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Knowledge and Technologies for Effective Wood Procurement

Deliverable 4.1

TERRAIN ACCESSIBILITY MAPS FOR 4 CASE STUDY AREAS

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Lead beneficiary:	**Georg-August-Universität Göttingen**
Main contact:	**Marian Schönauer**

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Table of Contents

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1 Summary

The extent and severity of disturbance of forest soils can often be managed through a greater awareness of the causes and effects. Soil disturbance in the form of wheel rutting and compaction can impede the future production potential of the site, promote the spread of diseases such as root rot (e.g. Heterobasidion spp.), and alienate environmentalists and recreational users of the forest (Spang 2014, Luther 2016). In addition, wheel sinkage and slippage directly increase the cost of timber extraction through higher fuel consumption and lower productivity, providing the verifiable goal of minimizing soil damage for any forest contractor.

Wet soil conditions reduce soil bearing capacity irrespective of the soil type. The occurrence of wetter or drier areas is difficult to predict during forest operations, as stands are often dense and visibility is limited. In order to maintain longer-term trafficability and site productivity, the most recent developments in methods and technologies should be applied, also in improving the public perception of the forest industry as a pro-active and responsible manager of the land on which it depends. The Depth-To-Water-algorithm (DTW) is such a method that helps to identify critical areas.

To our current state of knowledge, the DTW algorithm developed by Murphy et al. (2009) is the least data demanding approach for mapping wet areas and consequently zones of low soil bearing capacity or risky trafficability, and so can be applied on a European scale. The algorithm is based on a grid of flow accumulation in conjunction with a grid of slope values and ultimately provides a single number for any point in the terrain, the depth to water. The DTW-index determines the flow direction according to the elevation difference between adjacent cells in the landscape, in direction to exposed surface water. In other words, the metric DTW-index shows the depth from a particular point in the area to the nearest surface of open water. Low values of the DTW-index indicate lower drainage condition of that point, and therefore a higher probability for wetness at that point. Using algorithms developed by the University of New Brunswick, DTW-indices with four different flow initiation areas (0.25 ha, 1.00 ha, 4.00 ha, 10.00-40.00 ha) were calculated for study areas in Finland, Germany, Norway and Poland. By using different flow initiation areas, the seasonal variation of flow paths can be simulated. The created maps were assessed using five randomly selected squares with a side length of 1500 m. The partial wet areas, showing a DTW-index <1 m, and the partial intersection of forest road length passing these areas were determined. With the application of the DTW-maps in forest operations, critical areas in terms of low DTW-index, permanent and perennial streams can be identified and physical soil disturbances can be avoided, or access managed according to season (Ågren et al. 2015). With the increased knowledge of the ground wetness of a harvesting site, a handful of expedient preventions can be applied during the harvesting operations.

The University of New Brunswick (Canada) is acknowledged for generously contributing time and resources in calculating high resolution DTW maps representing varying seasonal conditions.

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2 Introduction

2.1 Issues and background

Forest soil disturbances often occur as a consequence of harvesting operations. The reasons for disturbances are many, but might be better managed if the more sensitive areas in a forest are known beforehand. This leads to non-conformist harvesting operations with heavy forest machinery. The increased knowledge of sensitive spots within a forest stand can support the mitigation of heavy impacts, e. g. deep ruts. Existing mappings of these sensitive spots are not in every-day use, since their information is too specific. In TECH4EFFECT, we want to combine maps, which can prevent soil disturbances, with already available maps like road maps, forest inventory maps etc.

This deliverable describes the principle of trafficability maps, and the preliminary evaluation of the application in 4 case study areas. Ultimately, the report serves as a milestone, indicating that the maps have been generated and will now be taken into use in the respective case studies.

2.1.1 Relevance

Despite technical improvements in recent decades, driving on skid trails with heavy machinery continues to cause soil disturbance, such as compaction of the topsoil (Cambi et al. 2015), the formation of deep ruts due to occurring shear forces (Horn et al. 2007) or erosion on skid trails (Zemke 2016). The formation of ruts is driven by soil displacement which occurs on wet soils primarily, rather than soil compaction (Williamson, JR und Neilsen 2000). Apart from the associated restriction of technical trafficability, parts of society are increasingly critical of such visible disturbance caused by the use of large machines in forests (Spang 2014, Luther 2016). In order to maintain and strengthen the acceptance of practices within the forest industry, a paradigm change by the forestry enterprise to reduce soil disturbances in light of foreseen climate change might be beneficial. Maintaining technical trafficability of skid trails is also a primary goal for economic and efficient timber harvesting. Otherwise, there is a risk of high costs for restoration measures of impassable skid trails or even the designation of new skid trails and thus a loss of production area.

2.1.2 Impact on forest soils exerted by heavy machinery

Soil disturbance is mainly due to high and varying compressive and shear forces during the driving of forest soils by machines for timber harvesting and timber extraction (Sohns 2014). Impacts of heavy machinery on forest soils are manifold and composed of:

- Diversification of the work spectrum of forest machinery, in particular special machines which cover almost every work task,
- The increasing number of forest machines in the forest, as a consequence of economic limitations and safety reasons,
- The harvesting operations expanded to full-year operations,
- Numerous technological improvements and applications which led to an expansion of machine operations on areas which have not been accessible yet, and
- Usage of bigger and heavier machines in the forest (Ziesak 2004)

and it doesn't seem like these impacts will be reduced in near future.

The sensitivity of forest soils to machine induced disturbances varies greatly by soil type, soil moisture and soil density as well as seasonal temperature and moisture changes (Sohns 2014). In particular, the latter factors, which are additionally influenced by climate change, represent a major challenge for

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soil-careful timber harvesting in the future. Heavy summer rainfall, extended drought period and lack of winter frosts will significantly increase the susceptibility of soils to compaction as well as the frequency of emergency interventions in order to process impacts of hurricanes and calamities, as a result of which the frequency of traffic will also increase (Geologischer Dienst NRW 2016).

Cambi et al. (2015) stated, that the number and depth of ruts, which grow with the number of machine passes, can considerably decrease the site productivity through loss of growing medium, erosion and increased water runoff on slopes. Still, the most significant increase of soil bulk density occurs after the first machine pass (Jamshidi et al. 2008).

Since almost any traffic with machines can lead to persistent soil disturbance, the policies in Germany enforce the creation of a permanent skid trail network, in order to concentrate the impact on the soil on distinct areas, as recommended by Vossbrink und Horn (2004). Rutting to a certain degree is tolerated on permanent skid trails (Schäffer 2002), but since it is intended to allow for year-round forest operations, excessive soil disturbance along the skid trails must be avoided. Damages of this kind, such as deep ruts, endanger the permanent trafficability.

2.1.3 Prevention of soil damage

Even if the trafficability of a site can be defined to large extent by the soil type, information on the current soil moisture is indispensable for the assessment of the trafficability risk, since the soil bearing capacity and as consequence the trafficability decrease with increasing soil moisture, regardless of the soil type (Eckelmann 2009). For the determination of soil moisture of forest soils, the determination of suction tension by means of a tensiometer or the determination of soil moisture content by injection of a TDR or FD probe as a field method or conventional sampling and drying of soil samples as a laboratory method are available (Feldwisch und Friedrich 2016). However, these methods are complex and not very practicable on a large scale planning level for on-site contractors.

In a large Canadian forest industry, high-resolution trafficability risk maps from the UNB based on wet-areas mapping (WAM) are currently being used in conjunction with depth-to-water analyses (DTW for the identification of water-influenced stock areas) to minimize traffic damage through improved resource planning (Vega-Nieva et al. 2009, Campbell et al. 2013). In Sweden, a similar system is used in infrastructure and harvest planning (Ågren et al. 2014). In Finland, soil moisture was derived from digital terrain models and the risk of damage from traffic on rural roads was estimated (Niemi et al. 2017).

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3 Methods

3.1.1 Study areas

Four study areas have been selected in the partner countries Finland, Germany, Norway and Poland. Each study area has an approximate size of 50 km², where field trials can be conducted in the near future. These field trials will analyse the local risks of soil disturbance due to machine traffic and, as such, allow for validation of predictability of soil disturbances, in particular rut depth, by means of DTW-maps. Therefore, simulated and real operations will be performed and measurements of soil penetration resistance and shear strength, and soil moisture content will be conducted in conjunction with pedological analyses.

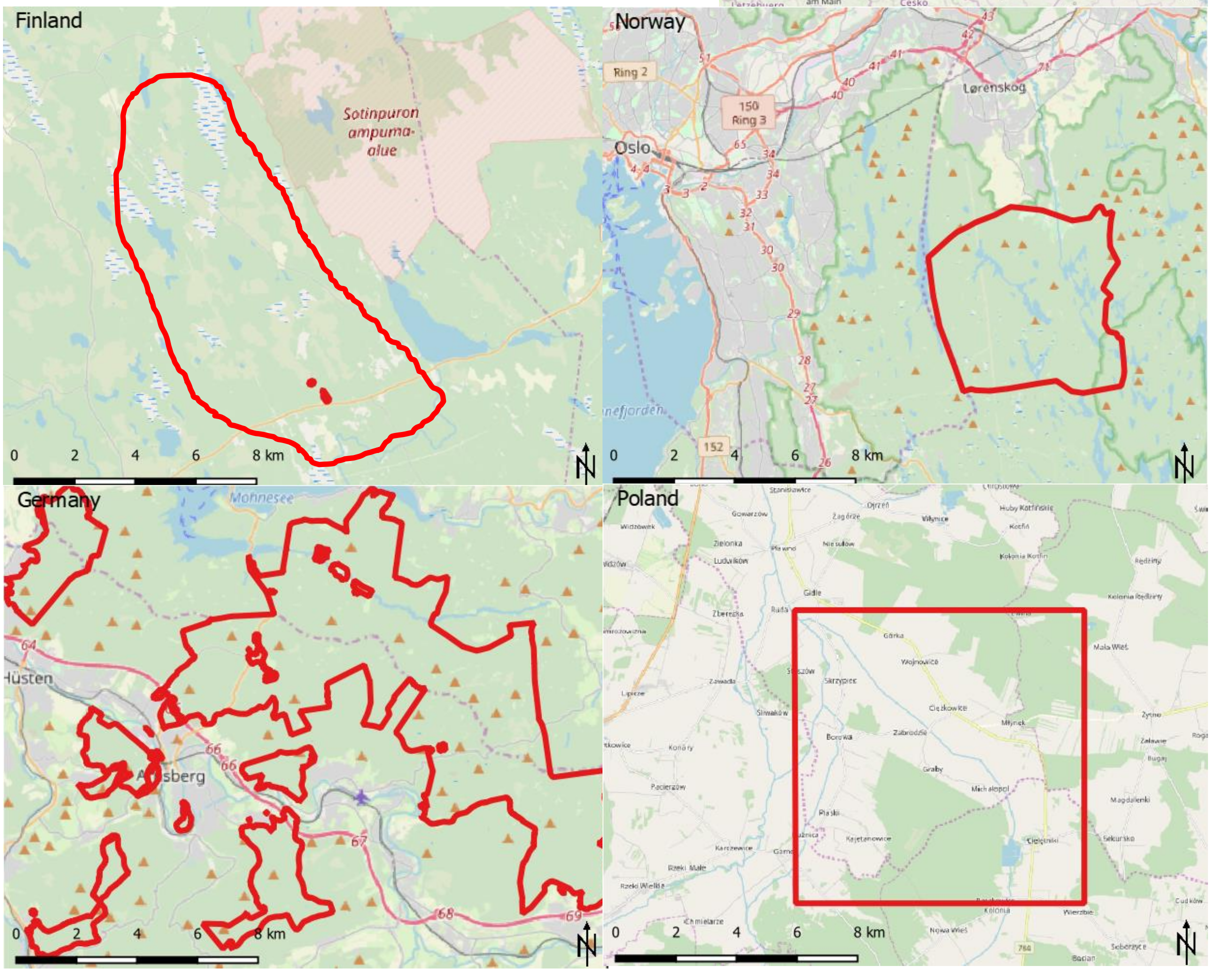

Figure 1: The location of the four study areas in Finland, Germany, Norway and Poland, indicated by a black triangle (top right) and a red outline (source: OpenStreetMap).

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Table 1: Site characteristics and long-year means for temperature and annual precipitation of the study areas of the participating countries.

	Finland	Germany	Norway	Poland [1]
Terrain	Flat, slightly hilly [2]	Predominantly hilly, mountainous	Steep hills of exposed or lightly covered bedrock interspersed with low wet areas	mostly flat, varied by river valleys, and upland terrain in the eastern part
Elevation	140 to 250 m, mean 175 m [2]	160 to 550 m, mean = 320 m	150 to 360 m, mean =217 m	188 to 270m, mean = 229 m
Location	Pohjois-Savo [2]	Sauerland, North-Rhine-Westfalia	Losby Estsate, Lørenskog, Akershus County	South Poland, Border of Silesian and Lodz Voivodeship
Geomorphology	Karelids [3]	the north-western foothills of the Rothaargebirge [4]	South-eastern offshoots of Scandinavian Mountains	Contact of the Silesian-Krakow Upland, Kielce Upland and the Nidziańska Basin[4]
Bedrock	Migmatitic tonalite, biotite paragneiss and granite [3]	Claystone and Sandstone from Devon and Karbon [5]	Gabbro, diorite, tonalite, partially converted Granite-biotite-gneis, biotite-muscovite gneiss[6]	Sandr sands and gravels and tills as well as glacial sands and gravels
Soil types	Podsol and peat [3]	Brown soils to Pseudogleys	Morainic till between rocky outcrops, some marine shale in low areas	13 types of soils, mainly brown and fawn soils
Mean Temp.	3.0°C [2]	8.9°C [3]	4.1 °C [7]	7.9°C
Mean annual precipitation	665 mm [8]	790 mm [9]	860 mm	582 mm
Typical tree species	Scots pine, Norway spruce and downy birch	Beech, spruce, pine	Norway spruce, Scots pine, birch	Pine, larch, spruce

[1] Biuro Urządzania Lasu i Geodezji Leśnej 2017.
[2] National Land Survey of Finland.
[3] ESRI Finland 2019.
[4] Diercke.
[5] Geologischer Dienst Nordrhein-Westfalen.
[6] Geological Survey of Norway
[7] Norwegian Meteorological Institute
[8] Natural Resource Institute Finland.
[9] Deutscher Wetterdienst 2019.

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3.1.2 Depth-To-Water algorithm

According to our current state of knowledge, the DTW-algorithm developed by Murphy et al. (2009) is the least data demanding approach for mapping wet areas and, hereby, identifying zones of low soil bearing capacity or trafficability. The presented method for the creation of a Depth-To-Water maps is based on geomorphological assessments and does not consider soil type, its variation and texture as a direct input parameter in the calculation. Consequently, the algorithm is not able to cover the special situations in peats or rocky overlays, and caution at the everyday use is necessary. Still, the advantages of being independent of high-resolution soil mapping overcome the disadvantages of partial inaccuracy and inapplicability. In order to conduct the mapping approach in four European countries, this aspect even gets more evident.

The weaknesses of previous, topographically derived soil wetness indices, which are built on digital elevation models only, are in their inability to model spatial patterns of soil moisture or drainage conditions and the over-dependence on convergent flow accumulation (Murphy et al. 2009). UNB developed a new algorithm that is able to skirt these weaknesses. The combined information of hydrographic data and topographically derived flow accumulation are used to define a surface water feature layer in the first step. The required DEM is provided by governmental institutions.

Table 2: Provider and spatial resolution of the digital elevation model, used for the calculation of the DTW-index.

Country	*Data provider*	*Resolution DEM [m]*
Finland	National Land Survey of Finland	2.0
Germany	Bezirksregierung Köln	1.0
Norway	The Norwegian Mapping Authority	1.0
Poland	Polish Main Office of Geodesy and Cartography	1.0

In turn we created a 1.0 to 2.0 m resolution raster DEM using the exact height values of the LiDAR data sampled with a nearest neighbour function. In a first step we used the LiDAR-derived bare-earth DEM for finding and removing local depressions using the FILL function (Tarboton et al., 1991; Tarboton, 1997). The pit-free DEM was then used to delineate the shortest (least cumulative slope) flow path of each surface water cell by flow direction and slope. This process ensures the assignment of each cell to the downslope surface water cell with the most likely hydrological connection. Thereby, each cell within the DEM represents its real area of a landscape (e.g. 1 raster cell with a side length of 2 m is representing 4 m^2).

To allow the estimation of the predicted flow direction of these flow paths, two requirements are necessary: (1) the processing of the DEM, which is done by a "fill"-function, since artificial point depressions of the D8 flow accumulation algorithm would occur otherwise and (2) a mapping of culvert crossings (or expert appraisal instead) followed by manual breaching. After this preparation of the DEM, the surface flow accumulation, using the D8 algorithm to create unidirectional flow lines, is processed. In order to produce a surface flow network, upon which later calculations of the DTW-index are based, a threshold of 2.500 to 100.000 raster cells (representing 0.25 ha or 10 ha,

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respectively) is used. When this certain threshold is reached in a flow path, a flow line can be delineated in a grid of flow accumulation. A threshold of 4 ha is used as a standard value, since this value has been shown to work well across varying terrains.

The created grid of flow accumulation in conjunction with a grid of slope values is sufficient for the calculation of the DTW-index, which approximates the elevation difference between the cell in the landscape and the assigned surface water cell (grid of flow accumulation). The path of the least cumulative slope will be identified by a least-cost function, which is minimizing the distance and the slope from each landscape cell to the closest flow line. The distance is given by the cell size or its diagonal length, if the cell is draining into a cell on the edge (in this case a multiplier α is used). This path of least slope gradients is estimated for each cell and giving the DTW grid, which is formally defined as:

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

Where $\frac{dz_i}{dx_i}$ is the slope of a cell i and a, the multiplier, is 1 in case of parallel drainage and 1.414214 in case of diagonally drainage. x_c is the grid cell size [m].

3.1.2.1 The application of the DTW-index

The DTW scale is metric and can be interpreted as a relative measure of soil drainage condition, which approximates the tendency of a point in the landscape to be saturated. Cells with a small value of DTW show a high tendency of surface water or water containing layers in the soil (Murphy et al. 2009). In practice, it can be referred to it as a metric index of likely end-of summer soil drainage conditions and soil bearing capacity, classified as follows:

0	<	DTW	<	10	cm	Very poor
10	<	DTW	<	25	cm	Poor
25	<	DTW	<	50	cm	Imperfect
50	<	DTW	<	100	cm	Moderate
100	<	DTW	<	1500	cm	Well
		DTW	>	1500	cm	excessive

Areas of lakes, streams and flow lines in the flow accumulation grid are set with a DTW-index of 0. Low values indicate wet soils, whereas the values of the DTW-index tend to increase with the distance to delineated flow lines in the landscape. The higher the value, the drier the soil is supposed to be. This nearly empirical approach is supported by the likely situation, that distinct points in a landscape are wetter, if located next to a delineated flow line or wet area and vice versa.

The reputed Topographic Wetness Index, which combines local upslope contributing area and slope (Sörensen et al. 2006), and the cartographic Depth-To-Water-index are the best performing soil wetness predictors, whereas the DTW-index has the advantage to be scale-independent for the most

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part and showed a higher accuracy of 80% in a Swedish case study (Ågren 2013). Ågren (2013) concluded, that the DTW may form the next generation of high-resolution wet-area maps, which will be applied in forestry and elsewhere.

3.1.2.2 DTW-index for the four countries and evaluation of the applicability

The DTW-index was calculated with four different flow initiation areas (FIA, 0.25 ha, 1.00 ha, 4.00 ha, 10.00-40.00 ha) for the study areas of the participating countries. The maps are accessible; please contact Georg-August-Universität, foresteng@uni-goettingen.de.

Five squares with side length of 1500 m were selected randomly in the mapped area of the participating countries, resulting in a total sample area of 1125 ha, for a descriptive assessment of the DTW-index and forest road infrastructure. The DTW-maps with 0.25 ha and 4.00 ha FIA were clipped to the five samples and analysed. The clipped DTW-maps were processed, using R stat – the areas with a DTW < 1 m were vectorised into area-shapes. The intersection of mapped forest roads and skid trails with the created area-shapes with $DTW_{FIA=0.25\ ha}$ < 1 m or $DTW_{FIA=4.00\ ha}$ < 1 m was estimated using QGIS3 and MS Excel 2016.

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4 Results

4.1 Depth-To-Water maps

4.1.1 Evaluation of selected sections of the four study areas

In general, the DTW-index responds to the terrain slope. In this survey, the averaged slope shows a weak correlation with the partial wet area (liner model: p=0.096 or p=0.218 for FIA of 0.25 ha or 4.00 ha, respectively). Although Finland has the highest frequency of areas with $DTW_{FIA=4\ ha}$ < 1 m, the forest roads are under-represented within these areas with 16.5% compared to the total road length (Table 3). The roads in the study area of Germany are unfortunately over-represented in areas with $DTW_{FIA=4\ ha}$ < 1 m with an intersection of almost 16% compared to the total road length. This is comparatively high, if the partial area with $DTW_{FIA=4\ ha}$ < 1 m is taken into account, which is lowest in Germany 5.7%. Norway in turn shows a low percentage of almost 1.9% of forest roads in areas with $DTW_{FIA=4\ ha}$ < 1 m, even though the partial area with $DTW_{FIA=4\ ha}$ < 1 m amounts 10%. If Norway and Germany are compared regarding the areas with $DTW_{FIA=0.25\ ha}$ < 1 m, the comparison gets worse. The built roads in Norway pass areas with $DTW_{FIA=0.25\ ha}$ < 1 m with 3.8% compared to the total road length, in Germany this ratio amounts 61.5%. Poland shows a more or less systematic alignment of forest road infrastrucutre, where wet areas with $DTW_{FIA=4\ ha}$ < 1 m are partially avoided (20.5% intersection as against 29.7% wet areas in total).

Table 3: *The table shows an overview of the average slope, the partial area with $DTW_{FIA=0.25\ ha}$ < 1 m or $DTW_{FIA=4.00\ ha}$ < 1 m compared to the sample area of 1125 ha, the intersection of forest roads and skid trails with areas with $DTW_{FIA=0.25\ ha}$ < 1 m or $DTW_{FIA=4.00\ ha}$ < 1 m and the density of forest roads or skid trails in the five samples of each participating country.*

Country	Avg. slope [%]	partial area with $DTW_{FIA=4\ ha}$ < 1m [%]	partial area with $DTW_{FIA=0.25\ ha}$ < 1m [%]	Intersection of roads and areas with $DTW_{FIA=4\ ha}$<1m [%]	Intersection of roads and areas with $DTW_{FIA=0.25\ ha}$<1m [%]	Density of forest roads [m/ha]
Finland	5.4	37.7	76.4	16.5	60.8	20.7
Germany	16.9	5.7	25.7	15.9	61.5	36.5
Norway	32.4	10.0	22.4	1.9	3.8	18.6
Poland	2.4	29.7	84.6	20.5	85.9	36.4

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4.1.1.1 Finland

The main forest roads follow the areas with high DTW-index, which are mostly oriented in north-west to south-east direction (Fig. 2). Main roads are mainly following along this axis (A). This geomorphology is built by glacial deposits and shows a homogenous surface with an elevation ranging from 140 to 230 m above sea level. The DTW shows a mean of 275 cm and is thereby low (wetter) compared to the German or Norwegian study area. The landscape is characterized by many lakes. Although the infrastructure is mainly coherent with our mapping, unfavourable paths also occur. Several road compartments located within mapped critical areas, given as areas with DTW ranging from 0 to 25 cm can be found in a selected section (B).

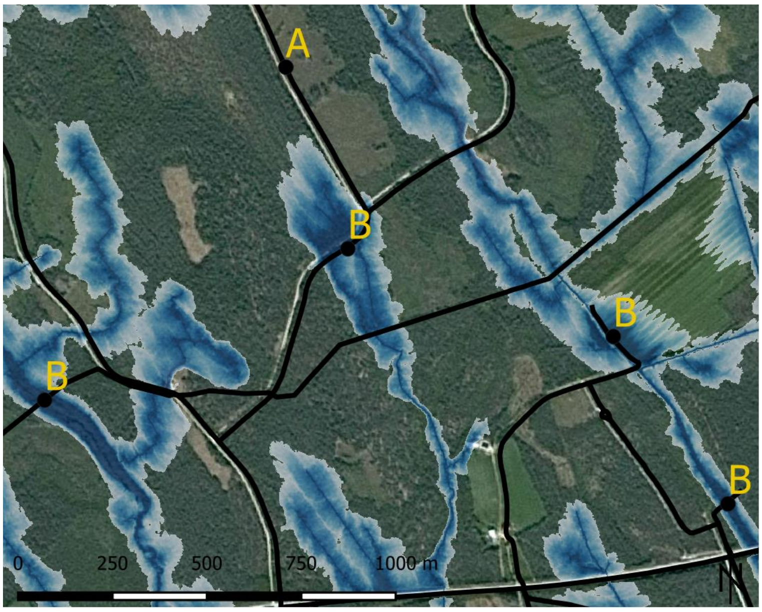

Figure 2: A map section of the DTW-maps in the predominantly flat Finnish case area.

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4.1.1.2 Germany

The patterns observed in the Finnish study area, that the course of forest roads is mainly on "safe" locations could not be detected in the study area in Arnsberg, Germany that often (Fig. 3, A). The main forest roads frequently follow the most unfavourable areas or paths, from a wetness point of view, with DTW below 100 cm (B). In some cases the forest road served as a dam and created wet areas beneath the forest road structure (C), although this can result from road culverts not having been prevalent in the DEM. The unfavourable course of forest main roads may be associated with the mountainous area, with an elevation ranging from 160 to 550 m above sea level and steep slopes, giving restrictions in staking the gradeline. As mentioned above, the DTW is increases with increasing slope. Consequently, the index has its average value of 640 cm, almost the 2.5-fold compared to the Finnish one.

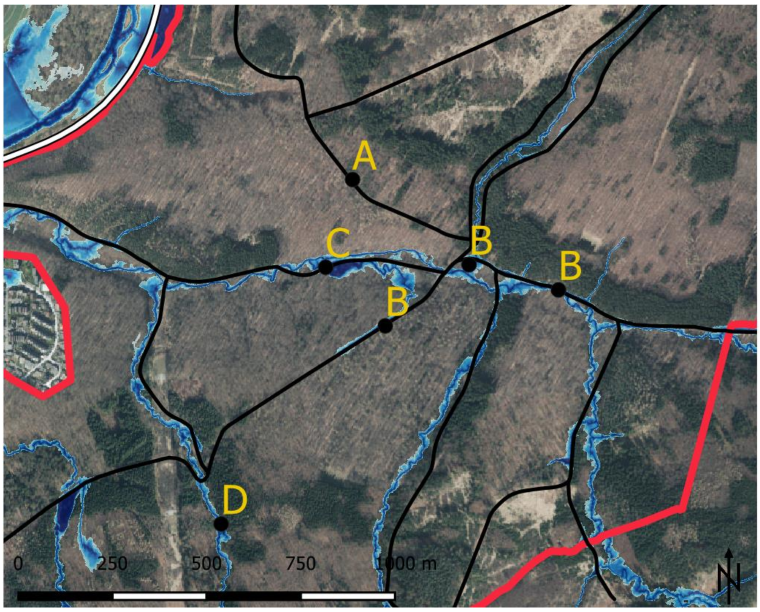

Figure 3: A map section of the DTW-maps in the German study area.

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4.1.1.3 Norway

The landscape of the study area in Norway is marked by its numerous lakes and a hilly morphology with moderate slope of 31% in average, leading to mean overall DTW-values of 925 cm. The forest roads are partly well positioned beside detected sensitive areas (DTW < 100 cm, Fig. 4, A), but unfavourable alignment of forest road infrastructure appear too (B). At point (B), the elevation of the forest main road is two meters above the lake elevation, something that is likely determined by the steeper terrain leading down to the lake. The delineated area with DTW = 0 cm spreads in a northern direction from the lake (C), where reeds and peats are growing. The landscape of the study area in Norway is characterized by lakes, which are bordered by peats or reed. In general, peats and especially highland moors have to be delineated manually, since these wetlands have the tendency to form raised bogs. The topographically-derived DTW-mapping would otherwise interpret raised bogs to be drained uplands (Oglivie 2017), according to the formula. These raised bogs were not found at a remote analysis in the Norway's study area. In this case (C) the reed or peat showed a flat surface, which was higher by 2 m compared to the level of the lake.

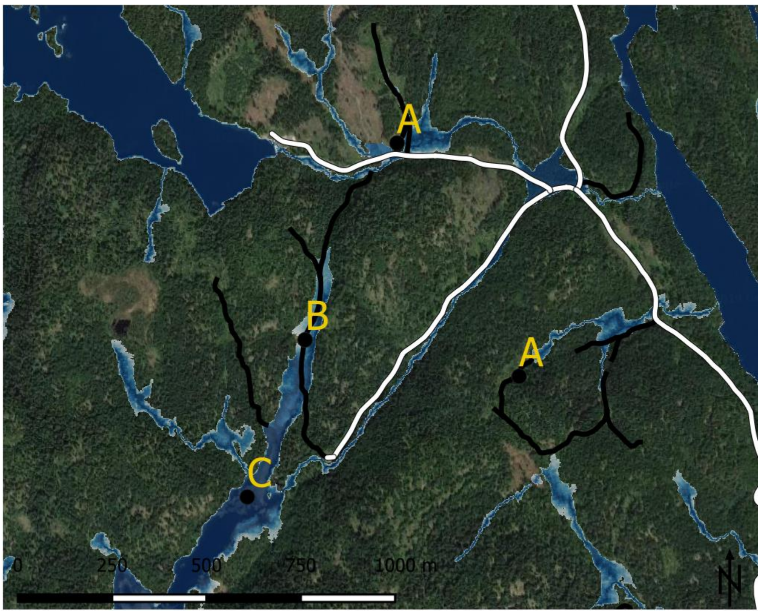

Figure 4: A map section of the DTW-maps in the Norwegian study area.

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4.1.1.4 Poland

The Polish study area is located at a moderate to flat landscape with an average slope of 2.3% only and an elevation between 200 and 240 m above sea level. The forested area is covered by a network of systematically made forest roads (green lines), which cross areas with low values of DTW (<100 cm, Fig. 5, B). This may be due to droughts and specific climatic conditions in recent years, there were hot summers, and winters were very mild. A large portion of forest main roads evades moist areas (A), in addition, areas with a high degree of moist areas are excepted from the schematic skid trail system (C). On some sites it seems, that the skid trails are aligned considering the local water regime (D).

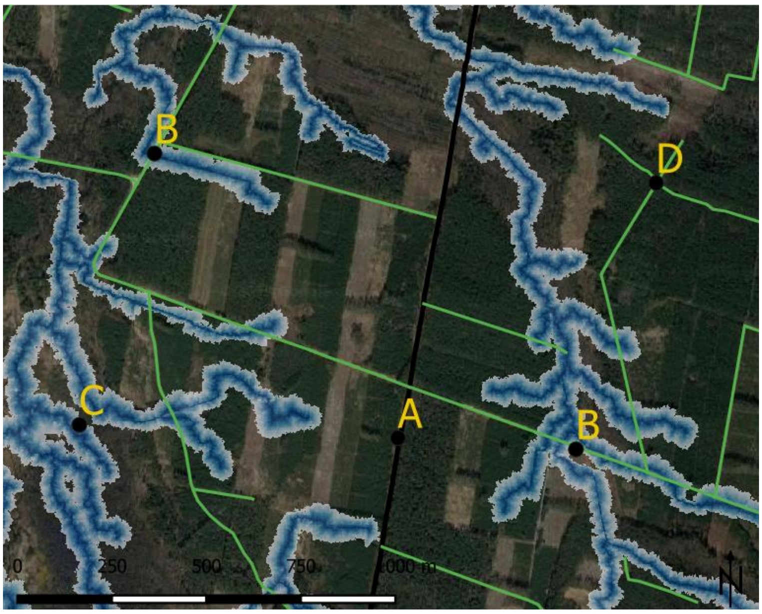

Figure 5: A map section of the DTW-maps in the Polish study area.

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5 Conclusions

5.1 Mitigation of soil disturbance

Although the DTW-maps are based on digital terrain models and a grid of slope values only, they still have the potential to contribute to the reduction of soil disturbances like rutting and compaction. By this, permanent and year-long trafficability and therefore accessibility of skid trails in Germany can be secured. Still, the validity and applicability can be improved by incorporating other data sources in the algorithm, like soil mappings (Mohtashami et al. 2017).

In the field measurements of Jones (unpubl.) the rut depths, vol. moisture content, soil bulk density, and soil penetration resistance were measured in combination with numerous logging operations with different undercarriages. She determined, that the occurring rut depth after logging operations are influenced by the machine dimensions and number of passes, the pore-filled soil moisture content and the soil property variations, in a descending order of weight. Jones (unpubl.) argues, that many studies confirmed a correlation between soil disturbance and soil moisture. In accordance with these results, Naghdi et al. (2009) analysed the influence of terrain slope and soil texture on displacement of soil and average rut depth. While the slope correlated significantly, a dependency between rut depth or soil displacement with soil texture along the skid trail after 20 machine passes was not observed. Coherent to this findings, Cambi et al. (2015) point out, that from all soil parameters which affect rutting and other soil disturbances, soil moisture and terrain slope are the primary influencing factors.

5.1.1 DTW-maps for practitioners

The main advantage of this mapping is that the perennial stream network can be detected, which helps machine operators identifying sensitive areas with regard to trafficability. This can be realized by providing the maps on on-board computers of forest machinery. With the application of the DTW-maps in forest operations, critical areas in terms of low DTW-index, permanent and perennial streams as well as physical soil disturbances can be identified and avoided (Ågren et al. 2015). With the increased knowledge of the harvesting site, a handful of possible preventions can be applied during the harvesting operations:

5.1.1.1 Planning of forest road infrastructure

A good design and planning of forest road infrastructure is a pre-requisite for lowering soil disturbance (Chamen et al. 2003). It is crucial for year-round harvesting operations and trafficability. As shown above, skid trails and forest main roads are often positioned without taking wet areas into account as a primary factor in determination. Since the study areas of the partner countries seem to have a sufficient access to forest stands by the already existing road infrastructure, additional construction of better aligned forest roads is improbable. Still, the increased knowledge based on the DTW-maps could direct the planning of forest operations (thinning, single tree removal, opening up, etc.) by permanent skid trails, in order to provide forest stands with a forest road network, as recommended by Vossbrink und Horn (2004).

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5.1.1.2 Spatially adjusted measures

DTW-maps can contribute to secure trafficability of skid trails or even of forest roads by adapted measures, like the deposition of brush mats or bridges created by logs. Labelle et al. (2019) showed in their field surveys, that brush mats have the possibility to mitigate machine-induced soil disturbances. Relative and absolute soil compaction and penetration resistance were measured and led to the finding that the deposition of strong brush mats could reduce soil compaction. This way growth-inhibiting conditions could be reduced from 40.5% to 3.6% of the measured points. Poltorak et al. (2018) report, that brush mats of 15 or 20 kg m^{-2} significantly reduce soil displacement and the affected area by timber harvesting on skid trail segments. However, logging residues are a biofuel source (Ågren et al. 2015), and a more precise use of residues on areas designated as susceptible in the DTW map could help to resolve a dilemma of multiple use.

5.1.1.3 Inherent usage of technological solutions

Different technical solutions can reduce the soil impact. Alakukku et al. (2003) state, that the selection of machines and equipment in conformity with the actual bearing capacity can prevent soil compaction. For example, a low tyre inflation pressure reduces the stress on the topsoil. The rutting depth in particular can be reduced, by the usage of bogie tracks, as suggested by Bygdén et al. (2003), who measured a reduction of 40% in rut depth. The rut depth could also be suppressed by trafficking the forest stand with a lightweight machine (Jansson und Wästerlund 1999).

5.1.1.4 Temporal adjustment of forest operations

The extent of the actual flow network changes with seasonal, climatic and weathering effects. For a realistic prediction of soil impact, these year-round variations in load-bearing capacity in dependence of different hydrothermal soil conditions, must be taken into account (Vega-Nieva et al. 2009). Seasonal variation of flow paths can be simulated by the usage of different flow initiation areas. To account for the temporal variability of the flow path network, LiDAR derived maps, like our DTW-maps can be used (Ågren et al. 2015). In a Swedish case study, Ågren et al. (2015) supported the usage of seasonal varying DTW-maps, since the soil bearing capacity was substantially lower in a currently running flow path, due to the high moisture and organic matter content, and vice versa the moisture content was significantly related to the soil bearing capacity.

5.2 Further work

Longer term monitoring of the validity of the DTW-maps discussed in this work will be carried out during the final project year. This includes periodical measurements of soil bearing capacity along transects representing different conditions, as well as modelling against sampled soil properties.

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