Soil Watermap Usage in Planning of Thinnings

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Master Thesis no. 284
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Abstract

Off-road driving with heavy machinery (harvesters and forwarders) in logging operations nowadays is essential. It is the main reason why efficiency of harvesting has increased so significantly. Unfortunately it also has its downsides – one of which is increased soil damage in strip roads. Soil damages may have impact on tree growth in the stand, on future regeneration success or in nutrient loss. There is also a risk of increased mercury leaching from soil. There are several ways to decrease damage to soil during logging operations, like logging in winter time when soil is frozen, using light weight machinery, etc., but most of them are not appealing to industry since they either increase cost or decrease efficiency or both. In efforts to further decrease impact to environment and increase efficiency new ways to improve logging operations have to be found.

One of these ways is using soil watermaps that are based on depth-to-water index (DTW). This GIS–based index is based on precise LiDAR scans of terrain, field inventory and sophisticated GIS processing. End result – soil watermap shows potential wet areas in stand that could be more susceptible to rutting. By using these maps, theoretically, it is possible to reduce damage to soil. Aim of this study was to test accuracy of soil watermaps in Norway spruce (*Picea abies*) thinnings.

After selecting stands, locations of strip roads and soil damages were registered. Data analysis revealed that overall stand wetness according to soil watermaps didn't show any correlation with amount of soil damage. Damaged parts of strip roads were significantly more often located on wet areas. Soil watermap value distribution analysis showed that most important difference between undamaged and damaged parts of strip roads where for areas with values 0 – 0.6 (the most susceptible to rutting). Comparison of stand re-planning using soil watermaps proved that it is possible to decrease trafficking on wet areas that are projected by soil watermaps.

Key words: DTW, depth to water, soil, watermaps, Norway spruce, thinnings, damage, strip road, LiDAR, terrain

Contents

1. Introduction

Since arrival of harvesters and forwards logging operations have become more and more efficient. Although this has allowed to increase production and to manage forests that before were considered to be too remote it also has its downsides. One of which is soil damage that is caused by heavy machinery that is used for harvesting.

Damage caused to soil during harvesting operations can cause regeneration difficulties (Williamson and Neilsen, 2000). ‘’Soil compaction makes skid trails inhospitable to roots in terms of water and oxygen availability and can result in a long-term reduction in natural regeneration’’ Cambi et al., 2015. Soil damage in thinnings may reduce growth rate of residual stands because of the damage to roots (Roll-Hansen & Roll-Hansen, 1981, Piri, 2003).

Although harvester operators walk through stand before logging it is difficult and time consuming to determine the best strip road placement to decrease damage to soil and to be efficient. There are several alternatives to decrease damage to soil, besides walking through stand and packing strip roads with logging residues. For example, using light weight harvesters and forwarders that cause less damage to soil, logging during very dry summer or when soil is frozen, using ‘’wooden roads’’, etc. ,but these practices either increase costs, decrease efficiency or force forestry to become even more seasonal and this is not a feasible solution for whole forest industry. It is necessary to find new ways to plan logging operations.

One of these ways that have potential of helping in planning of forestry is soil watermaps. By using LiDAR (Light Detection And Ranging) technology it is possible to acquire very precise DEM’s (Digital Elevation Model) which can be further used to predict soil drainage, approximate depth to groundwater and possible ‘’dangerous’’ places with low soil bearing capacity.

1.1. Soil damage impact on nature

Soil creation process takes a lot of time and its structure can be fragile. Humus layer is particularly prone to compaction (Horn et al., 2007). Soils with bulk densities larger than 1.4 Mg m^{-3} are more resistant to compaction (Powers et al., 2005). Soil compaction may reduce water and oxygen availability (Bodelier et al., 1996). If soil gets damaged it can take many (even more than ten years for sandy soils) years until it returns to original state (Greacen and Sands, 1980). Almost all plants rely on soil to mediate necessary nutrients, gases and water to them (Dominati et al., 2010). Soil has very important role to sustain water quality in streams, rivers and lakes. Main factors that contribute to forest increasing water quality are its soils macroporosity, low bulk density and high hydraulic conductivity and infiltration rates. These factors decrease surface runoff and redirects water to subsurface pathways where contaminant sorption, nutrient uptake and cycling are more rapid (Neary et. al., 2009). Soil damage by soil dampness and/or compactness may have impact on tree growth in the stand, on future regeneration success or in nutrient loss (Cambi et al., 2015). There is also a risk of increased mercury leaching from soil (Munthe and Hultberg, 2004).

1.1.1. Ruts

During rut creation process plant (including trees) root systems are damaged which leads to short term decrease in vitality. Also compactions in soil are created which makes it harder for roots to penetrate it. Trees that have their root systems damaged are more susceptible to root rot (Nilsson and Hyppel 1968, Isomäki and Kallio 1974). Ruts, which are perpendicular to water drainage direction, can block water drainage and create local flooding upwards of rut (Figure 1.1.) (Sutheland, 2003).

Increased leakage of mercury and methylmercury from soil after logging operations which used heavy machinery have been shown by Munthe and Hultberg (2004). Munthe et al., (2007) were connecting increased leakage of mercury with anaerobic conditions that are created in soil after local flooding of soil. These conditions are suitable for sulfide reducing bacteria, which promote increased mercury methylation and leakage (Munthe et al., 2007). Materials that are used in packing of strip roads provide nutrients for anaerobic bacteria (Eklof et al., 2016). In Sweden and Finland double up to four fold increase of mercury leaching after clear cuts has been seen (Munthe et al., 2007). The mercury leaching was correlated with increased moisture in soil and increased temperature of soil after clear cuts which was caused by the removal of tree canopy that covered the soil surface and was providing transpiration of excess water from soil (Munthe et al., 2007). Released mercury moved to water ecosystems where it may accumulate in living organisms. Eklof et al. (2016) showed that concentration of mercury in Fennoscandinavian fish is significantly overexceeding EU allowed levels of 0.02 mg Hg kg^{-1}.

Increased soil dampness decreases air exchange in soil and soil temperature in thinned stands which is one of reasons for decreased rates of tree growth after thinnings. Ruts, which are parallel to the direction of drainage, can increase soil erosion, organic and non-organic particle mobilization to water ways and sedimentation in them (Sutheland, 2003). Non-organic particle mobilization not only lead to increased concentration of mercury in fish, but also to sediment infiltration into clean gravel beds (Lisle, 1989), which makes it more difficult for some fish species to breed. On the other hand organic particle mobilization increases eutrophication which increases plant growth in water. After plant death increased amount of biomass is decomposed and zones with oxygen depletion can emerge. In process of decomposition ammonia and hydrogen sulfide can be created which can lead to ‘’death zones’’ where water becomes poisonous and has no oxygen (UNEP).

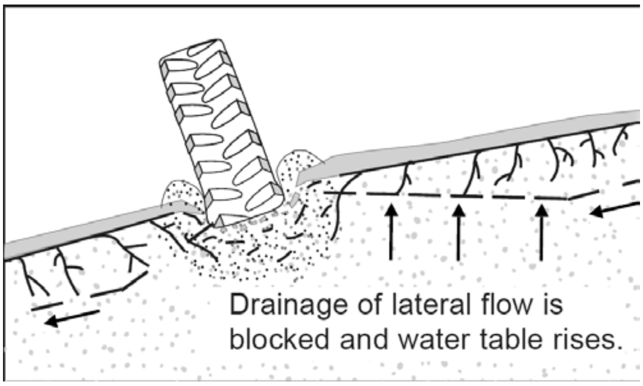

Figure 1.1. Drainage water blockade created by rut (Suthland, 2003)

1.1.2. Soil compaction

Soil compaction decreases air exchange which decreases the amount of available oxygen to roots. Compacted soils have decreased drainage ability which can lead to increased amount of surface water. Surface water can lead to increased soil erosion. Also it is more difficult for roots to penetrate compacted soil and take up necessary water and nutrients (Cambi et al., 2015). Kozlowski (1999) measured increase of bulk density by 45–52% in the upper soil layers (0-8 cm). Increase of bulk density up to 88% in upper soil layer (0-10cm) has been seen in intersections of strip roads. Compaction was registered up to depths of 30 cm. First few passages had the highest impact on soil bulk density. Threshold when tree growth is restricted ranges 1.2 -1.4 Mg m^{-3}, depending on tree species (Lousier, 1990). Bulk density >1.2 Mg m^{-3} has been shown to restrict Norway spruce (*Picea abies*) growth (Halverson and Zisa, 1982).

1.2. Thinning of Norway spruce (Picea abies) stands

Norway spruce is economically the most important tree species in Sweden with 41 % of growing stock (Skogsdata, 2016). In 2012 it provided 49 % of total wood consumption in Sweden (Eriksson, 2012).

Nilsson et al. (2010) came to conclusion that thinnings in Norway spruce (*Picea abies*) stands have little effect on total volume of merchandisable timber production. Thinnings decreases self-thinning of stand, increases single stem volume (timber with larger dimensions usually is more valuable) and provides income faster. Huse (1978) concluded that 39 % of all wounds caused to spruce during thinning operations were root wounds while Siren, (1981, 1982) found that proportion of broken roots consisted 6 - 12 %. Roll-Hansen & Roll-Hansen (1981) found that root injuries with size between 4-90 cm^2 had 15 % rate if infection by *Stereum sanguinolentum* (wound decay fungus). Decayed trees in Sweden produce around 10 % less timber comparing to healthy ones over 5 year period (Bendz-Hellgren 1997). In long term losses can be considerably higher (Bendz-Hellgren 1997). ‘’In southern Finland, *Heterobasidion* was isolated from 7 % of root injuries and 14 % of trunk injuries on Norway spruce damaged by timber harvesting machines’’ (Piri, 2003).

C. Wallentine (2007) mentions: ‘’The positive aspects of thinning may be jeopardized if the thinning is not done with sufficient knowledge and care’’. This could be motivated by previously mentioned facts and findings about root rot.

1.3. Creation of soil watermaps

As mentioned before, soil watermaps rely on precise LiDAR data, to obtain high resolution Digital Elevation Model (DEM) or Digital Terrain Model (DTM) (depending on literature terms differ). To obtain DEM from LiDAR data (example seen in Figure 1.2.) Digital Surface Model’s (DSM) points that don’t represent terrain elevation (houses, trees, electro lines, etc.) are removed by an algorithm and points representing terrain elevation are retained – DEM (Figure 1.3.).

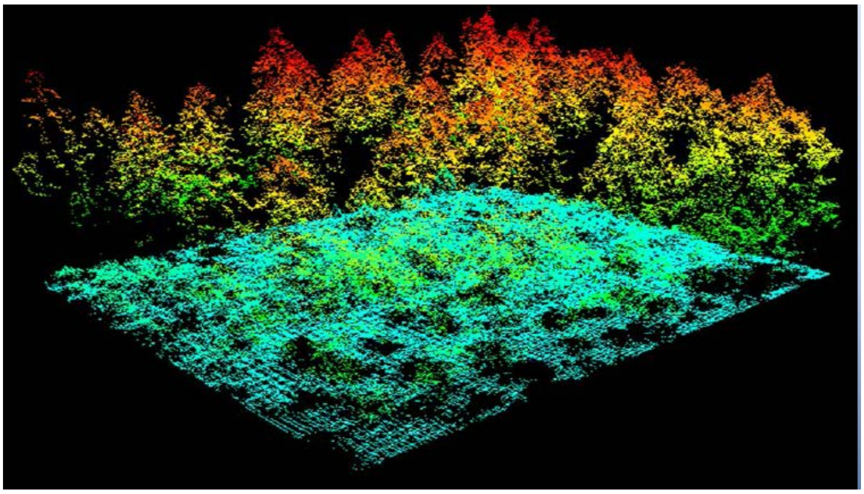

Figure 1.2. Lidar data cloud where red, yellow and green points represent tree canopy and understory of stand, blue points represent soil surface (Philippe, 2016)

High resolution is necessary to determine micro-depressions, ditches, stream and other irregularities in the terrain that can help to determine soil wetness. The difference between high definition DEM and low resolution DEM is significant (Figure 1.3.).

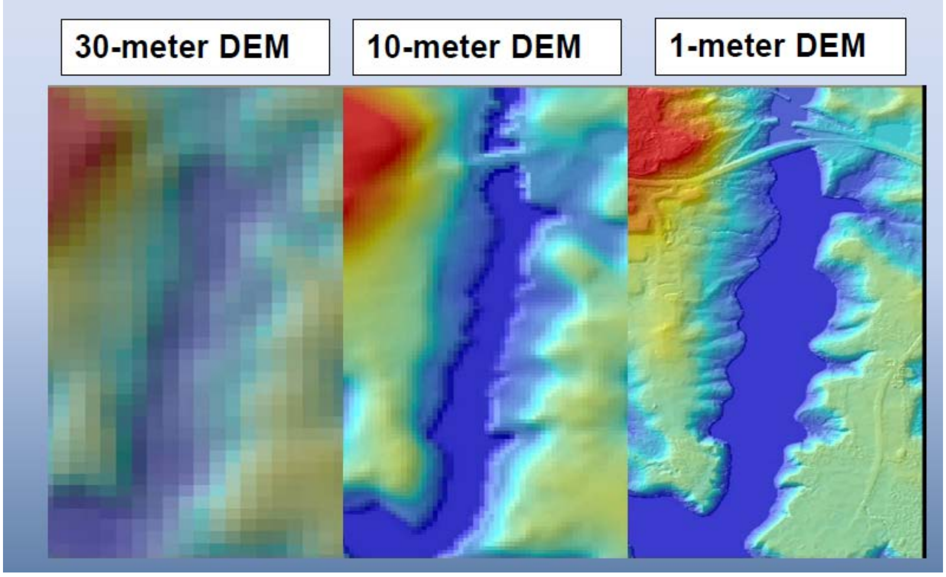

Figure 1.3. DEM comparison depending on its resolution (Philippe, 2016)

Projected DEM, depending on methodology, are merged with cartographically determined streams, rivers, ditches, bogs and lakes and surface water runoff basins and are projected for these waterways (Arp, 2009). After this projecting waterflow blockades (that in reality are bridges, roads, culverts, etc.) are manually determined and eliminated from maps. After removal of blockades runoff basins simulation is repeated and blockade removal is also repeated, if necessary (Ogilvie et al., 2011). This process can be seen in Figure 1.4.

Figure 1.4. Waterway blockage manual removal (Ogilvie et al., 2011)

After processing of DEM further analysis is done. From DEM Depth to Water index (DTW) is projected. DTW shows distance of groundwater from the soil surface (DEM). To project DTW previously determined flow channels are used. In these flow channels where surface water is seen DTW value is 0 (groundwater is on soil surface). After this step closest water ways are connected and groundwater depth is determined (Figure 1.5., 1.6) (White et al., 2013). Although DTW is expressed in meters it should be interpreted as relative value which shows soil wetness (Henriksson, 2015). Soils where DTW value is lower than 1 (projected groundwater is closer than 1m to surface) are considered as wet.

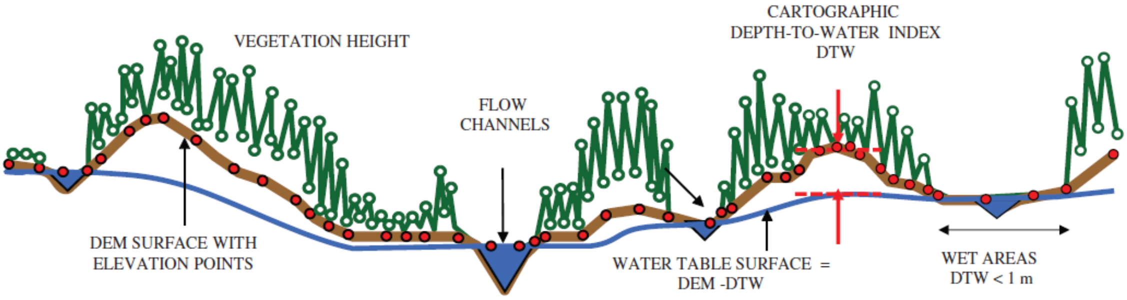

Figure 1.5. DSM, DEM and DTW projection example (White et al., 2013)

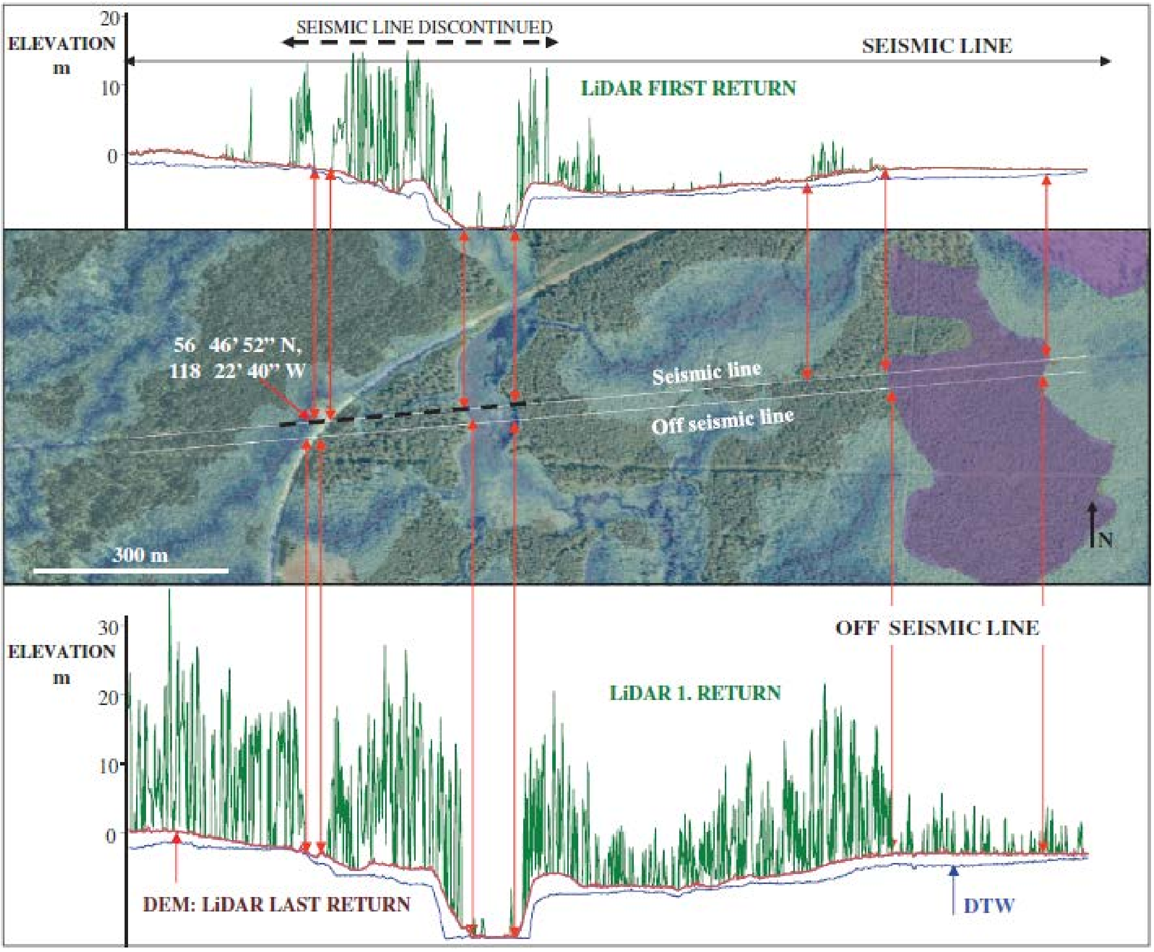

Figure 1.6. DSM, DEM and DTW real life projection (White et al., 2013)

To improve soil watermap precision several methods can be used. For example Topographic Wetness index (TWI) and soil maps can be used. TWI reflects angle of certain area. High TWI means that the area is flat and has high risk having surface water. This index is scale dependent. Agren et al., 2014 determined that the most precise results could be obtained using resolution with pixel size 24m × 24m.

1.4. Soil watermap usage

Depth-to-Water index is a relatively new term which has been created thanks to development of LiDAR and cartography. This technology is not fully studied and research continues as well as implementation in forest planning.

Currently soil watermap primary usage is planned to be used as added information when planning and optimizing forest harvesting regeneration. Mainly to reduce damage to soil damage and decrease logging costs. Currently soil watermaps are used in research and forestry in two ways (Mohtashami et al., 2012):

1. As visual help, for example, planning strip roads (Figure 1.7.)
2. As cost-surface model, to determine most cost efficient rout (compare routs) using computer program (Figure 1.8.) (Mohtashami et al.2, 2012)

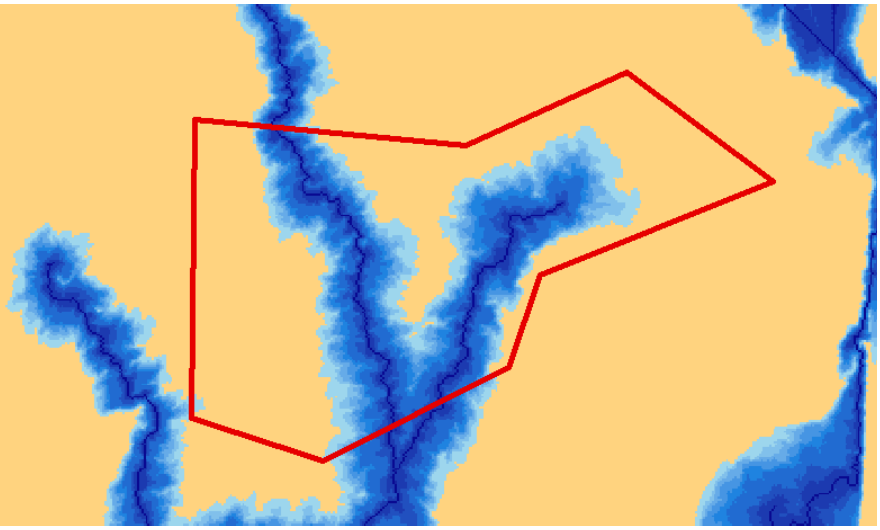

Figure 1.7. Soil watermap usage as visual help to plan strip roads in stand (stand borders - red line).The watermap in the background represents dry or mesic areas (beige) and the gradient of risk for wet areas in a scale dark blue (high risk) to white (low risk)

Soil watermaps with topographic map typically can be used in small scale planning – mainly, planning position of strip roads. If logging manager has the information about most of the stands that are considered during a logging season, it is possible to plan logging operations for different stands depending on season. This might decrease damage to soil even further. While harvesting wet stand it is difficult or sometimes even impossible to avoid the wetter areas but by using soil watermaps it should be possible to significantly decrease driving on wet spots or plan ahead using additional tools to reduce damage to soil in wet areas.

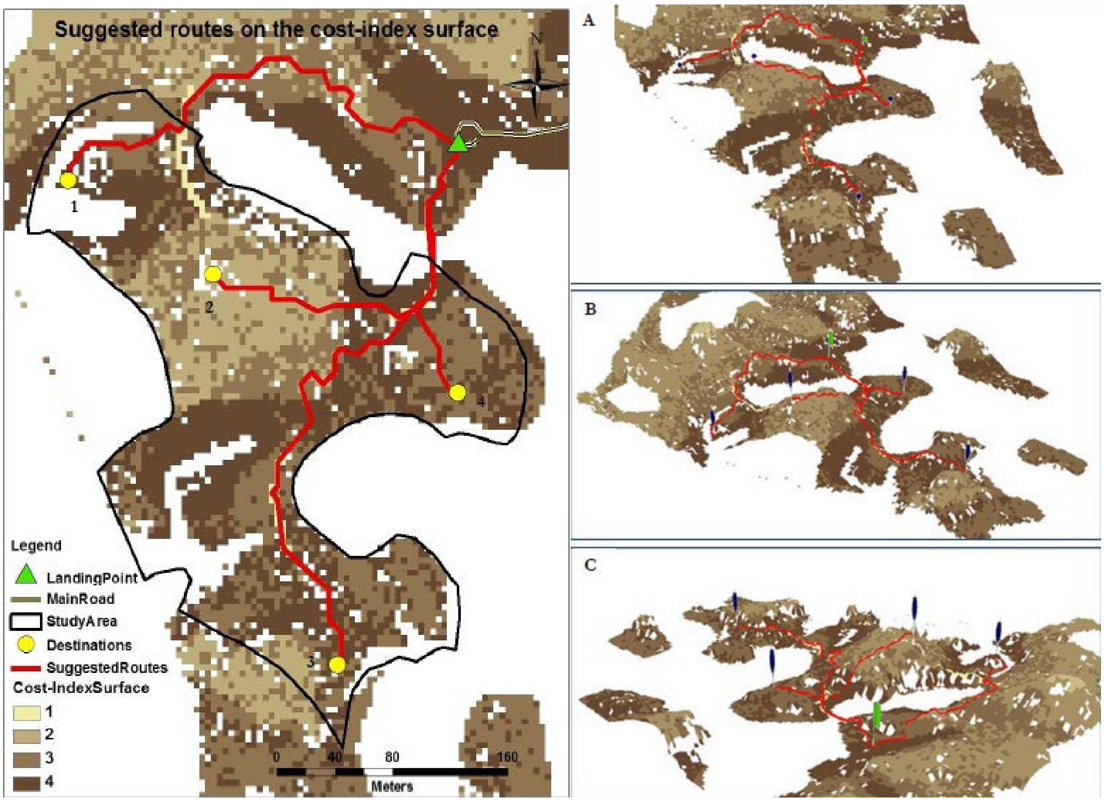

Figure 1.8. Cost surface model usage during planning of harvesting operation, view from top and 3 sides where light brown areas have lower cost-surface value and darker have higher cost-surface value (Mohtashami et al.2, 2012)

To create cost-surface map soil watermap pixels, if necessary, are merged to create pixels with size 4x4m. It is necessary in order for the pixels to be as wide or a bit wider than the forwarders, so it would represent roads that forwarder will drive on. All protected areas, like areas with high biological diversity, caves, historical objects, etc. can be excluded from cost-surface and considered as barriers (Mohtashami et al.2, 2012). Each pixel gets assigned with coefficient/value depending on DTW value. Using this data, as well as harvesting site and upper landing locations computer program calculates most cost-efficient rout. Cost-surface map can be used in large scale planning, for example, transportation of timber from several stands to upper landings. If cost-surface map is precisely calibrated it theoretically can be used to compare transportation alternatives, for example, building infrastructure objects like road or bridge to decrease forwarding distance.

1.5. Objectives and hypothesis

The main questions investigated in this study were:

Can soil water maps be used for detection of risk areas in the planning of strip roads? If so, is it possible to do an optimization of the strip roads using soil watermaps in high risk stands?

The hypothesis tested was: Damage to soil in thinnings is correlated to presence of wet spots (soil watermap value ≤1) according to soil watermaps.

If the hypothesis was confirmed, the next objective was to provide recommendations to decrease damages to soil during thinning operations.

2. Materials and methods

2.1. Stand selection

To reach objectives, soil watermaps and stand inventory data were obtained from Södra (Sweden's largest forest-owner association, with more than 50,000 forest owners as its members). It was done to optimize field inventory work and increase precision of field data. From obtained data (more than 740 stands), 35 stands were selected for the field inventory. Strip road inventory in Norway spruce thinnings was done in Southern Sweden (Figure 2.1.). Stand selection was not influenced by season when thinning had been done or if it was first or second thinning. For stand to be selected it had to meet several criteria:

- The stand should have been thinned in last 2 years in commercial thinning
- Stand size should have been larger than 1 ha
- Soil water map for the stand had to have a variation in wetness index – at least 20 % of the stand should have dry (soil watermap value >1) or wet (soil watermap value ≤1) areas according to soil the watermap
- Dominant tree species in the stand (more than 50 % of basal area) had to be Norway spruce (*Picea abies*)

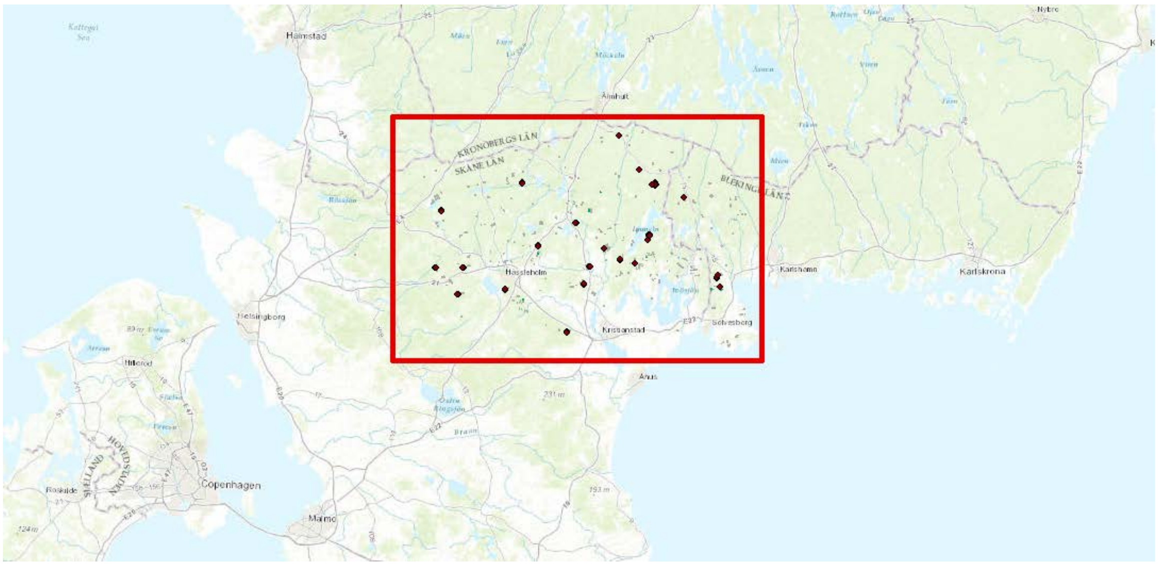

Figure 2.1. The red frame indicate the region in Southern Sweden where inventory was done, black dots indicate individual surveyed stands

2.2. Soil damage measurements

All strip roads in thinned stands were mapped with an Ipad using ArcGis Collector, with GPS position of maximum ±5 m (most of the time precision was ±3m). The strip roads were divided in two categories – where soil was damaged and where it was not damaged. Locations of strip road parts with no damage were registered as polylines (a digital map features that represents a place or thing that has length but not area at a given scale). Parts with soil damage had their location and depth registered as point features (a digital map feature that represents a place or thing that has neither length nor area at a given scale) (Figure 2.3.). Location of damage was registered each 2.5 -3 m. For soil damage to be registered it had to meet these criteria:

- It had to be at least 10 cm deep (according to Figure 2.2.)
- It had to be at least 5 m long
- Damage should be at least on one side of strip road
- For damage to be considered continuous after it has been registered as damage it couldn't have part of not damaged strip road in-between for more than 5 m

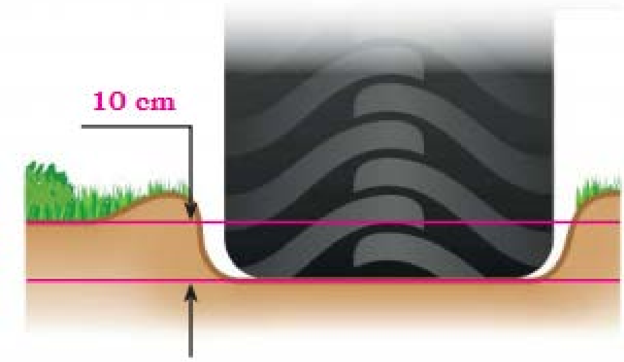

Figure 2.2. Example of rut depth measurements (LVM, 2014)

2.3. Data analysis

Data were analyzed using ArcGIS 10.3 and Microsoft Excel.

Each polyline and point shape file was given ID that represented stand number that they were located in. 5 m buffer (a polygon enclosing a point, line, or polygon at a specified distance) was created for each polyline (undamaged part of strip road) and point feature (damaged part of strip road), representing the strip roads of the stands (Figure 2.3.). This was done to account for width of forwarder (2m to each side) and GPS precision (±5m).

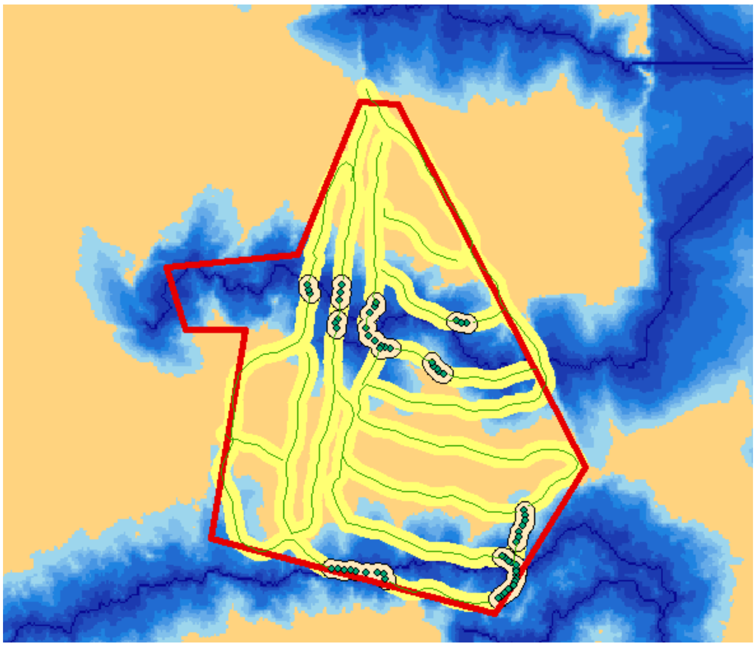

Figure 2.3 Stand borders (red line) with damaged (beige) and undamaged (yellow) strip road buffers. Green points indicate the exact measured damage location. The watermap in the background represents dry or mesic areas (brown) and the gradient of risk for wet areas in a scale dark blue (high risk) to white (low risk).

The index values from the watermaps were extracted for the buffer zones of damaged and undamaged strip road. The extraction of the wetness values was done with ‘’zonal histogram’’ - tool in ArcGIS 10.3.

The index of wetness represents the risk of standing water for the area in the pixel, where 0 indicates highest distribution and 0.99 low. All values above 1 indicated dry or mesic areas. The retrieved values were classified in 7 groups (Table 2.1) where area with value 0 was considered to have surface water (most wet) and area that had value over 1 was considered to be ‘’dry’’. Further on, areas with wetness index ≤1.0 will be defined as ‘’wet’’ if not specified otherwise in the text.

Table 2.1. The pixel value representing the scale of soil wetness index

Pixel value	Clasification
0	Surface water
0.01 – 0.2	Very wet
0.21 – 0.4	↕
0.41 – 0.6	
0.61 – 0.8	
0.81 – 1.0	Slightly wet
1.01 - 25	Dry

9 stands were excluded from further analysis because either sanitary thinnings were done to them or there were special soil conditions (see discussion).

The proportion of wet area (soil watermap value ≤1) in damaged and undamaged parts of the strip roads were compared and statistically tested - for difference. The test was done pairwise for the stands.

Comparison of proportion of wet area in stand and proportion of damage strip roads was done to see if it is possible to predict proportion of damaged strip roads just by proportion of wet area in stand. If this comparison would confirm correlation than it theoretically would be possible to predict stands with high risk of soil damage just by using soil watermaps.

Also detailed wet area value distribution analysis comparing proportion of area covered by each pixel value group (Table 2.1.) for all stand average values was done. Wet area distribution of stands, overall strip roads (damaged and undamaged parts of strip roads merged together), damaged and undamaged strip road parts were compared. This was done to see if there are any wetness index values (with soil watermap value ≤1) that are more susceptible to soil damage.

2.4. Improvement comparison of strip road planning using soil watermaps to used strip road planning

Stands with the most severe strip road damage (> 10 % of the total strip road area) were selected to study potential improvements in planning with guidance from the water maps. Soil watermaps, stand borders and exit points of stands were provided to logging manager (Figure 2.4.). The manager's task was to provide strip road plans for Norway spruce thinnings (whole stand) that was both efficient and with a reduction of strip roads in wet spots. The efficiency was measured as length of the planned strip road in comparison to the one already performed. For the comparisons the 5m buffer was made for re-planned strip roads and same data analysis was done as previously. Both re-planned and original strip road total lengths were calculated and compared for the selected stands.

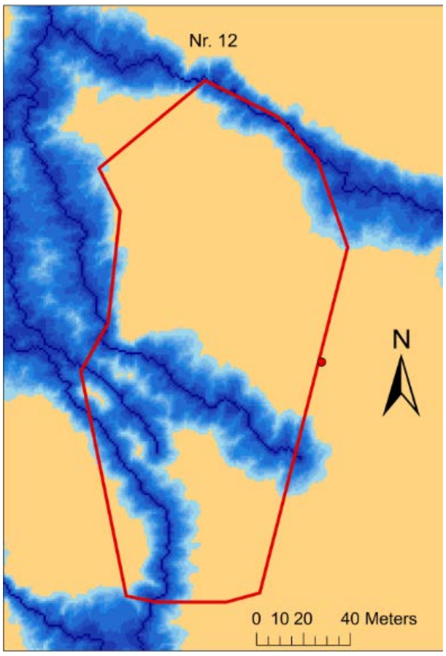

Figure 2.4. One of maps provided to logging manager. Stand borders (red line) and entrance point (red point). The watermap in the background represents dry or mesic areas (beige) and the gradient of risk for wet areas in a scale dark blue (high risk) to white (low risk).

2.5. Statistical analysis

T-test was used to prove statistically significant difference between wet area distribution of undamaged and damaged strip road parts. For T-Test significance value to reject null hypothesis was chosen to be $p<0.05$. Wilcoxon signed-rank test was also used to prove statistical difference because data were not normally distributed. In Wilcoxon signed-rank test for null hypothesis to be rejected alpha was chosen $\alpha<0.05$.

T-Test with significance value $p<0.05$ was done to confirm that re-planned stand strip roads have significantly less wet area comparing to original strip roads.

3. Results

In total 35 stands were inventoried, of them 26 stands had measured soil damaged areas in the strip roads and were further analyzed. The stands were on average 2.7 ha large, minimum was 0.8 ha, while all others were larger than 1 ha and with maximum 5.6 ha. Proportion of wet areas (soil watermap value≤1) in each of the damaged stands varied between 11 % and 67 % (Figure 3.1.). On average 35% of total stand area were located on ‘’wet’’ areas according to soil watermaps. Most of the stands where Norway spruce monocultures. Rest was mixed stands with Norway spruce as main tree species (more than 50 % of basal area).

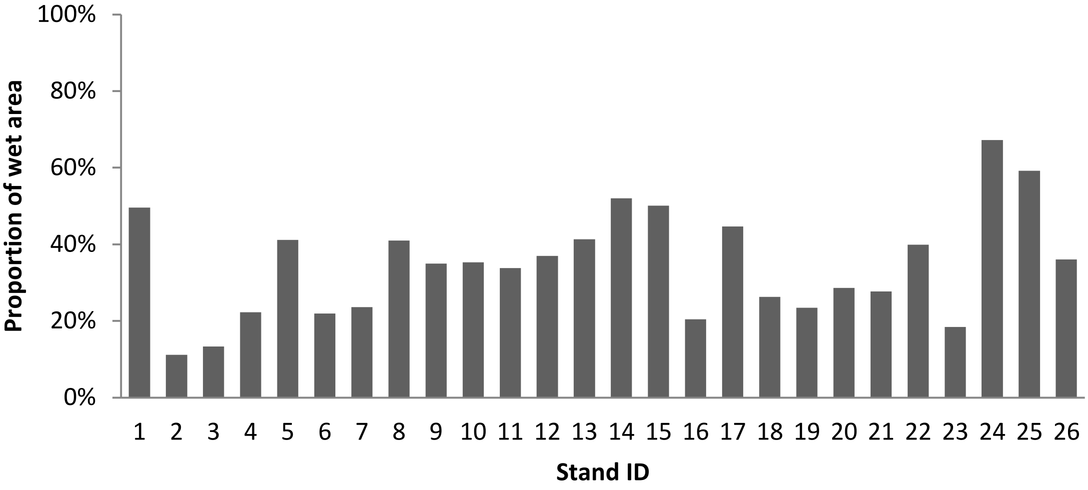

Figure 3.1. Proportion of wet area in the stands

3.1. Proportion of damaged soil

The proportion of the total area of the strip roads that were damaged due to the recent thinning operations was low in most stands (Figure 3.2.). On average 7.9 % of the strip roads area were classified as damaged by driving of the machines.

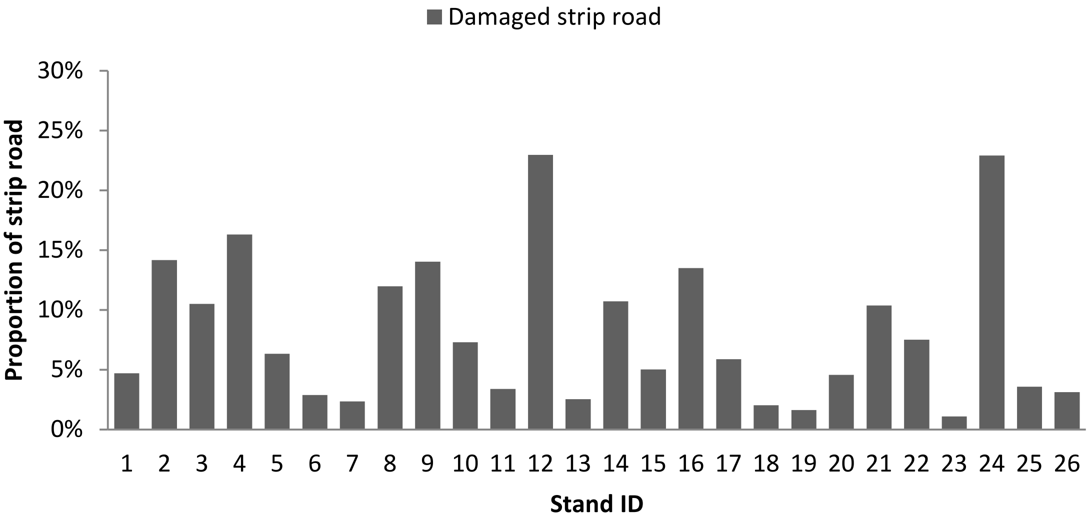

Figure 3.2. Proportion of damaged strip road in each stand from total strip road area

3.2. Proportion of ‘’wet’’ area in strip roads

The part of the strip roads that was classified as damaged in the inventory was more often in wet areas (soil watermap value≤1) than undamaged parts of the strip road (Figure 3.3., Table 3.1.). 21 of 26 stands had higher proportion of wet area in the damaged strip roads. On average damaged parts of strip roads according to soil watermaps were located on wet areas 67% of the time and undamaged parts 33% of the time. Stands had a significant increase ($p<0.001$) (Appendix 4.1.; 4.2.) increase in proportion of wet area in damaged strip roads comparing to undamaged strip roads (Table 3.1.).

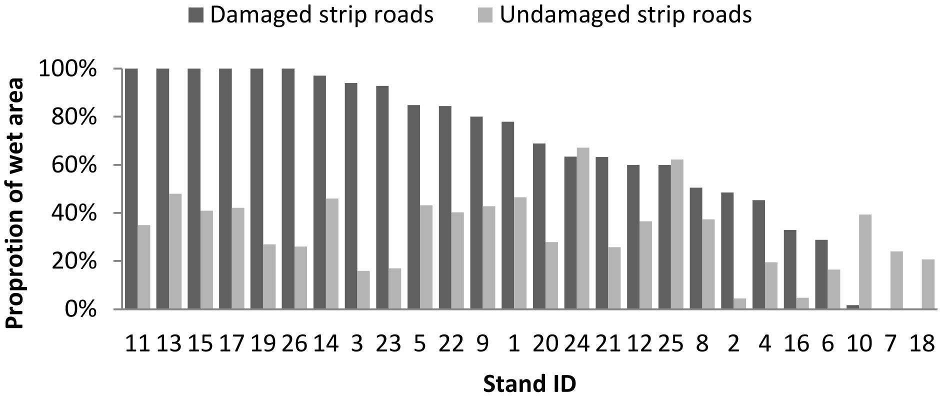

Figure 3.3. Proportion of wet area (%) in damaged and undamaged strip roads parts in each stand

Table 3.1. Proportion (%) of wet area (soil watermap value ≤1.0) in damaged and undamaged part of the stand

Stands with higher proportion of wet area in damaged parts of strip road			Stands with lower proportion of wet area in damaged parts of strip road		
Stand ID	Damaged strip road, %	Undamaged strip road, %	Stand ID	Damaged strip road, %	Undamaged strip road, %
1	78	46	7	0	24
2	49	4	10	2	39
3	94	16	18	0	21
4	45	20	24	63	67
5	85	43	25	60	62
6	29	16			
8	50	37			
9	80	43			
11	100	35			
12	60	37			
13	100	48			
14	97	46			
15	100	41			
16	33	5			
17	100	42			
19	100	27			
20	69	28			
21	63	26			
22	84	40			
23	93	17			
26	100	26			

3.3. Comparison of proportion of wet area in stand and proportion of damage strip roads

Although comparison of undamaged and damaged strip roads showed good correlation between damage to soil and strip road placement on wet area (soil watermap value≤1) (Figure 3.3.), proportion of wet area in stand did not show any correlation with proportion of damaged strip roads in stand (Figure 3.4.).

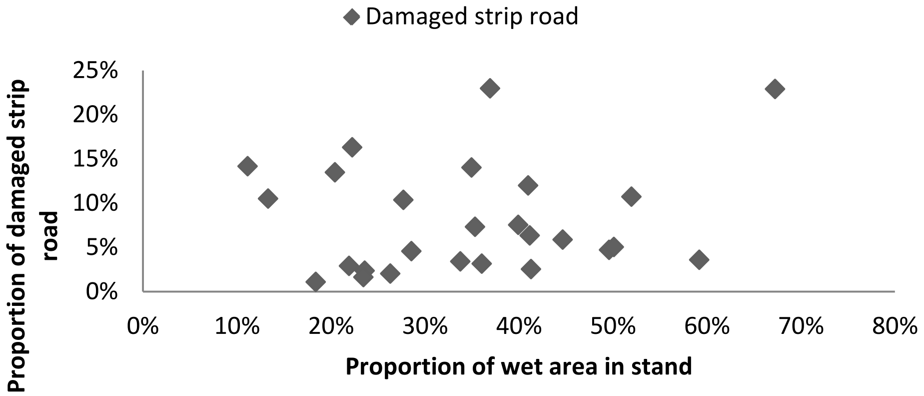

Figure 3.4. Proportion of damaged strip road depending on stand proportion of wet area in stand

3.4. Stand overall wet area distribution

On average 7.9 % of all strip roads were with soil damages (figure 3.2.). Table 3.2. and figure 3.5. shows that from all strip roads that were located on projected areas with soil watermap value 0, 24 % were strip roads with damages to soil. While from all strip roads that were located on ‘’dry’’ areas (soil watermap value >1) 5 % were with damages to soil. This shows that it is 5 times more likely to have soil damages by driving on areas with soil watermap value 0 comparing to driving on ‘’dry’’ areas and 3 to 4 times more likely when driving on areas with soil watemap values between 0.01 and 0.6 instead of driving on ‘’dry’’ areas.

Table 3.2. Proportion of strip roads with soil damages depending on soil watermap values

Soil watermap value	Damaged	Undamaged	All together	Damaged, %
0	456	1448	1904	24
0.01-0.2	4156	17845	22001	19
0.21-0.4	3440	18623	22063	16
0.41-0.6	3190	19049	22239	14
0.61-0.8	2364	18956	21320	11
0.81-1.0	1709	17277	18986	9
1.01-25	10166	202403	212569	5
Sum	25481	295601	321082	8

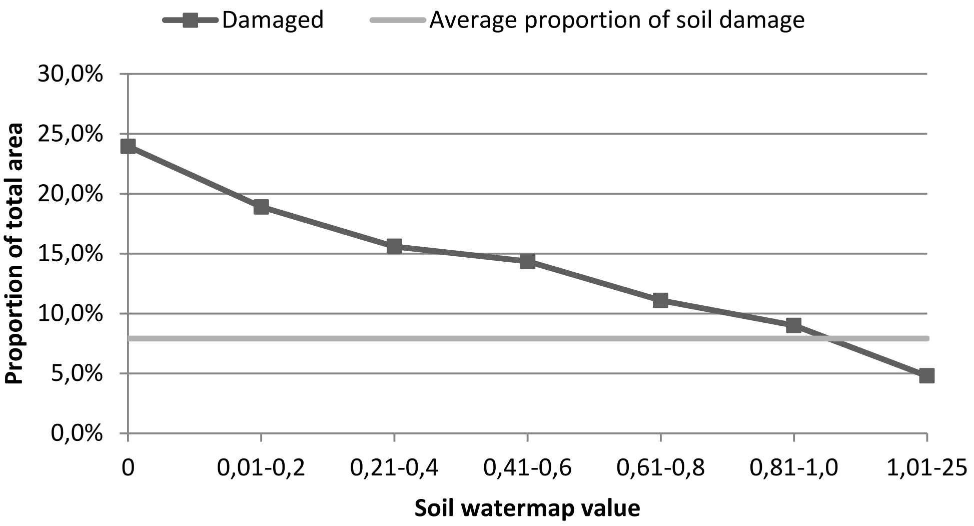

Figure 3.5. Proportion of strip roads with soil damages depending on soil watermap values

Comparison of wet area distribution (Figure 3.6.) showed that distribution of wet area in stand and all strip road are the same. Distribution of undamaged strip road parts was very similar to stand distribution. Damaged parts of strip road had significantly ($p<0.05$) larger proportion of wet area than undamaged parts for soil watermap values 0 – 0.6 (Table 3.4.). This indicates that there seems to be higher risk of damage for lower soil watermap values (wetness index 1 to 4).

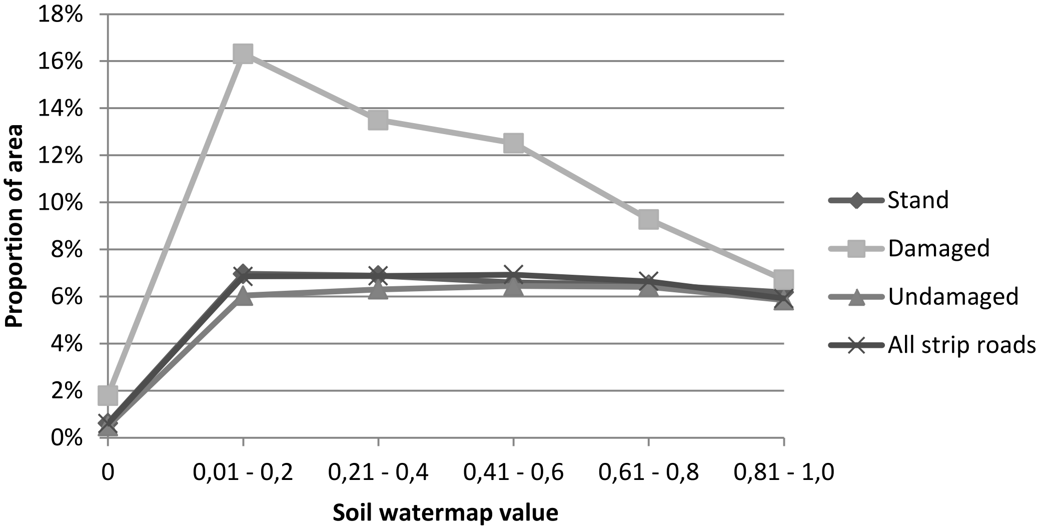

Figure 3.6. Proportion of the area classified by soil watermap value

Proportion of ‘’dry’’ area is also very similar for undamaged strip roads, all strip road values and stand overall values – around 70 %, while 40 % of damaged strip road parts were located on ‘’dry’’ areas (Table 3.3.).

Table 3.3. Detailed distribution of pixel values in stand, damaged strip roads, undamaged strip roads and overall in strip roads

Wetness index	Value	Stand, %	All strip roads, %	Undamaged strip roads, %	Damaged strip roads, %
1	0	1	1	0	2
2	0.01 – 0.2	7	7	6	16
3	0.21 – 0.4	7	7	6	14
4	0.41 – 0.6	7	7	6	13
5	0.61 – 0.8	7	7	6	9
6	0.81 – 1.0	6	6	6	7
7	1.01 - 25	66	66	68	40

T-test (two samples for means) was performed for distribution of damaged and undamaged strip road distribution (Table 3.4.). It was done to test if certain soil watermap values are more susceptible to soil damage. This could be very useful for decision making while planning strip road placement. Analysis showed that damaged and undamaged parts of strip road have statistically important difference ($p<0.05$) for soil watermap values 0 to 0.6.

Table 3.4. Detailed distribution of pixel values in damaged strip roads and undamaged strip roads and their T-test P values

Wetness index	Values	Undamaged strip roads, %	Damaged strip roads, %	P(T<=t) two-tail
1	0	0	2	0.0072
2	0.01 – 0.2	6	16	0.0023
3	0.21 – 0.4	6	14	0.0007
4	0.41 – 0.6	6	13	0.0015
5	**0.61 – 0.8**	6	9	**0.2417**
6	**0.81 – 1.0**	6	7	**0.5679**
7	1.01 - 25	68	40	0.0001

3.5. Confirmation of significant statistical difference between proportion of wet area in strip roads

According to paired sample T-test proportion of wet area was significantly higher in damaged strip road areas compared to undamaged strip road ($p<0.001$) (Table 4.1. in annex).

The null hypothesis that damage to soil in Norway spruce (Picea Abies) thinnings is not correlated to presence of wet spots (soil watermap value ≤ 1) according to soil watermaps was rejected. Proportion of wet area was significantly higher in damaged strip road part compared to undamaged strip road part. Critical value was much higher (98) than absolute value of smallest of sums (negative sum = 27) (Table 4.2. in annex).

3.6. Comparison between strip road planning using soil watermaps and original strip roads

4 stands strip roads were re-planned by professional logging manager. Re-planned stands showed more optimized rout selection (Figure 3.7.). On average strip road length was decreased by 23 % after re-planning (Table 3.5.).

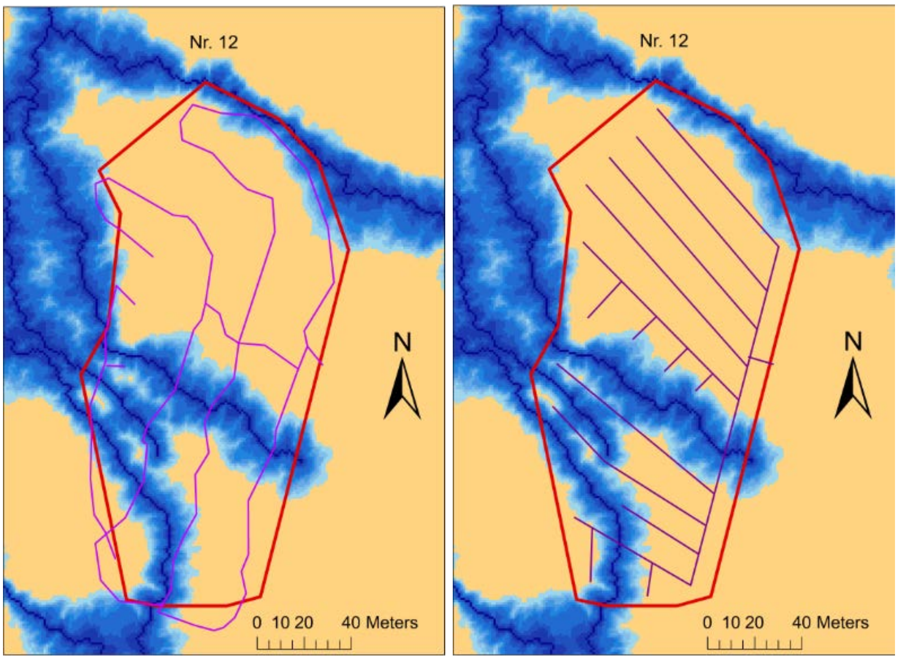

Figure 3.7. One of maps re-planned re-planned by logging manager (right) and original strip road placement (left). Stand borders (red line) with strip roads (purple lines) and entrance point (red point). The watermap in the background represents dry or mesic areas (beige) and the gradient of risk for wet areas in a scale dark blue (high risk) to white (low risk).

Table 3.5. Strip road length

Stand ID	Original stand, m	Re-planned stand, m	Decrease in distance, %
8	961	868	10
12	1039	826	21
14	1914	1033	46
21	1338	1292	3
Average	**1313**	**1005**	**23**

Re-planned strip roads also showed significant ($p<0.05$) (Table 4.3. in annex) decrease in proportion of wet area (Table 3.6.; Figure 3.8.). On average strip roads showed decreased placement on wet areas by 11 % (relative to original placement decreased by 29 %).

Table 3.6. Proportion (%) of wet area (soil watermap value ≤1.0) in strip roads

Stand ID	Original, % wet	Re-planned, % wet	Decrease in wet area, %	Relative decrease in wet area, %
8	37	25	12	33
12	40	23	18	44
14	48	35	12	26
21	27	26	2	6
Average	**38**	**27**	**11**	**29**

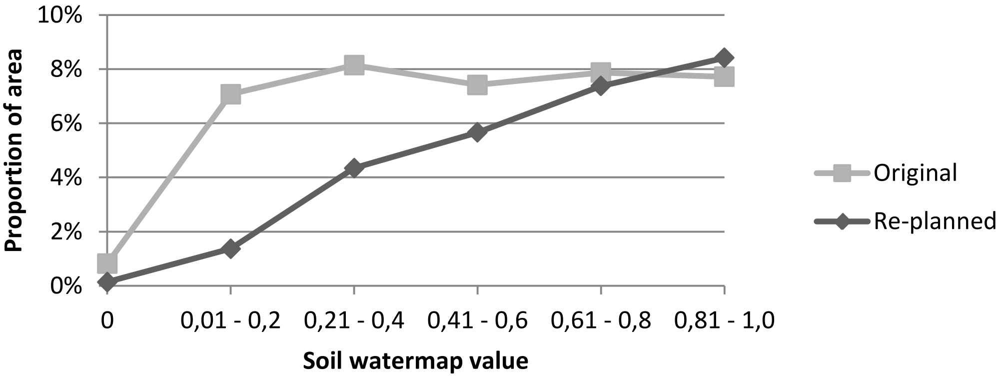

Figure 3.8. Proportion of the area classified in the wetness index

Analysis of original and re-planned strip road pixel distribution showed significant ($p<0.05$) decrease in share of pixels with soil watermap values 0.01 – 0.2 and 0.21 – 0.4 as well as significant ($p<0.05$) increase of dry area (soil watermap value >1) (Table 3.7.).

Table 3.7. Detailed distribution of pixel values in re-planned strip roads and original strip roads and their T-test P values

Values	Re-planned, %	Original, %	P(T<=t) two-tail
0	0	1	**0.0711**
0.01 – 0.2	1	7	0.0015
0.21 – 0.4	4	8	0.0329
0.41 – 0.6	6	7	**0.2630**
0.61 – 0.8	7	8	**0.7415**
0.81 – 1.0	8	8	**0.4094**
1.01 - 25	73	61	0.0468

4. Discussion

4.1. Predicting damage to soil using soil watermaps

This study showed that wet areas projected in soil watermaps correlate with damage to soil during thinning operations in Norway spruce (Picea abies) stands. Damaged parts of strip roads had significantly ($p<0.001$) larger proportion of wet areas compared to undamaged strip roads. On average 60 % of damaged strip roads were on wet areas while only 32 % of undamaged strip roads were on wet areas. From this one can conclude that to decrease damage to soil in thinning of Norway spruce stands it would be favorable to avoid wet areas represented in soil watermaps. This difference could have been even larger if bedrock would not be so close to soil surface. During field inventory for this study, there were several examples where the bedrock had come to surface and there were surface water in-between rocks, but there were no damages to soil that could be registered.

Driving on wet areas projected in soil watermaps doesn't mean that it will necessary lead to damage to soil, but risk of having soil damages is increased up to 5 times. This as well could be partly explained by the fact that soil watermaps based on depth to water index (DTW) don't take into account soil type (mineral or organic) and good logging and planning practices. Also, depth of bedrock to soil surface (bedrock coming out of soil) may have influenced the lack of correlation between proportion of wet area in stand and proportion of damage to soil.

When comparing wet area distribution of damaged and undamaged strip roads (Figure 3.6., Table 3.4.) it is visible that largest difference in wetness index distribution is for soil watermap values with very high risk of being wet (between 0 and 0.6.) and for dry/mesic areas (soil watemap value >1). Importance of planning strip roads on dry area is already mentioned, but from more detailed analysis of the distribution in the measured data one can suggest that by avoiding driving on areas with soil watermap value lower than 0.6 is crucial for decreasing damage to soil.

4.2. Decreasing damage to soil by using soil watermaps in planning proces

Providing logging manager with soil watermaps, stand borders, enterance point and instructing how to use them resulted in re-planned strip roads being shorter, significantly ($p<0.05$) more often placed on dry/mesic areas in soil watermaps and were significantly ($p<0.05$) less placed on areas with soil watermap values 0.01-0.4, which are suggested to have higher risk of having soil damage during logging.

Decrease of strip road length could be indirect effect of using soil watermaps since more time is spent planning placement of strip roads. One can conclude that by using soil watermaps in planning process it is possible to significantly decrease driving on wet areas. Table 3.6. also showed lack of significant change in driving where surface water is visible (soil watermap value =0) indicating that current logging practices already avoid places with surface water. However, it has to be mentioned that for this analysis stands with most damaged and largest possibility to improve were chosen. It was done to investigate the concept of using soil watermaps in planning process to decrease damages to soil. Therefore, these results do not reflect an average improvement of strip-road planning.

4.3. Recommendations for using soil watermaps to decrease damage to soil during thinning operations in Norway spruce stands

- Avoid wet areas (soil watermap value ≤1)
- If not possible avoid the most wet areas, with value ≤0.6
- If there is a need to cross very wet area (soil watermap value ≤0.6) do it in one place, because it is easier to do strip road packing in only one place
- Use topographic map parallel to soil watermaps to take into account steep terrain
- Consider logging stands that have close to 100 % of wet area in soil watermaps during winter time or very dry summer

4.4. Suggestions for future research

- Do a comparison between regular terrain maps and soil watermaps to determine if increase in precision of wet area prediction justify costs
- Research possibilities to decrease damage to soil in areas that have 100% wet area proportion. For example if driving on areas with soil watermap value >0.6 would decrease overall damages.

5. Conclusions

- Driving on wet areas projected on soil watermaps have significantly higher risk of producing ruts
- Driving on wet areas projected on soil watermap with values ≤0.6 have 3 to 5 times higher risk of producing ruts during logging than driving on dry areas (soil watermap value >)
- Soil watermaps can be used to decrease damage to soil during thinning operations in Norway spruce stands
- Improvement of strip road placement using soil watermaps during thinning operations is possible

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Annex

Table 4.1.

Results of paired sample T-test – two samples for means for Table 3.1.

	Variable 1	*Variable 2*
Mean	0,667181045	0,329578083
Variance	0,107219866	0,024382352
Observations	26	26
Pearson Correlation	0,297970306	
Hypothesized Mean Difference	0	
df	25	
t Stat	5,413137448	
P(T<=t) one-tail	0,000006423	
t Critical one-tail	1,708140761	
P(T<=t) two-tail	0,000012847	
t Critical two-tail	2,059538553	

Table 4.2.

Wilcoxon signed-rank test results for Table 3.1.

	Value	Absolute value
Positive sum	324	324
Negative sum	-27	**27**
Critical value	**98**	
α	0,05	

Table 4.3

Results of paired sample T-test – two samples for means for Table 3.5.

	Variable 1	*Variable 2*
Mean	0,382185	0,270834
Variance	0,007027	0,00313
Observations	4	4
Pearson Correlation	0,587496	
Hypothesized Mean Difference	0	
df	3	
t Stat	3,26723	
P(T<=t) one-tail	0,023437	
t Critical one-tail	2,353363	
P(T<=t) two-tail	0,046875	
t Critical two-tail	3,182446	