream areas, required for initiating modeled flow channels, has been used to adapt wet areas in DTW maps to seasonal and temporal changes [26–28]. However, attaining a proper threshold value, for required area to initiate flow channels or separate wet/dry areas, for different seasons is an iterative procedure requiring field verification for practical applications [27,29]. Reeves et al. [30] developed a predictive geospatial model for identifying areas more susceptible to soil disturbances in harvesting sites, based on data regarding topography, land cover, and harvesting season. The harvesting season (winter/non-winter) was quite coarsely classified, lacking the temporal resolution required for more detailed scheduling of harvest sites. Although these kinds of trafficability prediction models have been effective in reducing the extent of severe rut damage [31], their precision might be affected by the static nature of these models. Using hydrological models to incorporate temporal variation of soil condition in trafficability models could be a way to improve predicting the risk for rutting.

Jones and Arp [32] used observed and hydrologically modeled soil moisture content at different soil depths to show how soil resistance, measured as cone penetration depth, and daily soil moisture fluctuations influence rutting. The results were used to develop vehicle-specific maps of estimated rut depth using seasonally adjusted DTW maps in three

Canadian study sites. Jones and Arp [33] further contributed to the modeling of spatiotemporal soil moisture and cone penetrability variability, using hydrologically predicted soil moisture, elevation, soil particle size, soil bulk density, and land cover. Salmivaara et al. [34] used hydrologically modeled soil moisture content in combination with empirical data, such as logging transportation mass and vehicle rolling resistance, to provide a framework for producing rut-depth maps across a Finnish study site. However, the general applicability of these frameworks at high spatial resolutions needs to be examined by studying the suggested models under different terrain conditions.

By studying various logging sites, being cut at different periods, and spread throughout Sweden, we have tried to cover both temporal and spatial variability of soil condition in relation to rut formations. The main objective of this study was to evaluate whether risks for rutting can be predicted based on hydrologically modeled data within and across logging sites. The hydrological model used in this study is called HYPE (HYdrological Prediction for Environment) and is normally used for daily predictions of soil condition. The version of HYPE adjusted for Swedish conditions is called S-HYPE. The following research questions were specifically addressed:

1. Will inclusion of S-HYPE-modeled data improve existing descriptions of rut depth within logging sites?
2. Will inclusion of S-HYPE-modeled data improve existing descriptions of proportion of forwarder trails with ruts across logging sites?

Improved prediction of risk for rutting will give possibilities to improve planning of forwarder trails and scheduling logging sites by considering temporal variation of soil trafficability.

2. Materials and Methods

An empirical database containing data regarding ruts and forwarder trails [35] was used in this study. The database contained data regarding 35 logging sites, of which 27 sites (341 ha) had the complete data required for this study. The logging sites were well distributed in terms of operation season, size, and location in Sweden (Figure 1) and mainly comprised Norwegian spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). The sites were harvested during 2014 and 2015, using cut-to-length (CTL) mechanized systems. Each system involved a single-grip harvester, weighing approximately 20 Mg, and a forwarder with a laden weight of approximately 40–45 Mg. Detailed technical specification of machines used on these logging sites were missing in the database, since the data had been collected to address other research questions than those studied here.

2.1. Input Data

Input data used in this study can be divided into three main categories (Table 1).

Field-surveyed data: Information about forwarder trails and visible ruts along the trails was procured in the field using the ArcGIS collector application. Ruts, defined as wheel-tracks with exposed mineral soil having a minimum depth of 10 cm at the deepest part and minimum length of 1 m, were surveyed as GPS-positioned point observations. Tracks on peat soil did not require exposed mineral soil to be counted as ruts. To simplify the field work, rut depth and length were estimated and collected in predefined classes. Depth classes were defined as 10–20 cm, 21–50 cm, and >51 cm, and length classes as 1–5 m, 6–10 m, 11–20 m, and >20 m.

Data about forwarder trails were also collected in the field, describing the estimated number of machine passages including both loaded and unloaded forwarder passages. This information was used to define forwarder trail type in classes: strip forwarder trails with 1–5 passages, base forwarder trails with 6–10 passages, and main base forwarder trails with >10 passages. Any ground protection measures, such as slash or temporary timber bridges over wet areas, were also recorded in the field for both ruts and the forwarder trails. These data were later reclassed into a binary categorical attribute, ground protection or no ground protection, in the inferential analysis. A total of 5021 GPS-positioned rut-points and 234 km of forwarder trails were used as field-surveyed data across the logging sites. A more detailed description of the sites, forwarder trails, and ruts is presented in Table A1.

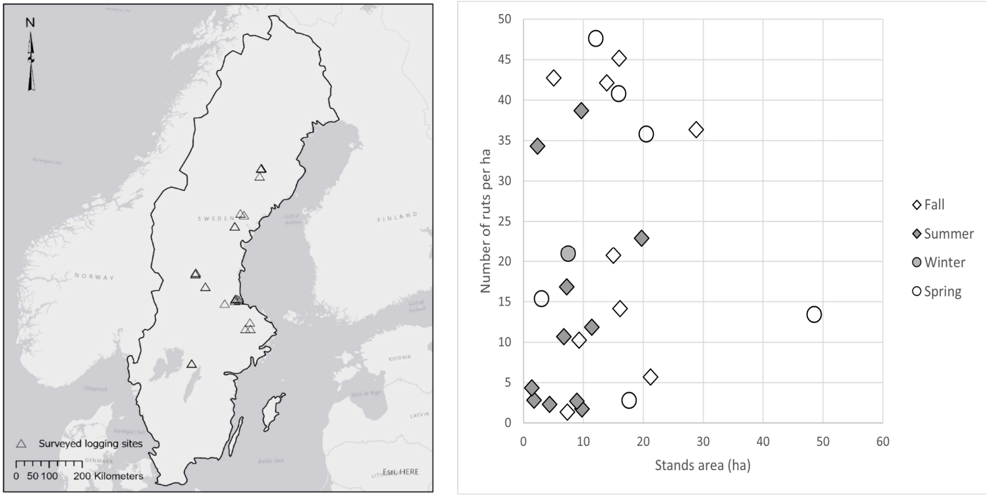

Figure 1. (**Left**) Surveyed logging sites in Sweden. (**Right**) Distribution of ruts per hectare logging site area with the season of logging site operations indicated. Ruts were defined as machine tracks with a minimum depth of 10 cm and a minimum length of 1 m.

Spatial data: Digital maps were consulted to collect spatial data about soil type, elevation, and estimated soil wetness at the studied logging sites. Soil type information was extracted from Quaternary soil maps of the Geological Survey of Sweden (SGU). Elevation and estimated soil wetness, modeled in DTW maps, were extracted from raster layers with 2 m resolutions available at the Swedish Mapping, Cadastral and Land Registration Authority and the Swedish Forest Agency, respectively. DTW maps were reclassed into binary classes, where areas with DTW $\leq$ 1 m were considered wet, and areas with DTW > 1 m as dry.

Hydrologically modeled data, (S-HYPE): The HYPE model has been developed by the Swedish Meteorological and Hydrological Institute (SMHI) to simulate flow channels and circulation of nutrients such as nitrogen and phosphorous [36]. The Swedish version of HYPE, S-HYPE [37], has been used as a platform for hydrological forecasting and warning services in Sweden since 2013. S-HYPE subdivides the Swedish landscape into 37,000 sub-basins, at the time of study, with areas of 700–1000 hectares. The sub-basins are, in turn, classified into 65 combinations of soil type and land use. The soil type data used in S-HYPE are extracted from soil maps of the Swedish Geological Survey (SGU), and are further simplified into classes of peatland, clay, till, thin soil or uncovered bedrocks, and fluvioglacial sediments. Using these data together with altitude and climatological data, the S-HYPE provides various hydrologically modeled variables, including soil moisture, ground water level, soil temperature, and frost depth, which were utilized in this study.

S-HYPE variables were provided as time series, covering a time span from 1981 to 2015. Hydrological data corresponding to logging periods for each of the sites were derived from S-HYPE time series. Wherever study units, e.g., ruts or logging sites, overlay more than one soil type or sub-basin, S-HYPE variables were weighted accordingly through the inferential analysis (Table A1). The mathematical operations were performed using ArcGIS 10.7 and MS Access software. A detailed presentation of all S-HYPE variables (a total of 30 variables) used in the study is provided in Table A2.

Table 1. Summary of input data used in this study: field-surveyed, spatial, and S-HYPE-data.

Input-Data	Contained Data	Data Category	Data Type	Reference
Rut length and depth	Length classes: 1–5 m, 6–10 m, 11–20 m, >20 m. Depth classes: 10–20 cm, 21–50 cm, >51 cm	Field surveyed	Shape file	
Slash protection	Yes/No	Field surveyed		
Trail type	Three classes: strip trails = 1–5 passes, base trails = 6–10 passes, main base trails > 10 passes.	Field surveyed	Shape file	
Soil type	Soil type in top 50 cm of the soil according to Quaternary maps	Spatial data	Shape file of varying resolution: 1:25–100,000 and 1:750,000	Geological Survey of Sweden, https://www.sgu.se/en/ (accessed on 15 August 2020).
Soil moisture	Estimations by depth-to-water (DTW) index, converted to two classes, wet (DTW < 1 m) and dry (DTW > 1 m)	Spatial data	Raster (2 m)	The Swedish Forest Agency, https://www.skogsstyrelsen.se/ (accessed on 1 April 2020).
Elevation	Digital elevation model created from high-resolution laser scanning of Sweden	Spatial data	Raster (2 m)	The Swedish Mapping, Cadastral and Land Registration Authority, https://www.lantmateriet.se/ (accessed on 1 April 2020).
S-HYPE	Modeled hydrological variables, see Table A2	Hydrologically modeled data	Text datasheets per soil type and sub-basin area	https://www.smhi.se/forskning/forskningsenheter/hydrologisk-forskning/hype-1.557 (accessed on 12 August 2017).

2.2. Statistical Inference

The sampled ruts in logging sites and sub-basin areas were analyzed by inferring variations of "rut depth" and "proportion of forwarder trails with ruts" using two regressor subsets:

1. Field and spatial data only.
2. Field, spatial, and S-HYPE data.

The subsets 1 and 2 differ mainly with regard to the regressors that reflect soil conditions. The soil moisture content estimated by DTW indices was only included in the first subset, whereas the S-HYPE variables were used to estimate soil conditions in the second subset of regressors.

2.2.1. Rut Depth Variation

The ruts used in this study had been originally surveyed for other purposes than the research questions addressed here and were therefore sampled at any distance (with an average of 9.5 m) between sampling positions. To avoid autocorrelative redundancy in sampled ruts, the dataset was resampled, and a minimum distance of 35 m was assigned between the sample points. This autocorrelative threshold distance was identified with Kriging technique using an anisotropic semi-variogram [38] and may be considered as a generally valid minimum sample distance in the type of boreal forest environments covered in the present study. The resampled dataset contained 1756 field-collected rut samples and was supplemented with map-collected sample points along the existing forwarder trails, where no rut damage had been identified. The latter type of sample points was called null ruts and they were extracted retroactively on top of digital logging maps. The addition of null ruts facilitated inferences regarding differences across disturbed and undisturbed forwarder trails and increased the sample size to 2063 sample points.

The soil moisture condition was described by DTW indices, extracted at each sample position, in regressor subset 1. Weighted-average S-HYPE variables at buffer zones around each sample position described the soil condition, using regressor subset 2. The sample points were matched with S-HYPE data by calculating the associated weighted averages of the S-HYPE time series variables, using information regarding logging periods, sub-basin areas, and soil types within buffer zones around each sample position. The buffer zones were made using a radius value (r) = rut length/2. The dependent variable was defined as the number of ruts within the predefined rut-depth classes (Section 2.1) and was assumed to follow a Poisson distribution [39]. The regressor variables shared by the two subsets included trail type, ground protection, and elevation.

Partial least squares (PLS) analysis was used [40] to estimate the true dimensionality of the regressor matrix, and to identify the associated regressor base. PLS was also used to create rank-ordered lists of relatively independent regressor variables. The top-ranked PLS regressors were used to fit a generalized mixed log-linked model [38] describing the observed variation of rut depths. Using a nested model design made it possible to account for the covariance structures assumed to stratify the dataset due to rut measurements within logging sites across sub-basins. In the mixed model design, logging site identities were exclusively used as random regressors when using field and spatial data as only regressors (subset 1). The logging site identities were nested within random sub-basin identities when S-HYPE variables were included in the rut depth prediction model (subset 2). More explicitly, the reason for the mixed effect design is that logging sites were harvested in different periods, by different operational teams that may have used different routines in their logging operations. Ruts within logging sites may therefore have properties not shared by ruts in other sites. The nested design was used because inclusion of S-HYPE variables required considering that individual sub-basins shared individual S-HYPE model outputs, presumably not shared by logging sites across different sub-basins.

The two subsets were compared in terms of efficiency in explaining the observed variation of the response variable, e.g., rut depth within logging site scale.

2.2.2. Proportion of Forwarder Trails with Ruts Variation

Potential regressor variables were compiled to infer the proportion of forwarder trails with ruts across logging sites. The proportion of forwarder trails with ruts was assessed by dividing the total rut lengths from all sample points by the corresponding length of forwarder trail within the respective classes of trail types and ground-protective measures. The proportion of wet areas within logging sites was also assessed using DTW maps, to reflect the soil moisture condition, when using the regressor subset 1. Logging sites with peat as dominant soil type (two sites) were excluded from the analysis due to large differences in bearing capacity between mineral soil and peat soil.

Three new variables were derived from S-HYPE data to assess the relative values of precipitation (Rel-prec), groundwater level (Rel-gwat), and soil moisture at root zone (Rel-srfd) to describe the soil condition in regressor subset 2. The relative values were calculated by dividing the average values of the associated S-HYPE variables during the logging operation (3–10 days) by averages of these variables for the reference period 1 January 2000 to 31 December 2014. The S-HYPE variables were calculated as weighted averages, using the proportion of soil type per logging site area as a reference prior to the assessment of relative values.

Using the method of parameterization described above, the dependent response variable, proportion of forwarder trails with ruts, was now a real number within the interval [0, 1]. The variation of this response variable was inferred with a logit-linked generalized mixed linear model [38]. The two regressor subsets (1 and 2) were again tested and compared with regard to their efficiency in explaining the variation of proportion of forwarder trails with ruts, over logging site scale. All explanatory regressors apart from logging site identities were considered as fixed effects. Logging site identities were considered as random variables in the evaluation of subset 1 and were (again) nested within random sub-basin identities in the evaluation of regressor subset 2.

Analyses of spatial data, including kriging analysis, were performed in ArcGIS 10.7. The statistical inferences (PLS analysis) were performed in Dell Statistica 13.0, and the generalized mixed linear model analysis using GENMOD procedure in SAS® statistical software (Version 9.4, SAS Institute Inc., Cary, NC, USA), ArcGIS 10.7 (Esri, Redlands, CA, USA), MS Excel, and MS Access (Microsoft, Redmond, WA, USA) were used for database management.

3. Results

3.1. Rut Depth Variation

With PLS applied to the resampled data, using only spatial and field data as regressors (subset 1), a list of relatively independent rank-ordered variables explaining the observed rut depth variation was created. The high-ranked PLS regressors identified and used as input variables to the generalized linear models were trail type, ground protection, elevation, and DTW soil moisture. Trail type, ground protection, and elevation were identified as significant regressors ($p < 0.05$), explaining 18.8% of rut depth variation observed within logging sites according to the PLS analysis.

When S-HYPE variables were used to describe the soil condition in regressor subset 2, estimated second layer soil moisture (Sml2) was added to the top significant variables ($p < 0.05$) identified by PLS. Accordingly, a linear combination of trail type, ground protection, elevation, and Sml2 explained 19.3% of the rut-depth variation observed within logging sites (Table 2).

Table 2. Description of regressor subsets and models efficiency, R^2, for inferring variation of rut depth within logging sites. Regressors marked with (*) were identified as significant at $p < 0.05$ level.

Regressor Subset	Fixed Regressors				Random Regressors	R^2
(1) Field and spatial data	Trail type *	Ground protection *	DTM (elevation) *	DTW (soil moisture)	Logging sites	18.8%
(2) Field, spatial, and S-HYPE data	Trail type *	Ground protection *	DTM (elevation) *	Sml2 (soil moisture at second soil layer by S-HYPE) *	Logging sites nested within sub-basin areas	19.3%

3.2. Proportion of Forwarder Trails with Ruts Variation

The proportion of forwarder trails with ruts was inferred (with a generalized mixed linear model) across logging sites, using the first subset regressor including trail type, ground protection, soil type, and proportion of wet areas in logging sites, e.g., proportion of site areas with DTW $\leq$ 1 m. The two (fixed) factors trail type and ground protection were once again identified as significant regressors ($p < 0.05$), explaining 33.1% of the observed variation in proportion of forwarder trails across the sites. The inference across logging sites was repeated with second regressor subset, including the relative S-HYPE variables Rel-srfd, Rel-prec, and Rel-gwat, in the regressor matrix instead of soil moisture estimation by DTW. The relative soil moistures (Rel_srfd) and (Rel_gwat) were added to the list of significant ($p < 0.05$) variables. A linear combination of relatively independent field, spatial, and S-HYPE regressors explained 35.4% of the response variation observed across logging sites (Table 3).

Table 3. Description of regressor subsets and models efficiency, R^2, for inferring variation of forwarder trails with ruts across logging sites. Regressors marked with (*) were identified as significant at $p < 0.05$ level.

Regressor Subset	Fixed Regressors						Random Regressors	R^2
(1) Field and spatial data	Forwarder trail type *	Ground protection *	Soil type	Proportion of wet area in logging sites, % (areas with DTW ≤ 1 m)			Logging sites	33.1%
(2) Field, spatial, and S-HYPE data	Forwarder trail type *	Ground protection *	Soil type	Relative precipitation (Rel_prec)	Relative soil moisture * (Rel_srfd)	Relative ground water level (Rel_gwat)	Logging sites nested with sub-basin areas	35.4%

4. Discussion

An existing database on ruts and forwarder trail over 27 boreal logging sites throughout Sweden was used to analyze the hydrological S-HYPE variables within and across logging sites to evaluate their potential to predict risk for rutting. The PLS results of assessing the observed variation of ruts with different regressor subsets—(1) field and spatial data, and (2) a combination of field, spatial, and S-HYPE data—indicated that the S-HYPE variables could contribute to additional explanatory power, but at very small magnitudes.

When S-hype variables were added to the regressor basis, the explanatory power of the models improved from 18.8% to 19.3% for rut depth, and from 33.1% to 35.4% for proportion of trails with ruts inferences. The improvement was slightly more pronounced when the proportion of trails with ruts was inferred, which indicated that S-HYPE variables can perform better at larger scale, such as logging site areas compared to finer scales and rut depth positions within logging sites. The S-HYPE variable sml2, soil moisture content at the second soil layer, and relative values of S-Hype Rel_srfd and Rel_gwat were found to be significant factors ($p < 0.05$) in our study. The effect is logical, since both the rut depths and lengths, i.e., proportion of forwarder trail with ruts, increase at higher soil moisture/ground water levels. However, due to the material used, we cannot say that this is an effect of the weather and not of some other difference between the sites. This needs to be investigated further using a controlled experimental design, and not survey material, as used here.

Trail type and ground protection were identified as significant factors in both subsets, explaining rut depth/proportion of forwarder trails with ruts. Higher number of machine passages means in practice the passage of higher accumulated load over trail segments, which encourages rut development. The significance of trail type in explaining the ruts variations is in agreement with results reported by Marra et al. [41] and Eliasson [4]. The use of slash for ground protection distributes the machine loads over larger areas and can thereby reduce the risk for rutting when the measures are properly applied [42]. The field data of ruts and forwarder trail used in this study had been collected previously to evaluate how application of DTW maps could contribute to minimized rut formation. Based on this essential decision support material, logging planners and drivers were able to avoid wet parts of the terrain, or to strengthen them prior to passage to minimize rut formation. The logging operation method indicated the effectiveness of ground protection in minimizing the risk for rutting, but this has faded out the possible effect of soil moisture estimations by DTW maps for the same objective. Soil moisture estimations by DTW maps could not explain the rut depth variations within logging sites, nor the proportion of forwarder trail with ruts. The logging operation method also implied that the choice of forwarder trail, and hence the location of ruts, is far from random, which needs to be kept in mind when interpreting the results. Elevation values, extracted from DEM layers, were more effective for evaluation of rut variations at finer scale, e.g., rut depths within logging sites, but were not found effective for predicting the proportion of trails with ruts when elevation was aggregated over the whole area of logging sites.

S-HYPE variables, when added to field and spatial data, improved description of the observed variations of the ruts in terms of both "rut depths" within the logging sites and "proportion of forwarder trail with ruts" across the logging sites. The improvements were, however, quite marginal, which makes it difficult to extract more general conclusions. The low effect of S-HYPE variables may also be because they are partially derived from the field and spatial variables already in the model, and they therefore introduce covariance to the regressor matrix rather than add unique non-redundant information. We suggest that the main reason for the limited effect of S-HYPE variables is that the S-HYPE model is designed for operating at relatively large landscape scales, so it cannot reproduce the local effects that regulate rut formation. This might depend on uncertainties incorporated in the S-HYPE model. Uncertainties are intrinsic parts of hydrological modeling and may have a number of causes: data uncertainty, model parameter uncertainty, and model structure uncertainty [43].

Data uncertainty: The S-HYPE model is built on different classes of land use (e.g., forest/agriculture land), elevation, and soil type. The land use classification is quite coarse and does not account for spatial variation in standing trees or the understory vegetation type. Soil information is extracted from Quaternary soil maps of the Geological Survey of Sweden (SGU), whose quality and resolution vary across the nation, and may affect the outcomes of the hydrological modeled data.

Model parameter uncertainty: The parameters in S-HYPE are primarily linked to soil type and land use. There are, however, also local deviations of key parameters, called super parameters [44], by which the accuracy in streamflow is improved considerably. The focus of the parameter calibration is streamflow. The model simulates other internal variables, e.g., lake levels, groundwater levels, and snow depth, with a varying degree of accuracy. It can be calibrated to simulate internal variables with a high level of accuracy [36,45]; but without local adaption, the results are quite uncertain at the fine scale used here. The variation in time is usually more reliable than the absolute values, for instance, for groundwater levels. In turn, this means that the detailed information required within the scales of typical logging sites is lacking. In a study by Tyystjärvi [46], the spatial and temporal variation of soil moisture was estimated using three different hydrological models, JSBACH [47], SpaFHy [48], and Ecohydrotools [49], where modeled and observed soil moisture was compared across a study area in northwest Finland. The study indicated that all the models had difficulties in modeling small-scale spatial variation, particularly at the driest part of the terrain, but performed better when simulating the temporal variation of soil moisture over longer time spans. More spatially detailed input data were recommended to achieve accurate estimations.

Model structure uncertainty: The S-HYPE model is mainly developed to estimate the flow and turnover of water and nutrients, and for monitoring the quality of water resources. Detailed information, such as land cover and soil type, is upscaled by the S-HYPE model without affecting its main application areas, whereas the estimation of such variables at smaller landscape scales may suffer as a result. Furthermore, the location of the different soil types is not resolved within the S-HYPE model sub-basin units, with areas of typically 700–1000 ha. This implies that S-HYPE variables lack the spatial resolution required for estimating the local ground-bearing capacity, based on soil condition estimations within the logging sites or capturing the variation of bearing capacity across the logging sites.

The strength of the S-HYPE model lies in describing how hydrological landscape characteristics may vary with time across a specific area, rather than capturing the differences among parts of different sub-basin areas over the same time span. The dataset used in the evaluation consisted of information from different points in space rather than different points in time over the same area. The predictive power of the hydrological model is likely to be advice on when, rather than where, to avoid logging operations. This strength could be applied to improve DTW maps by adjusting threshold values concerning flow initiation areas (FIA), required for mapping flow channels, or to decide proper DTW limit to distinguish wet/dry areas. A 1 ha FIA threshold value and a DTW limit of $\leq$1 m to separate wet/dry areas are currently used in DTW maps available at the Swedish Forest Agency [19]. Higher values of relative soil moisture (Rel_srfd) or relative ground water level (Rel_gwat), compared to averaged conditions over longer periods, can indicate wetter soil moisture conditions. This information can be used to apply a lower FIA or higher wet/dry DTW threshold limit and thereby develop more dynamic soil moisture maps for forestry applications. However, new studies are required to evaluate exactly how to use S-HYPE variables for such purposes.

5. Conclusions

To predict risk for rutting, using a hydrological model applicable for planning of logging operations, the small-scale spatial variations of topography, soil type, and land cover need to be represented in the model. Further improvement of the S-HYPE model may be needed to adapt it to the requirements of identifying logging sites and forwarder trail with adequate bearing capacity. However, the use of S-HYPE data to adapt the DTW maps to temporal changes in soil moisture may be a possible alternative for developing more dynamic soil moisture maps for forestry applications.

Author Contributions: Conceptualization: J.S. and L.E.; methodology, S.M. and T.T.; software, S.M. and T.T.; validation, L.E., J.S. and T.T.; formal analysis, S.M. and T.T.; investigation, S.M.; resources, J.S.; data curation, S.M.; writing—original draft preparation, S.M.; writing—review and editing, all authors; visualization, S.M.; supervision: L.E. and J.S.; project administration, G.L.; data acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: We would like to thank Tomas Nordfjell, Carola Häggström, Ph.D. (Swedish University of Agricultural Sciences, SLU), and Linnea Hansson, Ph.D. (The Swedish Forestry Research Institute, Skogforsk) for their valuable comments on the manuscript.

Conflicts of Interest: Authors declare no conflicts of interest.

Appendix A

Table A1. Description of logging sites, showing number of sub-basin areas in S-HYPE, total area (ha), number of ruts per hectare, total length of forwarder trail, total length of ruts, forwarder trail types, any ground protection of the forwarder trail, and soil type distribution according to SGU Quaternary maps.

Logging Site ID	Number of Sub-Basins Sustaining Sites	Area (ha)	Number of Ruts per ha	Total Length of Ruts (m)	Total Length of Forwarder Trails (m)	% Forwarder Trails Protected with Slash	Forwarder Trail Type Distribution			Soil Type Distribution				
							% Main Base Forwarder Trails	% Base Forwarder Trails	% Strip Forwarder Trails	% Clay	% Glaciofluvial Sediment	% Till	% Peat	% Thin Soil and Bare Bedrocks
1	1	1.78	2.8	23	1760	65.94	1.89	60.07	38.04	-	-	100.00	-	-
2	1	2.33	34.3	303	1752	59.94	-	52.04	47.96	-	-	100.00	-	-
3	1	1.38	4.34	20	1388	84.41	-	60.43	39.57	-	-	85.52	14.48	-
4	1	6.74	10.69	240	7467	74.11	5.63	61.37	33.00	-	-	100.00	-	-
5	1	7.24	16.86	315	5406	86.68	0.00	67.04	32.96	-	-	100.00	-	-
6	2	28.87	36.34	3895	14,291	81.82	1.66	59.28	39.06	-	-	100.00	-	-
7	1	13.89	42.12	2160	6855	68.05	0.00	56.83	43.17	-	-	100.00	-	-
8	1	14.99	20.75	840	9406	80.20	2.46	63.12	34.42	-	-	44.82	51.26	3.93
9	1	16.1	14.16	740	12,529	84.28	0.00	64.77	35.23	-	-	98.25	1.75	-
10	1	8.92	2.69	75	7692	65.39	3.76	64.49	31.75	-	-	69.42	0.92	29.66
11	1	11.39	11.85	475	7432	63.48	0.00	51.86	48.14	-	-	99.63	0.37	-
12	1	48.56	13.43	2579	35,183	40.18	1.70	39.32	58.98	-	-	99.49	0.51	-
13	1	17.67	2.77	148	13,634	67.59	0.00	26.60	73.40	-	-	98.10	1.90	-
14	1	20.53	35.8	2235	14,805	71.61	1.83	46.69	51.48	-	-	100.00	-	-
15	1	3.06	15.38	163	1806	67.30	-	53.71	46.29	-	90.35	9.65	-	-
16	2	9.75	1.74	76	7493	85.67	3.30	58.37	38.33	-	-	2.71	3.68	93.61
17	1	19.74	22.95	1620	15,096	76.65	0.49	74.03	25.47	-	-	27.80	72.20	-
18	1	4.37	2.29	30	2922	80.04	3.07	58.22	38.71	-	-	100.00	-	-
19	1	7.36	1.36	50	4697	91.98	-	58.44	41.56	-	-	100.00	-	-
20	1	21.19	5.71	463	16,272	36.91	2.00	74.39	23.60	-	-	99.59	0.41	-
21	1	7.49	20.96	500	6137	76.48	2.04	64.85	33.11	-	-	98.39	1.61	-
22	2	5.03	42.72	1128	2739	40.27	12.74	13.48	73.78	8.70	-	78.39	12.91	-
23	1	15.95	45.15	2258	10,908	37.67	1.59	35.58	62.83	51.27	-	31.82	1.98	14.92
24	1	9	10	510	5480	12.06	0.00	27.74	72.26	4.34	-	65.42	0.72	29.52
25	1	15.92	40.77	3317	8600	51.74	2.45	24.20	73.34	-	-	79.94	4.53	15.53
26	1	12.1	47.6	5635	6944	38.13	1.01	18.46	80.53	-	-	82.74	1.22	16.03
27	1	9.66	38.71	2680	5633	56.59	1.48	15.62	82.90	-	-	97.64	1.28	1.08

Table A2. List of S-HYPE variables used in the study to evaluate the possibility of describing the risk of rutting during logging operations. Three soil layers (upper, middle, and lower), with varying thickness for each soil type, are used in the model.

Variable Name	Scale	Definition
temp	°C	air temperature, provided in Tobs.txt/Tobs_nnn.txt
ctmp	°C	corrected air temperature
snow	mm	snow water equivalent
sdep	cm	snow depth
soim	mm	computed soil moisture (including standing water)
som2	mm	soil water of upper two soil layers (including standing water)
sml1	mm	soil moisture upper soil layer (not including standing water)
sml2	mm	soil moisture second soil layer
sml3	mm	soil moisture third soil layer
smrz	mm	soil moisture root zone (upper two soil layers) (not including standing water)
sm13	mm	soil moisture all soil layers (not including standing water)
stsw	mm	standing soil water
srff	-	soil moisture root zone (upper two soil layers) (not including standing water) as fraction of wcfc volume
smfd	-	soil moisture (not including standing water) as fraction of soil depth
srfd	-	soil moisture root zone (upper two soil layers) (not including standing water) as fraction of root depth
smfp	-	soil moisture (not including standing water) as fraction of pore volume
srfp	-	soil moisture root zone (upper two soil layers) (not including standing water) as fraction of pore volume
smdf	mm	soil moisture deficit to field capacity of upper two soil layers
gwat	m	groundwater level
sfst	cm	frost depth
stmp	°C	soil temperature
stm1	°C	upper soil layer temperature
stm2	°C	middle soil layer temperature
stm3	°C	lowest soil layer temperature
cout	m3/s	simulated outflow from lake/subcatchment
prec	mm/[period]	precipitation as provided in Pobs.txt
cprc	mm/[period]	corrected precipitation
crun	mm/[period]	calculated local runoff from land area. Note that this is not the same as the flow to the local stream if floodplains are used.
cros	mm/[period]	simulated surface runoff. Note that this is not the same as the flow to the local stream if floodplains are used
psim	mm/[period]	precipitation including water that will be removed as "interception losses"
temp	°C	air temperature, provided in Tobs.txt/Tobs_nnn.txt
ctmp	°C	corrected air temperature
snow	mm	snow water equivalent
sdep	cm	snow depth
soim	mm	computed soil moisture (including standing water)
som2	mm	soil water of upper two soil layers (including standing water)

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VI

EFFECTS OF SOIL CLAY CONTENT ON RUT FORMATION

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Abstract: *In Sweden harvesting operations are performed throughout the year to ensure deliveries of fresh high-quality wood to saw mills and pulp and paper industries. It is challenging to operate heavy forest machinery all year round and at the same time minimise ground impacts. Depending on ground bearing capacity and machine configuration, rut formation and soil compaction is more or less likely. To help minimise ground impacts, planning and decision support tools have been developed using information on e.g. topography, soil type and estimated soil wetness to predict terrain trafficability. The current available soil type maps have variable quality and resolution in different parts of the country, and therefore needs development to match the demands on digital data in the forestry sector. SLU and the Geological Survey of Sweden has developed a detailed digital clay content map for agricultural lands. In a part of Sweden where this mapping was done for forest land as well, rutting in four final felled stands had already been surveyed as a part of Skogforsks evaluation of the depth to water maps. In the inventory the number of ruts were counted, and a classification were made of their length (4 classes) and dept (3 classes). This inventory data was combined with the clay content map to investigate the correlations between rutting and clay content. Results shows that the number of ruts per ha tends to increase with increasing clay content in the soil. An increase in clay content also increased the number of long ruts as well as the number of deep ruts. Based on the results clay content maps are likely to improve predictions of terrain trafficability. However, there is a need to analyse their interactions with the currently used digital terrain models and depth to water maps to ascertain that the clay content map provides additional information. New clay content maps have to be produced for forest land before they can be incorporated in planning and decision support tools, and further studies are needed to confirm the results of this small pilot study.*

Keywords: soil compaction, harvesting, forwarding, strip roads, decision support

1. Introduction

In Sweden harvesting operations are performed throughout the year to ensure deliveries of fresh high-quality wood to saw mills and pulp and paper industries. This also enables forest companies and forest owner associations to provide their own harvesting teams as well as their contractors with full time work throughout the year, thus enabling an efficient use of harvesters and forwarders.

Ground-based logging operations can cause rut formation and soil compaction (Wronski and Murphy 1994; Cambi et al. 2015), which can lead to negative impacts of future forest growth. Furthermore, rutting is considered aesthetically negative by both forest owners and the general public. Thus, Swedish forestry faces the challenge of how to operate heavy forest machinery all year round and at the same time minimise ground impacts. Depending on ground bearing capacity and machine configuration, rut formation and soil compaction is more or less likely. Therefore, a combination of planning, adaption of harvesting techniques and technical solutions are used to minimise ground impacts.

Recently planning and decision support tools have been developed to help minimise ground impacts using information on e.g. topography (Mohtashami et al. 2012), soil type and estimated soil wetness (depth to water maps) (Mohtashami et al. 2017) to predict terrain trafficability. An obstacle to use soil type in these applications is that the current available soil type maps have variable quality and resolution in different parts of the country, and especially so for forest lands. The soil type maps need development to match the demands on digital data in the forestry sector. SLU and the Geological Survey of Sweden (SGU) has developed a detailed digital clay content map for agricultural lands. This newly developed "Digital Map of agricultural land" contain estimates of clay and sand content (Söderström et al. 2016 a). In a pilot project, they have made a digital map of the clay content of arable land in Norrland for a 24000 km^2 area (figure 1) between Östersund and the Bothnian coast (Söderström et al. 2016 b). This area contains a lot of forest land and it was therefore interesting to investigate if this map provides an alternative to existing soil type maps. The occurrence of ruts had already been surveyed on four logging sites within this area for a study of the usefulness of depth to water maps (Bergqvist and Friberg 2016).

The aim of the study was to evaluate the correlation between the clay content estimates and rut occurrence and rut severity for the four sites were data already had been collected.

2. Material and methods

Data from four sites that were surveyed within the STIG project were used to evaluate the clay content map. The data had originally been used to evaluate the depth to water (DTW) maps, and as a part of that project operators had access to the DTW-maps when the sites were harvested. The survey data gathered for these sites contain information about all ruts within each site. Position, length, depth and estimated number of passes has been measured or classified for each rut. Rut length were classified in 4 classes (1-5 m, 5-10 m, 10-20 m, >20 m), rut depth was divided in 3 classes (10-20 cm, 20-50 cm, >50 cm), and number of passes were estimated in 3 classes (1-5 passes, 6-10 passes, >10 passes) (Bergqvist and Friberg 2016). GPS-positioned roads and ruts were projected onto the GIS-maps to extract corresponding soil and moisture classes to the field data and to measure the length of road segments in corresponding classes on each map. The new clay content layer was added to this GIS.

The clay content map is based on soil type data from the European LUCAS database, a digital elevation model with 10 m pixel size, soil type maps from SGU, and gamma sensor information (Söderström et al. 2016 b). The resolution of SGU:s soil type maps varies, in some part of the area, i.e. populated areas, the scale is 1:25 000 – 1:100 000; in others there is a medium detailed scale of 1:200 000, but there are forest areas in scale 1:750 000. Unfortunately, the four sites surveyed in the STIG project falls in the last group.

To simplify analyses and handling in the GIS clay contents were classified into four classes:

clay content < 5 %

5 % ≤ clay content < 10 %

10 % ≤ clay content < 15 %

15 % ≤ clay content < 20 %

The sites were dominated by clay content class 1 (Figure 1), and no substantial areas with a clay content over 20 % were noted on any site.

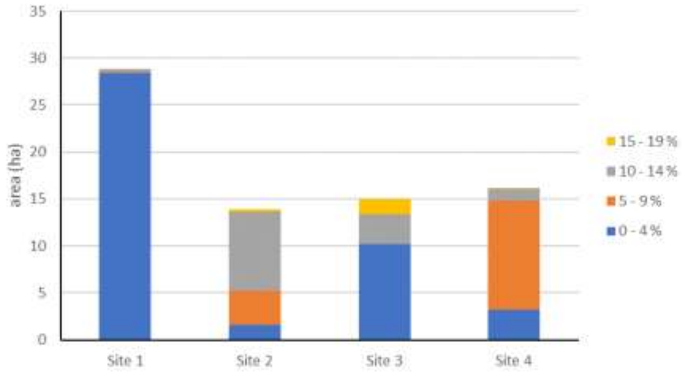

Figure 1. Site area and clay content class distribution.

3. Results

The highest number of ruts occurred on medium trafficked roads, and the least on high trafficked roads (Figure 2). This is not surprising since there are less high trafficked roads per ha and these roads are placed in favourable parts of the terrain. There is a non-significant tendency that the number of ruts increase with increasing soil clay content.

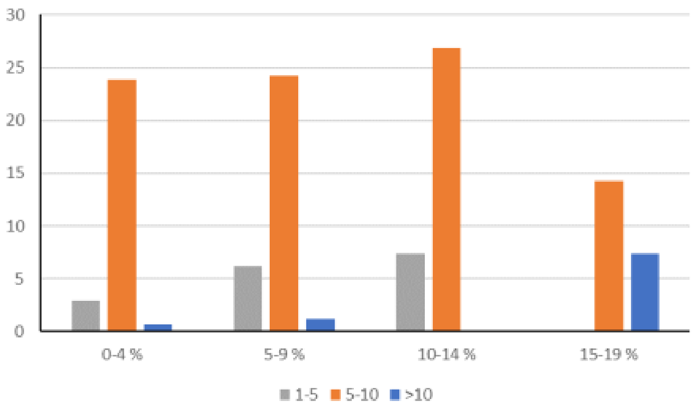

Figure 2. Number of ruts per ha depending on clay content and number of passes.

If site 1 is excluded from the analysis there is a tendency that the frequency of ruts increases with clay content as well as the frequency of deeper or longer ruts (Table

1 and 2), unfortunately this cannot be verified due to the large variability between sites.

Table 1. Number of ruts per ha separated on rut length, clay content class and site.
– means that the clay content class did not occur within the site

		Clay content			
Site	Rut length	0–4 %	5–9 %	10–14 %	15–19 %
1	1-5 m	30,1	714,3	16,5	-
	5-10 m	4,2	53,6	4,7	-
	10-20 m	0,5	0	0	-
	> 20 m	0,3	0	0	-
2	1-5 m	12,2	62,5	27,9	0
	5-10 m	3,2	10,5	5,3	0
	10-20 m	0	1,1	0,5	0
	> 20 m	0	0	0,8	0
3	1-5 m	16,1	-	23,5	21,0
	5-10 m	0,1	-	0,3	3,0
	10-20 m	0	-	0	0
	> 20 m	0	-	0	0,6
4	1-5 m	1,6	11,6	56,4	0
	5-10 m	0	0,6	4,55	0
	10-20 m	0	0	0,8	0
	> 20 m	0	0	0	0

Table 2. Number of ruts per ha separated on rut depth, clay content class and site.
– means that the clay content class did not occur within the site

		Clay content			
Site	Rut depth	0–4 %	5–9 %	10–14 %	15–19 %
1	10-20 cm	14,0	214,3	4,7	-
	20-50	20,4	535,7	16,5	-
	> 50 cm	0,7	17,9	0,0	-
2	10-20 cm	5,1	36,9	13,6	0,0
	20-50	9,6	35,5	19,5	0,0
	> 50 cm	0,6	1,7	1,4	0,0
3	10-20 cm	9,8	-	17,1	16,2
	20-50	5,1	-	6,8	7,8
	> 50 cm	0,0	-	0,0	0,0
4	10-20 cm	1,6	8,1	45,1	0,0
	20-50	0,0	4,1	16,5	0,0
	> 50 cm	0,0	0,0	0,0	0,0

4. Discussion

Due to the limited material used for this pilot study, it is hard to come to any final conclusions on the usability of the clay content maps. Clay content maps were tested on material from only four sites, and one of these sites lacked variation in clay content. The study shows that these maps can be a help to find sensitive areas so that traffic in these areas can be minimised during harvesting operations. However, there is need to further studies on how these maps interact with other information already provided to the operators. There are indications of correlations between the clay content and the DTW index for the studied sites. It may be so that the correlation with information from DTW-maps and digital terrain models are so large that the added value of clay content information is limited.

In the areas where detailed soil type maps are available, they can be used to classify the soil in bearing capacity classes. These classes have a significant influence on the risk for rut formation (Mohtashami et al. 2017). However, in the areas where only low-resolution soil type maps are available, some of the soil types are too general to be classified in a bearing capacity class. The most common group of soils in Swedish forests are till soils (moraines), and they are not separated into soil types in the low-resolution maps. The difference in trafficability and how trafficability is affected by soil water between a sandy, gravely till soil and a clayey silty till soil is large. The clay content maps will provide at least an idea of how fine grained the soil is even in areas with a low-resolution soil type map and should therefore provide some additional information to that already in use.

Before a new study is made there are some factors that influenced the results which should be highlighted and taken into account. The new study should not be made in an area where the lack of high resolution soil type maps is a limiting factor for the clay content maps. This can easily be achieved by performing the study in an area in southern Sweden where the forest land is closer to agricultural land and populated areas. Furthermore, more sites need to be surveyed and sites with little variation in clay content should be avoided if possible.

In a long perspective it would perhaps be more advantageous to have maps on silt content than on clay content, as it is well known that silt soils have lower strength than clay soils. Furthermore, silt causes problem with frost heaving of planted seedlings, increases the costs for road construction, and may limit the use of those roads to dry or frozen conditions. However, at the moment it is unclear if the methods to model clay content can be modified to model silt content.

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Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2022:67

This thesis presents GIS-based decision support systems that may be used to minimise soil impacts by mechanised logging operations. Using these systems, it is possible to estimate soil trafficability, examine logging trail layouts, schedule logging operations and carry out low impact logging operations. Easy access to soil trafficability maps, based on high quality GIS data, facilitate their implementation in practical forestry operations. Studied GIS data included digital elevation models, depth-to-water maps, hydrological data, soil type- and clay content maps.

Sima Mohtashami received her doctoral education at the Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences in Umeå. She holds a Master of Science (MSc) degree in Environmental Engineering and Sustainable Infrastructure from Royal Institute of Technology (KTH).

Acta Universitatis Agriculturae Sueciae presents doctoral theses from the Swedish University of Agricultural Sciences (SLU).

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ISSN 1652-6880
ISBN (print version) 978-91- 8046-010-1
ISBN (electronic version) 978-91- 8046-011-8