# Impacts of forestry operations on soil physical properties, water and temperature dynamics

Linnea Hansson
*Faculty of Forest Sciences*
*Department of Soil and Environment*
*Uppsala*

Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2019

Acta Universitatis Agriculturae Sueciae

2019:18

Cover: 3D images (2×2×2 cm) of the pore network from soil samples from the undisturbed soil (left) and below shallow wheel tracks (right) 1.5–3.5 cm below the mineral soil surface, slope A, *top2*, Rotflakamyran (photo: L. Hansson/J. Koestel)

ISSN 1652-6880
ISBN (print version) 978-91-7760-354-2
ISBN (electronic version) 978-91-7760-355-9

Print: SLU Service/Repro, Uppsala 2019

# Impacts of forestry operations on soil physical properties, water and temperature dynamics

## Abstract

Soil physical disturbances caused by forestry operations can be both intentional, e.g., soil scarification, and unintentional, e.g., soil compaction and rutting as a consequence of off-road traffic. All disturbances may alter the soil, and thus change its water and temperature dynamics, with consequences for both forest production and the surrounding ecosystems.

The overall aim of this thesis was to summarize how forestry operations – here: off-road traffic and soil scarification – affect the soil, its water content and temperature at clearcuts, as well as what implications this may have for, e.g., tree seedling establishment, field vegetation, and the surrounding ecosystems. The summary is based on four studies, three on off-road traffic at two clearcuts in northern Sweden and one on soil scarification (disc trenching) at a clearcut in central Sweden. The methods used were soil sampling, X-ray tomography, image and soil physical analyses, *in situ* measurements of soil temperature and water content, vegetation survey, evaluation of abiotic growing conditions, and finally, hydrological modelling.

The most notable results were that even stony till soils in recharge areas were compacted by off-road traffic, which especially affected hydraulic conductivity, reducing it by 70%. Changes in soil physical properties caused by traffic may lead to longer periods of high water content, increased risk of surface runoff and insufficient root aeration. Five years after the operation, volumetric water content was higher in wheel tracks, and this was corroborated by the species composition of the vegetation. Simulations demonstrated how the changed soil hydrological properties influenced the water dynamics. Restricted aeration was more frequent in wheel tracks and could explain patches of bare soil in the lower parts of the slopes of the experimental plots. Logging mats and residues prevented creation of deep wheel tracks by off-road traffic, despite the additional passes necessary to apply (and remove) them. However, the logging residues were pressed into the soil, with potential soil compaction and element concentration beneath them as a result. To conclude, care should be taken when planning off-road traffic, even on sandy till soils with high stone content.

After soil scarification, the soil temperature during growing season was higher in the furrows than in the area without disc trenching; the temperature effect lasted for at least six years, but decreased over time. No microsite was wet enough to hamper soil aeration after disc trenching. In conclusion, furrows offered a suitable microclimate for planting at the dry, boreal site.

*Keywords:* off-road traffic, soil compaction, soil physical properties, soil temperature, aeration, moisture content, Ellenberg, Hydrus-1D, X-ray computed tomography

*Author's address:* Linnea Hansson, SLU, Department of Soil and Environment,
P.O. Box 7014, 750 07 Uppsala, Sweden

# Preface or how it all started

I have been interested in forests, waters and soils as long as I can remember, and in secondary school, my interest for forestry awoke. In geography class, we learnt about the new management methods in which forestry operations were adapted to site-specific conditions. We also learnt about the revised Swedish Forestry Act (1993), where the environmental objective was made equal in importance to the productivity objective of forestry (proposition 1992/93:226). Since then, I have liked the idea of productive forestry management with minimal negative ecological impact and the Swedish Forestry Model (definition in, e.g., Lindahl *et al.*, 2017).

Before I started my PhD project, I worked as a forestry consultant for the Swedish Forestry Agency. This included giving courses and advice to forest owners as well as checking that the Swedish Forestry Act was being followed. At that time, soil disturbances caused by forestry machines was starting to gain attention within the forestry sector, and I realized how little research was being done in this field in Fennoscandia. During the decade that has passed since then, I am happy that the Swedish forestry sector has done considerable work to prevent severe rutting (deep wheel tracks), especially close to waters. Clearcutting methods, like *RÄTT METOD* (storaensoskog.se/rattmetod), have been developed to prevent soil disturbances. Portable bridges are more commonly used, and the planning of forestry operations has improved, e.g., with planning aids such as depth-to-water maps. Still there are many knowledge gaps in this field, concerning both how to prevent soil damage caused by forestry operations in a cost-efficient way and what long- and short-term effects the operations have on soils and waters and their ecosystem services.

This thesis aims to summarize and discuss my contributions to narrowing some of the knowledge gaps within the field of soil disturbances, both unintentional, e.g., those caused by off-road traffic during forestry operations, and intentional, e.g., soil scarification, which aims at giving seedlings a head start. I focus on how these forestry operations may affect soil physical properties, water and temperature dynamics. In addition, I discuss what consequences this may have for forestry production and the environment.

# Table of contents

# List of publications

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

I **Hansson, L.**, Koestel, J., Ring, E., Gärdenäs, A. (2018)
Impacts of off-road traffic on soil physical properties of forest clear-cuts: X-ray and laboratory analysis. *Scandinavian Journal of Forest Research*, 33 (2), pp. 166-177.

II **Hansson, L.**, Šimůnek, J., Ring, E., Bishop, K., Gärdenäs, A. (2019)
Soil compaction effects on root-zone hydrology and vegetation in boreal forest clearcuts. *Soil Science Society of America Journal,* 83 (S1) (in print)

III Ring, E., Högbom, L., **Hansson, L**., Nordlund, S., Andersson, M. (2019)
Logging mats and logging residue as ground protection during forwarder traffic on till hillslopes (manuscript)

IV **Hansson, L.**, Ring, E., Franko, M., Gärdenäs, A. (2018)
Soil temperature and water content dynamics after disc trenching a sub-xeric Scots pine clearcut in central Sweden. *Geoderma*, 327, pp. 85-96.

Paper I, II and IV are reproduced with the permission of the publishers.

The contribution of Linnea Hansson to the papers included in this thesis was as follows:

I Planned the study together with A. Gärdenäs and E. Ring. Performed the fieldwork, some laboratory work, parts of the X-ray scanning, and the data analyses, including image segmentation and analyses. (The illumination correction of the X-ray images was done solemnly by J. Koestel). Wrote the manuscript with contributions from the co-authors.

II Planned the study with assistance from A. Gärdenäs and P-E. Jansson. Performed fieldwork including a vegetation survey and logger and sensor installations, performed the sensor calibration in the laboratory and the data analyses. Executed the hydrological modelling and writing with assistance from the co-authors.

III Took part in the initial fieldwork, analysed part of the collected data (although not included in the manuscript), and assisted in planning of the manuscript and contributed in the writing.

IV Planned the data analyses and the focus of the study together with A. Gärdenäs and E. Ring, on six-season data, already collected by E. Ring. Carried out additional fieldwork (soil sampling) and some laboratory work. Contributed to the statistical model developed by M. Franko and analysed the data. Wrote the manuscript together with the co-authors.

# Abbreviations

| | |
|---|---|
| BD | dry bulk density |
| GNSS | Global Navigation Satellite Systems |
| Hg | Mercury |
| $K_{sat}$ | saturated hydraulic conductivity |
| LTSP | North American long-term soil productivity network |
| Pa | Pascal |
| Site R | Rotflakamyran |
| Site T | Trågalidsberget |
| VWC | volumetric water content |

# Papers at a glance

| Paper | Reference | Aims and experimental sites |
|---|---|---|
| **I** | Hansson, Koestel, Ring, Gärdenäs (2018). Impacts of off-road traffic on soil physical properties of forest clear-cuts: X-ray and laboratory analysis. *Scandinavian Journal of Forest Research*, 33 (2) | To analyse the impacts of repeated passes with a laden forwarder on the soil physical properties in the topsoil of two forest clearcuts situated on coarse till soils in northern Sweden (Rotflakamyran and Trågalidsberget). |
| **II** | Hansson, Šimůnek, Ring, Bishop, Gärdenäs (2018). Soil compaction effects on root-zone hydrology and vegetation in boreal forest clearcuts. *Soil Science Society of America Journal,* 83 (S1) | To study root-zone hydrology and vegetation in three microsites – in, between, and beside wheel tracks – 4–5 years after forwarder traffic, on sandy and stony till soils in two clearcuts in northern Sweden (Rotflakamyran and Trågalidsberget). |
| **III** | Ring, Högbom, Hansson, Nordlund, Andersson (2019). Logging mats and logging residue as ground protection during forwarder traffic on till hillslopes. *Manuscript* | To test whether soil protection measures, i.e., driving over logging mats or logging residue, can reduce deep rutting (wheel tracks) in two clearcuts in northern Sweden (Rotflakamyran and Trågalidsberget) |
| **IV** | Hansson, Ring, Franko, Gärdenäs (2018). Soil temperature and water content dynamics after disc trenching a sub-xeric Scots pine clearcut in central Sweden. *Geoderma, 327* | To describe and analyse the impact of soil scarification, i.e., disc trenching, on soil temperature and water content dynamics during the first six growing seasons after clearcutting (Hagfors). |

| Materials and methods | Main findings |
|---|---|
| Core samples (n = 71) were collected from the top 5 cm of mineral soil in and beside wheel tracks, after six passes with the forwarder. Soil physical properties were quantified using classical soil physical analyses and X-ray tomography. | Traffic reduced hydraulic conductivity by 70%, due to smaller total volume and lower connectivity of structural pores. Changes in soil physical properties caused by traffic may lead to longer periods of high water content, increased risk of surface runoff and insufficient root aeration. |
| Measurements of VWC, vegetation indicators and 1D hydrological modelling were conducted. VWC was measured continuously in three or four plots along a slope on each site. VWC was also measured once in the 117 vegetation survey plots. | VWC was highest in wheel tracks, corroborated by species composition. Simulations indicated that changed soil hydraulic properties influenced VWC results. Restricted aeration was more frequent in wheel tracks and could explain patches of bare soil. |
| Rutting depths were recorded both with GNSS-positioning and manual measurements, as well as the number of extra passes needed by the forwarder to apply and remove the soil protection from the entire slopes, in addition to the treatment of six passes with the laden forwarder. | Logging mats and residues prevented deep wheel tracks, despite the additional passes necessary to apply (and remove) them. However, the logging residues were probably pressed into the soil with potential soil compaction and element concentration below them as a result. |
| Soil temperature and VWC were measured hourly 20 and 45 cm below the original surface of the mineral soil in three types of microsites created by disc trenching and an undisturbed control microsite outside the disc-trenched area. | Growing season soil temperatures were higher in the furrows than in the control microsites. The temperature effect lasted for at least six years, but decreased over time. No microsite was wet enough to hamper soil aeration. Furrows offer a suitable microclimate for planting at this dry, boreal site. |

# 1 Effects of forestry operations on soils

## 1.1 Soil disturbances – an introduction

Forests cover 69% of the land area in Sweden, and this area includes 23.5 million hectares of productive forestland, where different forestry operations regularly take place (Fridman & Wulff, 2018). Soil physical disturbances caused by forestry operations can be both intentional, e.g., to increase forest production, and unintentional, e.g., as a consequence of off-road traffic. The steady development of forestry mechanization during the past six decades has increased these disturbances. Today the following machines may be used during a rotation period: 1) harvesters, both for regeneration felling and thinning, 2) forwarders for timber, tops and branches or stumps, 3) stump harvesters, 4) machines used for soil scarification, 5) tractors with fertilizer or ash spreading equipment, and in some cases, 6) excavators for cleaning of ditches and for protective ditching. The extensive traffic caused by these machines, together with the intentional disturbances, has the potential to induce undesirable effects on different components of the forest ecosystem, i.e., soil, water, vegetation and animal life.

Off-road traffic by forestry machines may cause rutting and/or soil compaction, and will have different ecological impacts depending on the area disturbed (Cambi *et al.*, 2015). In forest clearcuts, skid trails or wheel tracks usually cover about 12–30% of the area (Mohtashami *et al.*, 2017; Solgi & Najafi, 2014; Zenner *et al.*, 2007; Eliasson, 2005; Brais, 2001). In a report by Mohtashami *et al.* (2016), 89% of the clearcuts in central Sweden had some visible ruts caused by off-road traffic, and the most frequent rut depth was 5–25 cm. Productive losses, such as reduced tree seedling survival and growth, have been reported following soil compaction (Naghdi *et al.*, 2016; Kabzems, 2012; Murphy *et al.*, 2004), and reduced growth after soil compaction during thinning operations in Sweden was observed already several decades ago (Wästerlund, 1983). Tree growth may also be indirectly affected, as damaged tree roots are more susceptible to attacks of pathogenic fungi, e.g., root-rot (Håkansson *et al.*, 1988). However, soil compaction may also increase tree growth, depending on the initial soil properties (Cambi *et al.*, 2015; Ponder *et al.*, 2012; Brais, 2001) or have no effect on growth (Page-Dumroese *et al.*, 2006; Ares *et al.*, 2005; Kamaluddin *et al.*, 2005). Productive losses may also be a consequence of rutting, as there are risks of increased logging costs, due to increased fuel consumption and prolonged operation times when vehicles get stuck.

Soil scarification is a form of intentional soil disturbance that is carried out on most of the harvested forest areas in Fennoscandia. It promotes successful regeneration and good production in boreal forests worldwide (Hébert *et al.*, 2014; Nilsson *et al.*, 2010; Sutton, 1993), and may also increase ecosystem carbon stock by increasing the tree biomass (Mjöfors *et al.*, 2017; Egnell *et al.*, 2015). In Sweden, circa 80% of the yearly clearcut area is subjected to soil scarification (Swedish Forestry Agency, 2016). Of this area, 60% is disc trenched, 10% is patch scarified and 30% is mounded (Krekula *et al.*, 2018). Studies on soil scarification estimate that approximately half the area of a clearcut is affected by the soil scarification treatment (Piirainen *et al.*, 2007; Pohtila & Pohjola, 1985).

The aim of soil scarification is to give the planted or self-seeded seedlings a head start by changing the microclimate to promote higher soil temperature during the growing season and more favourable moisture conditions, potentially increasing nutrient availability (Lundmark-Thelin & Johansson, 1997; Johansson, 1994) through increased microbial activity (Pumpanen *et al.*, 2004), removing competing vegetation and reducing pine weevil damage (*Hylobies abietis*; Nordlander *et al.*, 2011).

Soil scarification typically creates three main types of microsites: 1) elevated tilts, ridges, berms or mounds, 2) patches, trenches or furrows where the organic layer is removed, and, 3) intermediate areas where the original vegetation and humus layer is intact. The microsites identified after off-road traffic are wheel tracks (also called ruts), the area between the two wheel tracks (between-tracks) and undisturbed soil, usually at least 2 m away from the ruts, as the soil close to the wheel tracks is often affected (Labelle & Jaeger, 2011), including lateral bulging and soil compaction.

Both soil scarification and off-road traffic close to streams can promote overland flow and particulate loading due to exposed mineral soil, reduced infiltration and channelling of water, especially in steep terrain (Jourgholami *et al.*, 2017; Aust & Blinn, 2004; Håkansson *et al.*, 1988).

## 1.2 Soil physical properties

Soil compaction is defined as an increase in bulk density (BD) or a decrease in porosity. The reduction in total porosity by compaction of forest soils is usually between 10-50% (Toivio *et al.*, 2017; Cambi *et al.*, 2016; Bagheri *et al.*, 2012; Frey *et al.*, 2009; Ares *et al.*, 2005; McMahon *et al.*, 1999; Gayoso & Iroume, 1991). Soil aeration is a crucial soil factor for plant growth, and air-filled porosity (i.e., total porosity minus volumetric water content is considered the main limiting factor for soil aeration (Ben-Noah & Friedman, 2018). Sufficient aeration is needed because plant roots and microorganisms consume oxygen and produce carbon dioxide during respiration. Furthermore, when anoxic conditions increase, methane, nitrous oxide and other toxic gases may be formed by microbial mediated reduction processes (Ben-Noah & Friedman, 2018; Cambi *et al.*, 2015). If the air-filled porosity decreases below 0.10 $m^3$ $m^{-3}$, gas diffusion essentially stops (Xu et al., 1992). Root density was decreased by decreased soil gas permeability in the upper 5 cm of the mineral soil after off-road traffic in a study in Germany (Gaertig et al., 2002), and air-filled porosity less than 0.10 $m^3$ $m^{-3}$ has been found to reduce seedling and tree growth in Finland (Wall & Heiskanen, 2009; 2003).

Studies on structural changes in the pore systems of forest soils caused by compaction are rare. As pointed out by Bottinelli *et al.* (2014), some properties of compacted forest soils, e.g., volume, tortuosity and connectivity of pores, need to be studied in 3D. On agricultural soils, X-ray tomography has been used to study compaction (Mossadeghi-Björklund *et al.*, 2016; Tracy *et al.*, 2012; Schaeffer *et al.*, 2007), but more studies are needed on forest soils. In Paper I of this thesis, X-ray tomography was used to study changes in soil physical properties caused by off-road traffic. Comparison of soil physical measurements in the laboratory and values obtained by analysing X-ray tomography pictures of the same samples offers possibilities to evaluate both methods in terms of quality and cost-efficiency. The two methods are compared in Paper I, and in Section 6.1 of this thesis, where the pros and cons of both methods are discussed.

Boreal forest soils often have a high content of stones and boulders, and a major challenge in studying such soils is obtaining undisturbed samples. This is probably one reason why there are relatively few studies of soil compaction on coarse-textured soils and why more studies like Paper I are needed. Examples of previous research include Labelle and Jaeger (2011); Startsev and McNabb (2009); and Block *et al.* (2002). The sampling is not only aggravated by coarse mineral soil material (rock fragments), but also by roots in the topsoil. The concentration of roots and associated mycorrhiza in the humus layer and the top mineral soil is high (Makkonen & Helmisaari, 1998; Persson, 1983), and thus, this soil depth is very relevant to study from a tree growth perspective. Changes in soil physical properties in the upper soil are also important to study for the prediction of infiltration, as discussed above.

## 1.3 Soil temperature and water content and their implications for tree seedlings

Soil temperature and water content dynamics in clearcuts are governed by the soil physical properties together with vegetation and macro- and microclimate (MacKenzie *et al.*, 2005; Bhatti *et al.*, 2000; Balisky & Burton, 1995; Chen et al., 1993). Soil scarification affects all of these, with the exception of macroclimate (Boateng *et al.*, 2010; Balisky & Burton, 1995). Generally, soil temperatures are increased in the planting locations created by soil scarification during the growing seasons (Buitrago *et al.*, 2015; Löf & Birkedal, 2009; Knapp *et al.*, 2008; Simard *et al.*, 2003; Örlander *et al.*, 1998; Kubin & Kemppainen, 1994). Increased soil temperatures in boreal clearcuts may be beneficial to seedling growth in many ways: the number of root tips and mycorrhizae may increase, as may the root biomass and nutrient uptake (Pumpanen *et al.*, 2012; 2002; Domisch *et al.*, 2001; Balisky & Burton, 1997). Too low temperatures (below 4–5 °C) are problematic for seedlings, as they impair root growth, reduce water uptake and conductance, and (below 8 °C) transpiration (Pallardy, 2008; Alvarez-Uria & Körner, 2007; Mellander *et al.*, 2004; Örlander & Due, 1986).

Soil water content is often affected by soil scarification, and in the upper 10 cm of ridges, mounds or tilts it is usually decreased, whereas it is unaffected or slightly increased in furrows, patches or trenches (Sutinen *et al.*, 2006; Mäkitalo & Hyvönen, 2004; Burton *et al.*, 2000). At wet sites, reduced water content is beneficial due to the risk of restricted aeration caused by a high VWC, as discussed above. The optimum condition for nitrogen and carbon mineralization is around 60% water-filled pores of total porosity (Seyferth, 1998; Linn & Doran, 1984). The lower water content threshold, where tree seedlings may be affected, varies with species: transpiration rates start to decline at soil water potentials of -0.1 to -0.2 MPa for various conifer species (Lopushinsky & Klock, 1974; Jarvis & Jarvis, 1963). Containerized seedlings have a higher root growth potential after outplanting in a clearcut, and thus, they are more resistant to drought than bare root seedlings are (Grossnickle & El-Kassaby, 2016; Grossnickle, 2012). However, their water uptake may still be reduced for two years or more, compared to self-seeded seedlings, due to the poorer root system (Örlander, 1986). Örlander *et al.* (1998) suggest a water tension of -0.1 MPa as a threshold for unfavourably dry conditions for planted seedlings. Drought does not only affect the seedlings during the season with insufficient water availability, but also in the following seasons, when they may be more affected by herbivores (Bansal et al., 2013).

As presented above, soil temperature and water content dynamics after soil scarification have been studied before, also in Fennoscandia. However, studies on forestland with detailed temporal resolution of both soil temperature and water content after soil scarification are rare (i.a. Simard *et al.*, 2003; Bhatti *et al.*, 2000; Burton *et al.*, 2000), especially studies including long-term dynamics. Few have investigated changes in effects of soil scarification on soil temperature and water content dynamics over time (i.a. Devine & Harrington, 2007; Kubin & Kemppainen, 1994). Paper IV is focused on this and includes high-resolution measurements. Such data are valuable on their own, but also for ecosystem modelling studies, such as Rappe George *et al.* (2017).

Wetter conditions in the wheel tracks are commonly found in soil compaction studies on forestland (Fründ & Averdiek, 2016; Wei *et al.*, 2016; Ares *et al.*, 2005). However, the gravimetric water content may be lower in compacted soils (Naghdi *et al.*, 2016), due to the increased dry bulk density, even though the VWC in the compacted soil is similar to, or higher than, the VWC of the undisturbed soil. Soil temperature after soil compaction has been studied within the North American long-term soil productivity network (LTSP), including different levels of organic matter removal and soil compaction (Tiarks *et al.*, 1997). Following soil compaction, the mineral soil temperatures at these sites have been found to decrease (Tan *et al.*, 2005), remain unchanged (Ares *et al.*, 2005), or increase (Kranabetter & Chapman, 1999), where the latter was considered to be due to the higher thermal conductivity of the denser soil. Li *et al.* (2003) also found increased soil temperature two years after soil compaction, but not after five years at another LTSP site. In addition, forest floor removal increased soil temperatures at the sites (Tan *et al.*, 2005; Kranabetter & Chapman, 1999).

Paper II includes an analysis of the soil water conditions 4–5 years after off-road traffic, and in this thesis, the results of the simultaneous soil temperature measurements will be presented and discussed.

## 1.4 Ground and field vegetation

From a plant perspective, the greatest concern with soil compaction is that the reduction in permeability of water, air, and roots in the soil will lead to insufficient water, oxygen, and/or nutrient uptake by the plants (Batey, 2009). Physical soil disturbances may affect biological processes like carbon and nitrogen mineralization in the soil (Kataja-aho *et al.*, 2012; Booth *et al.*, 2006; Finér *et al.*, 2003; Mallik & Hu, 1997). Ectomycorrhizal fungi have been found to decrease by soil compaction, whereas saprotrophic and parasitic fungi may increase (Hartmann *et al.*, 2014). Soil disturbances usually affect ground and field vegetation, which respond rapidly and at a fine scale (Duguid & Ashton, 2013). Thus, vegetation can be used to detect changes or differences between treatments, for example using Ellenberg indicator values (Ellenberg et al., 1991), as was done in Paper II. Ellenberg indicator values are commonly used to indicate environmental conditions such as soil moisture, light tolerance, pH, etc. (Bartelheimer & Poschlod, 2016). The cover of field vegetation species has been found to be affected by soil disturbances: soil compaction on skid trails promoted the biomass of *Kalmia* in different moisture regimes (north eastern Québec) and increased the biomass of *Rhododendron* and *Vaccinium* on mesic sites (Lorente *et al.*, 2012). In the same study, soil scarification generally reduced *Kalmia*, whereas *Rhododendron* and *Vaccinium* were reduced on mesic sites only. In Fennoscandia, some have studied how stump lifting (including soil disturbances caused by the extra traffic) affects the vegetation cover (e.g. Andersson *et al.*, 2017; Hyvönen *et al.*, 2016), but to see the wider picture of the consequences of off-road traffic (without stump lifting), more studies of these types are needed. In Paper II, effects of soil compaction on species composition and cover, 4–5 years after off-road traffic, were studied.

Removing competing vegetation is one of the most important aims of soil scarification, but this effect is usually short-term (Johansson *et al.*, 2013; Piirainen *et al.*, 2007), although differences in field vegetation biomass were found five years after soil scarification (Palviainen *et al.*, 2007). However, species composition may still be altered 14 years after the treatment (Bergstedt *et al.*, 2008). Regeneration of forests (including soil scarification) increased species diversity compared to the diversity in mature forests, with a peak in young forests, according to a study based on the Swedish Forest Inventory (Widenfalk & Weslien, 2009).

## 1.5 Soil recovery

Recovery from soil compaction in forested areas is commonly slow and continues for many decades (Ebeling *et al.*, 2016; Klaes *et al.*, 2016; Wei *et al.*, 2016; Cambi *et al.*, 2015; Ezzati *et al.*, 2012; von Wilpert & Schäffer, 2006), even when freeze-thaw cycles occur (Block *et al.*, 2002). As summarized by Goutal *et al.* (2012a), the measured recovery rates depend on: 1) the different methodologies used to assess natural recovery rate, 2) the original degree of disturbance depending on soil type, moisture content at the time of traffic, machinery used etc., and, 3) the processes influencing the recovery rate, such as vegetation, biological activity, climate, local variance in topography and geology.

In boreal regions, the growth and decay of roots and mycorrhiza may promote the recovery process (Bottinelli *et al.*, 2014; Meyer *et al.*, 2014), and may increase in importance if swelling clays are absent and no or few earthworms or other soil-mixing fauna are present in the soil. Soil frost (i.e., freezing and thawing) also contributes to soil recovery, but may be reduced by an early and thick snow cover. More information on the rate and extent of recovery of coarse-textured boreal forest soils in the Fennoscandian climate is needed if we are to evaluate the severity of the disturbance from a forest production perspective as well as for other ecosystem services. In Paper II, the conditions 4–5 years after off-road traffic were studied.

## 1.6 Soil protection

Compaction and rutting by off-road traffic may be reduced if brush/slash mats (logging residues) are used to spread the machine load over a greater area (Poltorak *et al.*, 2018; Ampoorter *et al.*, 2012; Labelle & Jaeger, 2011; Eliasson & Wästerlund, 2007; Han *et al.*, 2006). Labelle and Jaeger (2011) summarized the factors influencing the amount of logging residues needed for effective soil protection: 1) forest stand characteristics, 2) silvicultural treatment, 3) soil properties, and 4) harvester boom length. Soil water content at harvesting also determines how efficient brush may be in reducing compaction and rutting (Han *et al.*, 2006), and in general, the water content during the operation is critical to the severity of soil disturbance (Toivio *et al.*, 2017; Lopes *et al.*, 2011; Grigal, 2000). With rising VWC, cohesion between soil particles decreases and the soils reach maximal sensitivity to compaction at an intermediate water content, usually around field capacity (Ampoorter *et al.*, 2012). Higher water content results in soil displacement and deep rut formations, rather than compaction, as the forces from the machines cannot compress the soil further and instead move the soil (Hillel, 2003; Williamson & Neilsen, 2000).

Bulk density usually increases with the number of machine passes (Ezzati *et al.*, 2012), but most of the compaction occurs during the initial few passes (Toivio *et al.*, 2017; Jourgholami & Majnounian, 2011; Labelle & Jaeger, 2011; Han *et al.*, 2006). As soil compaction in many cases is impossible to avoid when using forestry vehicles, permanent tracks are suggested in the stands, the goal being to disturb as little soil as possible (Horn *et al.*, 2004; Vossbrink & Horn, 2004): the width between these tracks depends on the machines used, but is suggested to be between 20–40 m. Advance planning of strip roads to avoid sensitive terrain can improve profitability in forwarder operations, and tools for this are being developed. An example is the model appliance in ArcGIS, tested by

Mohtashami et al. (2012), where the most profitable route is suggested by analysing elevation, slope, aspect and soil type, and the terrain suitability for driving is classified into five different classes. In Sweden, the use of depth-to-water maps in harvesters and forwarders is increasing, which helps the operators to avoid sensitive areas with low bearing capacity (Laudon *et al.*, 2016; Ågren *et al.*, 2015), especially if combined with information on soil type (Mohtashami *et al.*, 2017).

The effect of soil protection in mitigating rutting and soil compaction has drawn attention in recent studies (e.g. Labelle & Jaeger, 2018; Poltorak *et al.*, 2018; Solgi *et al.*, 2018), but more studies like Paper III are needed with soil conditions, tree species and harvesting systems similar to those used in Sweden.

## 1.7 Summary

To conclude, off-road traffic is an integral part of most forestry operations during a rotation period in Sweden, but few studies in Fennoscandia have been conducted on the impacts of such traffic on forest soils, their temperature and water content, especially on unsorted, stony till soils; these impacts were studied in Paper I–III of this thesis.

Soil scarification affects most of the productive forestland in Sweden, and thus, detailed and long-term measurements of its effect on soil temperature and water content are important to understanding how abiotic conditions govern seedling establishment (Paper IV) and regulate environmental impacts such as nitrogen leaching (Rappe George *et al.*, 2017).

To summarize, the short- and long-term consequences of unintentional and intentional soil disturbances caused by forestry operations constitute a research area that still needs more attention, especially in Sweden – one goal of such research being to help policymakers to take decisions concerning to what extent soil disturbances are tolerable when considering productivity, profitability and the environment.

# 2 Aims

The overall aim of this thesis was to asses and discuss impacts of forestry operations – here off-road traffic and soil scarification – on soil physical properties, water content and temperature dynamics, and what implications this may have for forest production and the environment. The thesis is based on four papers, three about off-road traffic (Paper I–III) and one about soil scarification (Paper IV).

The specific objectives were to assess and/or discuss:

- changes in soil physical properties caused by forestry operations (Paper I, IV)
- changes in dynamics of temperature and water after forestry operations (Paper II, IV)
- how soils can be protected from severe rutting and soil compaction (Paper III)
- consequences of soil disturbances for field vegetation, seedling establishment and growth (Paper I, II, IV)
- environmental consequences of soil disturbances (Paper I–IV)

Further, image analysis and traditional soil physical analyses in the laboratory are compared (Paper I) and sensor installation and calibration discussed (Paper II and IV).

# 3 Site descriptions and experimental designs

The off-road traffic research was conducted in the north of Sweden (Västerbotten) at *294 Rotflakamyran* (site R) and *296 Trågalidsberget* (site T); the soil scarification research was conducted in central Sweden (Värmland), at *165 Hagfors* (Figure 1; Table 1). All three study sites were established by the Swedish Forestry Research Institute, Skogforsk.

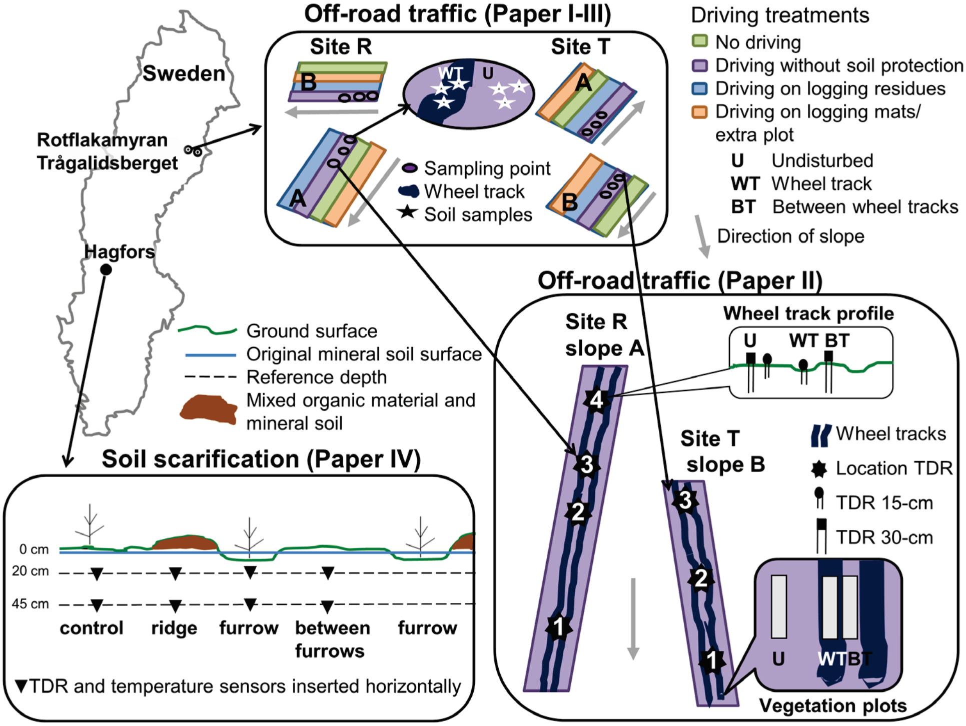

*Figure 1.* Location of the study sites Rotflakamyran, R, and Trågalidsberget, T (Paper I–III, off-road traffic), and Hagfors (Paper IV, soil scarification) including brief schematic experimental designs.

## 3.1 Rotflakamyran and Trågalidsberget (off-road traffic, Paper I–III)

The parent material of Rotflakamyran (site R) and Trågalidsberget (site T) consists of coarse glacial tills where the stone ($\varphi > 20$ mm) and boulder content is approximately 50% in the upper parts of the slopes (Table 1; Figure 2 and 3; Stendahl *et al.*, 2009). The soil texture is dominated by sand (ca. 50% of particles < 20 mm) and a relatively high silt content (ca. 30%), which increases in downhill positions at site T (Paper I–III). Site R was covered by Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst) before clear-cutting (Cut-to-length system), while site T was dominated by Norway spruce (Table 1; Paper I). The field and ground layer was dominated by blueberry (*Vaccinium myrtillus* L.) and *Hylocomiaceae* mosses (Paper II). The study plots were planted with Scots pine, without site preparation, in June 2014.

*Figure 2.*a) Rotflakamyran (at treatment, June 2012), and b) Trågalidsberget (two months after treatment, August 2013, photo: Linnea Hansson, SLU).

Table 1. *Overview of the experimental sites 294 Rotflakamyran (site R), 296 Trågalidsberget (site T) and 165 Hagfors.*

| | Rotflakamyran | Trågalidsberget | Hagfors |
|---|---|---|---|
| Latitude | 64°32.5′N | 64°19.3′N | 59°59.6′N |
| Longitude | 20°4.5′E | 20°35.7′E | 13°42.5′E |
| Elevation | 305 m AMSL | 145 m AMSL | 190 m AMSL |
| Inclination of slope[1] | 4–6° | 2–8° | - |
| Annual mean temperature | 1–2°C[2] | 1–2°C[2] | 3.5°C[3] |
| Mean acc. precipitation | 600-700 mm year$^{-1}$ [2] | 600-700 mm year$^{-1}$ [2] | 671 mm year$^{-1}$ [3] |
| Soil type (FAO) | Orthic (haplic) podzol | Orthic (haplic) podzol | Orthic (haplic) podzol |
| Parent material | Glacial till | Glacial till | Glacial till |
| Texture (FAO) | Sandy loam | Sandy/silt loam | Sandy loam |
| Soil moisture class/regime[4] | Mesic/moist | Mesic/moist | Sub-xeric |
| Site type (Cajander, 1949) | *Myrtillus* type | *Myrtillus* type | *Vaccinium* type |
| Main tree species of the harvested stand | *Pinus sylvestris*/ *Picea abies* | *Picea abies* | *Pinus sylvestris* |
| Site quality class[15] | 3.7 m$^3$ ha$^{-1}$yr$^{-1}$ | 3.7 m$^3$ ha$^{-1}$ yr$^{-1}$ | 5.9 m$^3$ ha$^{-1}$ yr$^{-1}$ |
| Time of clear-cutting | Dec. 2011 | February 2012 | March 2006 |
| Time of treatment | June 2012 | June 2013 | June 2006 |
| Study period | 2012–2018 | 2013–2018 | 2006–2011 |

1. Ring *et al.* (2019) ; 2. SMHI (2019b, b); 3.Alexandersson and Eggertsson Karlström (2001);
4. Hägglund and Lundmark (1987); 5. Ring *et al.* (2013)

### 3.1.1 The soil protection study (Paper III)

Sites R and T were created to study the effects of different types of soil protection during off-road traffic, employing a randomized block design with four treatments replicated on two slopes, here defined as blocks A and B, at each site (Figure 1): 1) control with no traffic, 2) driving without ground protection, 3) driving on logging residues (slash/brush), and 4) driving on logging mats (site R)/extra plot with no soil protection (site T). The logging mats were made of five planed logs mounted together (5 m × 1 m × 0.2 m, one for each wheel track). At site T, treatment 4 was excluded and an "extra plot" for treatment 2 was created; see Paper III for more experimental design details. The treatment plots were 15 m wide and about 100–150 m long, depending on the length of the slopes, and cleared from harvest residues before treatment. The treatment included driving with a laden forwarder (total weight: 35 Mg at site R and 33 Mg at site T, timber load approx. 10 Mg); the operator drove three times down and up (i.e., in total six passes) on all the study plots, except the control with no traffic. In addition, 10–20 extra passes in the most trafficked part (in the top of

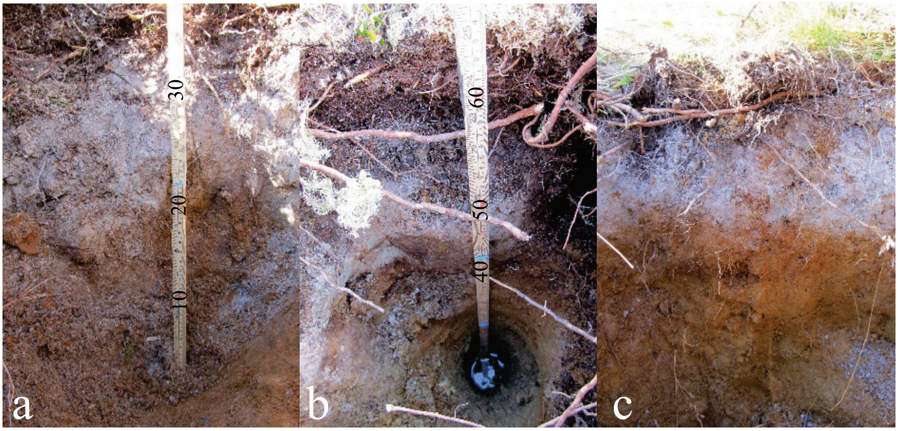

*Figure 3.* The soil profiles of Rotflakamyran, *a)* top of slope A, and *b*) lower part of slope A, and Trågalidsberget, *c)* downhill, slope B (photo: Linnea Hansson). The scale on the folding rule is in centimetres.

the slopes) were needed to apply the slash and 8–12 passes to apply and remove the logging mats (same forwarder used, without timber load). See Paper III for more details on the application and removal of the soil protection and its effect on the different parts of the slopes.

### 3.1.2 The soil compaction study (Paper I)

In the soil compaction study (Paper I), the upper 50 m of the slopes of treatment 2 (driving without ground protection, purple in Figure 1) were sampled. The inclination in the upper parts was <10% at both sites (Paper III), representing hydrologic recharge areas in the landscape (Ågren *et al.*, 2015). In Paper I, the sampling locations were called 1, 2 and 3, starting at the top of the slope, but in Paper II the bottom of the slopes was the reference. Hence, the locations in this thesis are renamed so that the soil sampling locations in Paper I are called *top1*, *top2* and *top3*, where *top1* is the highest position (i.e., the counting starts from the top of the slopes). The soil sampling took place two months after trafficking, in August 2012 (site R) and in August 2013 (site T). Eighteen core samples (3 locations × 3 replicates, both in the wheel track microsite and ca. 1.5–2 m beside wheel tracks in the undisturbed soil) were collected from the top 5 cm of the mineral soil in each of the four slopes/blocks (Figure 1). Due to the high content of stones and boulders, deeper sampling was not possible. In total, 71 core samples (one missing at site R, block A, *top2*, wheel track, due to a very high stone content) were collected and carefully transported to the laboratory where they were directly weighed. Thereafter, the samples were scanned using X-ray tomography (described in Section 4.5) prior to further analyses in the laboratory (Section 4.3).

### 3.1.3 The study of soil water and vegetation 4–5 years after off-road traffic (Paper II)

The study of soil water and vegetation was carried out 4–5 years after the driving treatments at sites R and T. Like in Paper I, the treatment plots with driving without soil protection were used and three types of soil microsites were identified: wheel tracks, between the wheel tracks and undisturbed soil beside the wheel tracks (Figure 1). A vegetation survey was carried out on all four slopes (Figure 1, Section 4.3), including measurements with a portable TDR (Time Domain Reflectometer) in all 117 vegetation plots on one occasion (see Section 4.1). In addition, permanent TDRs and temperature probes were installed in four locations at site R, slope A and three locations at site T, slope B (Figure 1, Section 4.1), hereafter called *bot1–bot4* (referring to the fact that the numbering starts at the bottom of the slopes). The *bot2–bot4* locations at site R were within the area of the *top1–top3* soil sampling locations in Paper I, and likewise, the *bot2–bot3* locations at site T. The collected volumetric water content (VWC) data were analysed on their own (e.g., seasonal mean and median values), and also used as calibration data for hydrological modelling with Hydrus-1D (see Section 4.7). The model was used to assess how the changes in hydrological properties caused by off-road traffic, found in Paper I, affected root-zone water dynamics.

## 3.2 Hagfors (soil scarification, Paper IV)

The experimental field site Hagfors is situated on a sub-xeric podzolized sandy-silty till soil where a former fertilization experiment took place (Table 1; Paper IV; Rappe George *et al.*, 2017; Ring *et al.*, 2013; 2011). The field and ground layer was dominated by lingonberry (*Vaccinium vitis-idaea*) and lichens (*Cladonia spp.),* respectively (Figure 4). The soil scarification was performed in May 2006 using a Bracke Forest disc trencher (T26, Bräcke, Sweden), creating three types of microsites: furrows, ridges, and between furrows. One repetition with the disc trencher includes ridge, furrow, between furrows, furrow, and ridge. More details about the microsites are provided in Paper IV. In June, containerized 1.5-year-old Scots pine seedlings were planted at a spacing of 2 m in the furrows of the disc-trenched areas and in the areas without disc trenching (Johansson *et al.*, 2013). In 2011, self-seeded pine and spruce seedlings equal in height to the planted seedlings (ca. 1 m) were present in all the types of microsites (in the horizontal transect).

### 3.2.1 Soil water and temperature dynamics after soil scarification (Paper IV)

Soil temperature and water content were measured hourly (2006–2011) in a 40-m horizontal transect in the central part of the Hagfors experimental site in an area between the experimental plots, without previous nitrogen fertilization (Figure 4; Paper IV; Rappe George *et al.*, 2017). Thirty-seven metres of the transect were within the disc-trenched area, perpendicular to the furrows, and 3 m in a control area, outside the disc-trenched area (Figure 1b in Paper IV). The soil temperature and water content sensors were installed at two depths (20 and 45 cm below the original surface of the mineral soil), in each of the three types of microsites created by disc trenching (furrows, ridges and between furrows) and the fourth control microsite (Figure 1, Section 4.1). The sensors were installed in four microsites of each type, except the control area where three microsites were selected. In total, 15 vertical transects were monitored including the two measuring depths (30 sensors of each type). As described in more detail in Paper IV, disc trenching transformed the soil surface into furrows and ridges, and thus, the distance between the ground surface (interface between the ground and atmosphere) and the sensors depended on the type of microsite (Figure 1). In 2011,

*Figure 4. a*) The centre of the Hagfors experimental site with the logger station, situated in the middle of the transect for soil temperature and water content measurements (photo: Linnea Hansson, September 2011). *b)* Soil profile and sensors installed at 20 and 45 cm from the original surface of the mineral soil before disc trenching. Microsites from the left: furrow, between furrows and furrow (photo: Eva Ring, Skogforsk, May 2006).

the “20 cm depth” sensors were 25 ± 1, 32 ± 9, 10 ± 4 and 24 ± 5 cm below the atmospheric interface in the control, ridge, furrow, and between furrows micro-sites, respectively. Soil temperature and water content data collected between 1 May and 31 October were used in this study, except for in total 30 days, for which data were missing.

Soil samples for analysis of soil physical properties were collected in 2006 and 2011 (Section 4.3): in 2006, at four positions along the ditch at six depths from the original mineral soil surface, and in 2011, from almost directly above the TDR sensors at two or three depths (approx. 10, 20, and 40 cm) in 11 out of the total 15 vertical transects (Paper IV). The distance from every vertical transect to the closest (planted or self-seeded) seedling stem of ca. 1 m height was recorded in order to facilitate analysis of the impact of the distance on the VWC results.

Driving on logging mats at Rotflakamyran (photo: Linnea Hansson)

Driving on logging residues at Rotflakamyran (photo: Linnea Hansson)

# 4 Measurements, analyses and modelling

This chapter describes the methodology used for measurements in the field and in the laboratory, including calibration of sensors and the steps in X-ray image analysis. Further, the methodology of analyses of acquired data and a brief model description and set-ups are included. More details and in-depth explanations are given in Paper I–IV.

## 4.1 Soil water, temperature and weather measurements (Paper II, IV)

The sensors for measuring soil water content in all studies were Time Domain Reflectometers, TDRs, (CS616, Campbell Scientific Ltd), with original rod-lengths of 30 cm. The numbers of TDRs were 16, 14 and 30 in site R, site T and Hagfors, respectively. At sites R and T, half of the sensors were shortened to 15 cm rod length, owing to anticipated installation problems due to the high stone content. At each place where a TDR was inserted, a temperature probe (T105 in Hagfors and T107 in sites R and T, Campbell Scientific Ltd, rod length 10 cm) was also installed approximately 10 cm from the TDR.

At site R and T, the sensors were installed vertically from the top of the humus layer (Figure 1). In the undisturbed soil, both 15- and 30-cm-long TDRs were installed, whereas only 15-cm TDRs were inserted in the wheel tracks and 30-cm TDRs in the between-tracks (Figure 1). At the Hagfors site, a ditch was dug for the sensor installation (the 40-m-long transect), and the sensors were pushed horizontally into the undisturbed wall of the ditch, followed by carefully refilling the ditch and restoring furrows and ridges on top of it (Figure 1 and 4).

The total measuring period was 22 June 2006 to 29 September 2011 in Hagfors and 30 May 2017 to 9 October 2018 at site R and T. If nothing else is stated, the measurements were hourly. All VWC measurements were corrected for variations in soil temperature using a temperature correction function of the output time signal suggested by Campbell (Paper II and IV; Campbell Scientific, 2016). Different types of calibration were tested. In the Paper IV, the standard quadratic calibration provided in the instruction manual was used (Campbell Scientific, 2016), but a site-specific calibration based on the samples for soil physical analysis collected in 2011, close to the TDRs, was also tested (described in Appendix B, Paper IV). At sites R and T, however, a new thorough calibration was needed, as the rod lengths of half of the TDRs were shortened, changing the relation of the output signal to VWC. The calibration was carried out in the laboratory, according to the manual, at 12 different water contents, using soil collected in two pits from each site and then all mixed (Campbell Scientific, 2016). At each water content, measurements with the TDRs (both rod-length) were compared with water contents derived from oven drying (three cylinder samples were collected for each water content, dried at 105°C during 24h).

In Paper II, the VWC was measured at three points in each of the 117 vegetation plots (evenly distributed within the plot) using a portable TDR sensor (TRIME-PICO64, HD2, IMKO Micromodultechnik GMBH, rod length 16 cm, universal soil calibration). More details on the measurements are given in Paper II.

Weather stations were installed at the three sites including devices for measuring air temperature, humidity, global radiation, wind speed and precipitation in Hagfors and at site R, and air temperature and precipitation at site T (Paper II and IV). Groundwater levels were measured bihourly in downhill positions at sites R and T (Paper II) and four times during the growing season in Hagfors (Paper IV).

## 4.2 Measurements of rut depths (Paper I, III)

In Paper III, rut depth was assessed both using manual measurements with a ruler, each metre along all the plots with no ground protection (Figure 1), and using a handheld GNSS (Global Navigation Satellite Systems) receiver, model Topcon GRS-1 (www.topconpositioning.com/), on all study plots (the most well-known GNSS system is the Global Position System, GPS). At the R and T sites, the mean number of registrations varied between 2.6 and 3.6 registrations per metre along the slopes (rut depth measurement error was approx. 4 cm). The original soil surface (at the place of the wheel tracks) was interpolated from the surrounding ground surface (not including lateral bulging) with Triangular Irregular Networks in ArcMap (Figure 4 in Paper III). The GNSS measurements were carried out in the autumn of 2013 at both sites. The manual measurements were made the day after driving at site T and the year after driving at site R. These later measurements agreed well with manual depth measurements at 2-m distance, made four days after the treatment at site R (estimated random error in depth was 2.8 cm).

In Paper I-II, rut depths at the sampling locations were measured from the original soil surface using a ruler.

## 4.3 Vegetation survey (Paper II)

In Paper II, a vegetation survey was carried out in 2017 to study the vegetation patterns 4-5 years after off-road traffic. Starting at a distance of 1–6 m from the lowest end of the plots (no soil protection) on the undisturbed soil, approx. 4 m to the left of the wheel tracks, vegetation plots (0.4×1 m) were laid out at 10 m intervals at 10 locations (9 at site T, slope A). Parallel to the plot in the undisturbed soil, two other plots were laid out, in the wheel track and between wheel tracks, respectively (Figure 1). As described in Paper II, the following data were recorded for each of the 117 vegetation plots: wheel track depth, the area of ponded water (%), the area with bare soil (%), heights of planted pine seedlings (if present) and self-seeded seedlings of pine or other tree species. Finally, the occurrence of species and their cover (at estimated full seasonal development) were recorded. The species were divided into the following groups: self-seeded tree seedlings, *Ericaceae*, graminoides (species with grass-like morphology), mosses, and other species (Appendix A in Paper II). Shannon diversity indexes were calculated for all plots.

Weighted mean Ellenberg indicator values (Paper II, Ellenberg *et al.*, 1991) were used for each plot and Ellenberg indicator to determine whether there were any differences between microsites, sites and slope positions in the growing conditions indicated by vegetation. The following Ellenberg indicators were used:

- soil moisture (F, where 1 indicates that the plant prefers xeric conditions, 5 mesic, 9 wet and 12 underwater conditions)
- disturbance (D, where 1 indicates that the species can colonize and compete in already closed forests and 9 that the species quickly colonizes bare soil and disappears quickly in the succession)
- light (L, where 1 indicates that the species prefers deep shade and 9 full light)
- reaction of soil (R/pH, where 1 represents extremely acidic conditions and 9 alkaline)
- Nitrogen/fertility (N, where 1–9 indicates an increase in fertility).

See Paper II for more details concerning the Ellenberg indicator values.

## 4.4 Soil sampling and physical laboratory analysis (Paper I, II, IV)

*Figure 5.* Sampling of the mineral soil with a sliding-weight core sampler at Rotflakamyran in 2012 (Photo: Annemieke Gärdenäs, SLU).

All core sample cylinders used in Paper I, II and IV were made of steel with an inner diameter of 72 mm and a height of 50 mm. A sliding-weight core sampler was used for sampling of the mineral soil, after the ground vegetation, litter and humus layer had been carefully cut away with a knife (Figure 5).

All details concerning the soil physical analysis of the soil samples are provided in Paper I, but the procedure is the same for the other studies and is briefly described below. Soil water contents at six tension steps were determined gravimetrically according to the ISO standard (ISO11274, 1998) at 0.5, 2, 5, 10, 60 and 1500 kPa. Saturated hydraulic conductivity ($K_{sat}$) was measured between VWC measurements made at 10 and 60 kPa using the constant head method (Andersson, 1955). Dry bulk density (BD) and porosity were calculated after drying the core samples for three days at 105°C. At each core sampling point, loose soil samples were also collected and used to determine particle size distribution (ISO11277, 2009), organic matter content, and particle density. Stones (>20 mm) were excluded from analysis of the loose samples, but included in the analysis of core samples.

## 4.5 Image analysis (Paper I)

Image analysis involves a number of steps from the actual scan to when the data can be retrieved from the scanned images. See Paper I for a detailed explanation of the procedure of image acquisition, reconstruction, illumination correction, image segmentation and feature extraction used on the 35 core samples from site R (all) and 12 samples from site T (one of the three replicates from each point and treatment). An overview of the different steps is provided below:

The image acquisition was carried out using the Phoenix v|tome|x m XRT (General Electrics) installed at the Dept. of Soil and Environment at the Swedish University of Agricultural Sciences, Uppsala. Circa 70 minutes were needed to scan one soil sample, collecting 2000 radiographs (images), each with a resolution of 50 µm. A copper filter was used to decrease beam-hardening artefacts, but further illumination correction was necessary after image reconstruction, as the steel cylinders caused severe beam-hardening and X-ray scattering, with ellipsoidal artefacts in the horizontal cross-sections of the images as a consequence (Figure 2 in Paper I). The software datos|x 2.1 was used for building a 3D image of the 2000 radiographs, which resulted in a 16-bit grey-scale resolution. For the advanced illumination correction, at tool in the ImageJ-plugin SoilJ (Koestel, 2018) was developed and used (Paper I).

Image segmentation is the procedure whereby each pixel/voxel in an image is classified as either black or white, according to the grey-scale value in that point; this creates binary images that can be used for feature extraction (Figure 3 in Paper I). The image segmentation steps are described in detail in Paper I. The 3D images needed to be cropped due to some remaining illumination artefacts, and in the end the volume of the segmented images was 124 cm$^3$ (diameter: 66 mm, height: 37 mm), compared to the volume of the soil sample of 204 cm$^3$.

To extract and calculate features such as total pore volume, pore thickness, and mean orientation of each pore cluster, *Particle Analyser* in BoneJ (Doube *et al.*, 2010) was used on all pore clusters (connected pore space in the 3D images) $\geq$14 voxels ($\approx$0.002 mm$^3$). Thickness (pore diameter) in a given point is defined as the diameter of the largest sphere that fits within the structure and contains the point. The distribution of thicknesses represents the pore size distribution that was resolved by the X-ray scanner. The 3D connectivity of the structural pore network was evaluated by investigating the percolation properties and the Euler-Poincaré characteristics ($\chi$); see Paper I for details. A high connectivity of the pore cluster is indicated by large negative values of the Euler-Poincaré characteristics. To avoid bias when calculating mean values of all pore clusters in a sample, the mean pore thickness, mean pore cluster orientation and Euler characteristics were weighted by the fraction each pore cluster contributed to the total pore volume (Paper I). This was necessary because 80–90% of the detectable pores belonged to the same pore cluster, and at the same time there was a high number of pore clusters with diameters close to the image resolution contributing very little to the total porosity.

## 4.6 Using threshold values for estimating growing conditions (Paper II, IV)

The soil temperature and water content conditions in the microsites were evaluated by, among other methods, assessing the number of days with a daily mean value above or below threshold values for seedling growth (Paper IV). In Paper II, the focus was on the number of days in which aeration might have been restricted, i.e., when the VWC was above a certain threshold value. For a background of the chosen threshold values, see Paper IV. The average threshold value as well as the average value ± the standard deviation was used to test whether the results were sensitive to a chosen threshold value.

The selected upper VWC threshold corresponded to an air-filled porosity of 0.10 $m^3$ $m^{-3}$ (Wall & Heiskanen, 2003; Xu *et al.*, 1992), which at Hagfors equalled a VWC of 0.34 $m^3$ $m^{-3}$ at 20 cm depth and 0.26 $m^3$ $m^{-3}$ at 45 cm depth, based on the soil physical properties of the samples collected in 2011. At site R, the upper VWC thresholds were 0.49 and 0.32 $m^3$ $m^{-3}$ in the undisturbed soil and wheel tracks, respectively. At site T the corresponding values were 0.45 $m^3$ $m^{-3}$ in the undisturbed soil and 0.38 $m^3$ $m^{-3}$ in the wheel tracks.

## 4.7 Model set-up in Hydrus-1D (Paper II)

Hydrus-1D (Šimůnek *et al.*, 2016; Šimůnek *et al.*, 2008) is a one-dimensional modelling environment (public domain) that can be used for analysis of water, heat and solute movement in soils. The program solves Richards' equation numerically, for both saturated and unsaturated water flow, and the Fickian-based advection dispersion equations for solute and heat transport. In the model set-up used in Paper II, only the hydrological part of the model was used (not the heat and solute transport), including root water uptake. The van Genuchten-Mualem single-porosity model with an air entry value of -2 cm was used to describe the soil water retention and hydraulic conductivity functions (Vogel *et al.*, 2001; van Genuchten, 1980). The Penman-Monteith equation (Monteith, 1965) was used to calculate evapotranspiration, and the field vegetation was static (i.e., had the same height and cover) during the simulation period (the growing season in 2017 and June 2018). The root water uptake (down to 25 cm soil depth) was based on the S-shape model (van Genuchten, 1987) and thus, only limited during dry conditions.

Hourly vertical water flow and root uptake were simulated in the wheel tracks and in the undisturbed soil microsites in the upper part of the slopes (recharge area), independent of adjacent conditions. Site T was selected, as the wheel tracks in the upper 50 m of the slopes were shallow (0-5 cm), and the traffic impact was mostly in the form of soil compaction, i.e., the rutting profile was negligible for the hydrology, and thus, the groundwater level (the lower boundary condition) could be assumed to be the same in both microsites. Groundwater level measurements from approx. 12 m up from the down-slope end of the plots in a control area were used, with the assumption that the groundwater level followed the topography along the slope mimicking conditions higher up. The upper boundary conditions, i.e., the atmospheric conditions, were also the same for both simulated microsites, based on the weather measurements from the sites (section 4.1).

A 1-m-deep soil profile was used for describing both microsites, and the soil properties were based on the soil physical properties measured in Paper I (mean values for site T) and some additional measurements made in deeper soil pits on the same sampling occasion as in Paper I. The only differences between the two modelled microsites were the soil hydraulic properties in the upper 0-5 cm of the mineral soil. For a more detailed description of the model set-up, see Paper II.

The VWC of the 15 cm-deep TDRs in locations *bot2* and *bot3* were compared with the simulated water content at 8 cm depth in the undisturbed soil and wheel tracks, respectively, and the VWCs of the 30 cm TDRs were compared with the simulated VWC of the subregion 0–30 cm of the undisturbed profile (Figure 1, section 3.1.3 and 4.1). To validate the model set-up, weather conditions, groundwater, and VWC measurements from June 2018 were used, employing the same parametrization as in 2017. With this approach, the impacts of different weather conditions on the differences in water flows and pressure heads between the two microsites were tested.

## 4.8 Statistical methods (Paper I, II, IV)

The statistical methods used in Paper I, II and IV are briefly described below. For details, see the respective paper. The free software R was used for all statistical work. P-values below 0.05 were considered significant in all analyses.

*Linear mixed-effect models* were used in Paper I (function “lme” in the package “nlme”) to analyse the effect of treatment (traffic or no traffic), site (R or T) and sampling location. In Paper II, linear mixed-effect models were used to examine the effect of microsite (undisturbed soil, wheel tracks and between-tracks), site (R or T) and sampling location (1–10). In Paper IV, linear mixed-effect models were used to test whether there were any differences in daily means of VWC and soil temperature at the two depths and to analyse effects of microsite, precipitation, air temperature, relative depth within microsite and time. In Paper IV, treatment was defined as microsite (furrows, ridges, between furrows and control). Necessary transformations were carried out on the response variables to acquire normally distributed residuals (specified in each paper). Post hoc tests were carried out on the results of the mixed-effect linear models. In Paper I, significant effects were calculated using F-tests, and Restricted Maximum Likelihood was used to estimate the variances of the random effects. In Paper II and IV, Wald tests were used as post hoc tests for the pairwise comparisons (function "emmeans"), including the Tukey method for adjustment of p-values.

*Kendall's correlation test* was used in Paper I to determine whether the degree of compaction in the wheel tracks was correlated with different inherent soil properties of the undisturbed soil.

*Linear regression* was used in Paper I to compare the porosity values obtained from the image analyses with the porosity values calculated from the soil physical analyses in the laboratory. In addition, logarithmically transformed $K_{sat}$ values from the soil physical analyses in the laboratory were compared to the image analysis results (Table 3 in Paper I). Linear regression was also used in Paper IV to test whether distance to the nearest seedling had any significant relationship with soil temperature or soil water content (measurements from 2011).

*Fisher's exact test* was used in Paper II and IV to test whether there were any differences between microsites in the numbers of days when a certain threshold value was exceeded.

The Hydrus simulations in Paper II were evaluated by comparing the *root mean square error (RMSE)* and the *coefficients of determination ($R^2$)* for the predicted versus observed values.

# 5 Results and discussion

This chapter is divided into themes following the specific objectives of the thesis. Both the unintentional and intentional soil disturbances are discussed where applicable. However, the bulk of the results presented in each section come from either the off-road traffic studies (Paper I–III) or the soil scarification study (Paper IV).

## 5.1 Changes in soil physical properties caused by forestry operations (Paper I, IV)

Off-road traffic in the stony and sandy recharge areas (upper parts of the slopes) changed the soil physical properties (top 5 cm of the mineral soil) as follows: dry bulk density, VWC at sampling and at $\leq$ -5 kPa increased, while VWC at -0.5 kPa, porosity and $K_{sat}$ decreased (Table 1 and Figure 5 in Paper I). Mean BD of both sites was 1.39 g cm$^{-3}$ in the wheel tracks, compared to 1.13 g cm$^{-3}$ beside the wheel tracks in the undisturbed soil. The differences at site R were larger than at site T (1.44 vs. 1.07 and 1.35 vs. 1.19 g cm$^{-3}$, respectively, for the wheel tracks vs. undisturbed soil). As a result, porosity was reduced more at site R (24%) than at site T (12%). The reduction was mainly in pores with diameters > 60 µm (calculated from the water retention measurements), where the wheel track volume of pores was reduced by 70% and 52% compared to the volume of pores in the undisturbed soil at sites R and T, respectively. This reduction in larger pores was corroborated by the results of the image analysis.

The image analysis revealed that the pore structural network resembled the appearance of root networks (Figure 7 in Paper I). Ninety per cent of the pores in the undisturbed soil were connected (80% in wheel tracks) in one large pore cluster, which went from the top to the bottom of the sample (i.e., was percolating), except all three wheel track samples at site R, slope A, *top3*, and one wheel track sample from slope B, *top1* and *top3*, respectively. Maximum pore thickness was larger in the undisturbed soil than in the wheel tracks, as was pore connectivity (Euler characteristics). However, the mean pore cluster thickness and orientation were not significantly different between the treatments (Table 2 in Paper I).

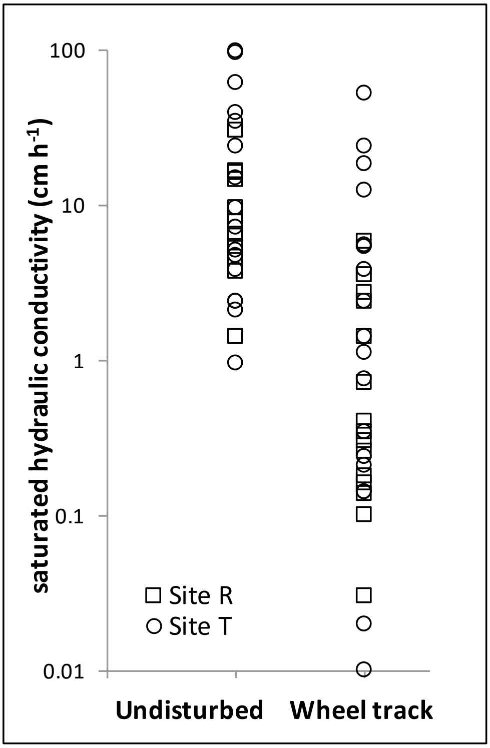

*Figure 6.* Saturated hydraulic conductivity ($K_{sat}$) in the undisturbed soil and in the wheel tracks, respectively. Site R is marked squares and site T with circles. Note the logarithmic scale on the x-axis.

Of all differences in soil physical properties between the wheel tracks and the undisturbed soil, the difference in $K_{sat}$ was the largest (Figure 6). One of the explanations of the large difference in $K_{sat}$ between the wheel tracks and the undisturbed soil is the reduction in larger pores, together with less connectivity in the wheel tracks. Smaller total pore space and lower pore connectivity also reduce gas diffusion and mass flow, which increases the frequency and duration of anoxic conditions (Goutal *et al.*, 2012a). In Paper I, 50% of the samples at site R and 25% of those at site T had air-filled porosities of less than 0.1 m$^3$ m$^{-3}$ during the dry summer conditions at sampling. This limit is often used as a critical threshold value for soil aeration (Paper II and IV; Wall & Heiskanen, 2009; 2003; Xu *et al.*, 1992). Longer periods of high water content may also be expected as the wheel tracks will drain more slowly due to a higher water holding capacity at water tensions of -5 kPa and drier.

After disc trenching, no differences in soil properties between treatments were discernible in the mineral soil at the same reference depth (Figure 1) regarding porosity and water retention curves. However, if the soil sampling would have included the top soil of the ridges, above the old ground surface, there would probably have been some differences, and they would have changed with time. Further, the possibility that the wheels of the disc trencher compacted the soil beneath the soil scarification treatment cannot be ruled out. However, both Burton *et al.* (2000) and MacKenzie *et al.* (2005) found similar BD in the disc-trenched furrows (ca. 10 cm deep) at 0–10 cm depth as in the control at 10–20 cm depth, which did not indicate any additional compaction by the disc-trencher itself – a finding in line with the soil property results from Hagfors (data not shown).

## 5.2 Changes in dynamics of temperature and water after forestry operations (Paper II, IV)

### 5.2.1 Soil temperature dynamics

The median soil temperatures, 4–5 years after off-road traffic, at 0–10 cm depth (including the humus layer) were different for all microsites in location *bot1* (downhill), with highest values between-tracks and lowest in the undisturbed soil (Figure 7a). In location *bot2*, the undisturbed soil was cooler than the other microsites (Figure 7b), whereas there were no significant differences uphill (Figure 7c). The significant higher temperatures in the between-tracks in the downhill positions than in the undisturbed soil and wheel tracks are probably due to the elevated position (rut depth approx. 70 cm on both sides). Higher up in the slopes, the ruts are less deep and thus the differences in elevation have less impact on the soil temperature. In addition, the higher temperatures in the between-tracks and wheel tracks could be due to a thinner humus layer and a lower total cover of vegetation, especially mosses, than in the undisturbed soil (data not shown). A thick moss cover and depth have been found to reduce soil temperature amplitudes (Soudzilovskaia *et al.*, 2013). An increase in the moisture content of the mosses is related to both an increased heat capacity and thermal conductivity, but the compound effect is that temperature amplitudes under the moss cover are slightly decreased with increasing moisture content (Soudzilovskaia *et al.*, 2013).

The soil temperatures during the six seasons following soil scarification in Hagfors were affected by the disc-trenching treatment at the reference depth of 20 cm in all microsites (Table 3 and Figure 2 in Paper IV). The temperatures beneath furrows, ridges, and between furrows were all warmer than the control microsites. The heating effect was largest in the furrows where the temperature was still increased, compared to the control microsite, in the 6th growing season after soil scarification. The treatment effect in the furrows probably depended on a combination of the sensors being closer to the soil surface (Figure 1) and the removal of the insulating organic layer from the furrows (Bhatti *et al.,* 2000). However, in the loose and elevated mixture of organic material and mineral soil in the ridges (brown in Figure 1), the soil temperatures were presumably higher during warm days, as previously found by, for example, Knapp *et al.* (2008) and Kubin and Kemppainen (1994). This probable extensive heating during warm days may be one explanation for why the soil beneath the ridges was warmer than the soil in the control microsite, despite the sensors in the ridges being on average 7 cm deeper down from the new ground surface than the sensors in the control microsite. An additional explanation is that the thick organic layer insulated the soil below the ridges during cold days and abated the cooling.

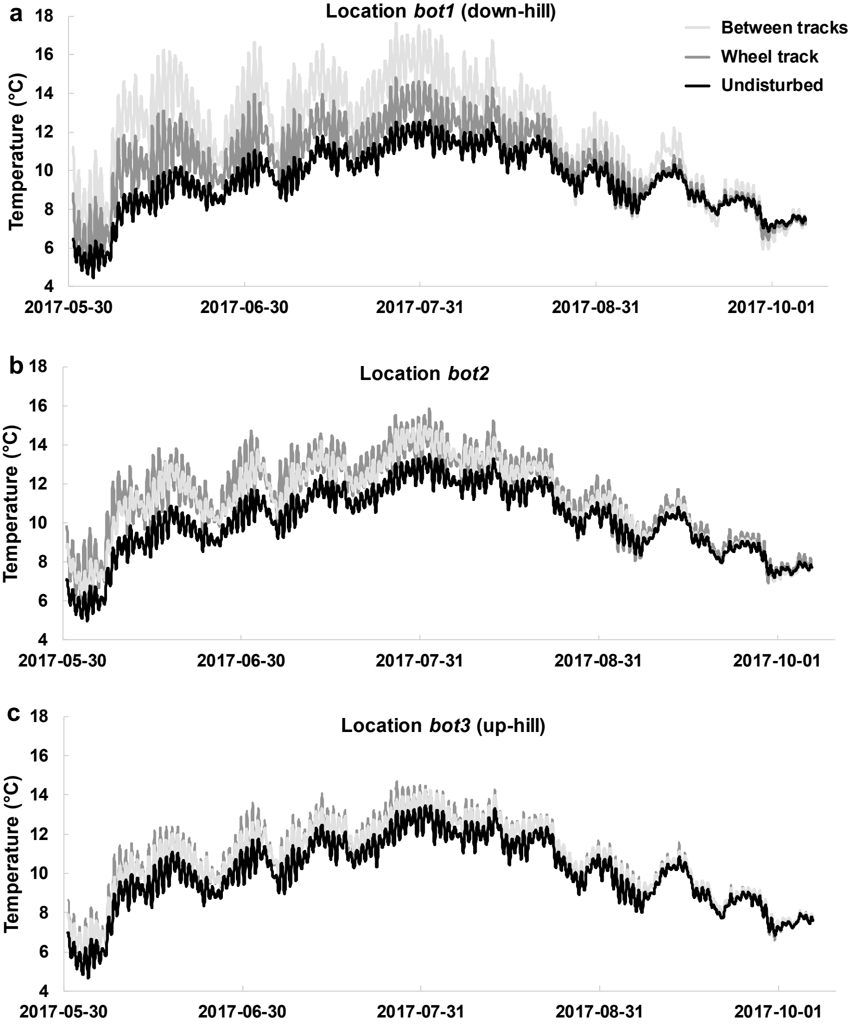

*Figure 7. a-c)* Hourly values of soil temperature at location *bot1-3* (mean values of the measurements from both sites) in the undisturbed soil (black, n=4 in each location), wheel tracks (dark grey, n=2) and between the wheel tracks (light grey, n=2) during the growing season of 2017.

In the end of the study period, there were no longer any differences in soil temperature among the disc-trenched microsites, probably because re-growing vegetation began covering the bare soil in ridges and furrows, with an insulating effect as a result, in addition to shading the soil and changing the albedo. According to the results of Johansson *et al.* (2013) from the same experimental site, there were no longer any differences in ground and field vegetation biomass among the disc-trenched microsites in the fifth season. Erosion caused by rain and compaction by snow could be other explanations for the changes over time: the mean height of the ridges decreased 45% between 2006 and 2012, while the depth of the furrows decreased 21% during that period (Paper IV).

The daily soil temperature amplitude (May–October) at 20 cm depth was initially about five times higher in the furrows than in the other microsites (Figure 4 in Paper IV); moreover, the seasonal amplitude was higher, indicated by the standard deviations of seasonal means (Table 3 in Paper IV). After three years, the mean daily temperature amplitude in the furrows declined and became closer to the amplitudes in the other microsites, probably due to the same mechanisms as discussed above.

### 5.2.2 Soil water dynamics

Wetter conditions in wheel tracks are often found in soil disturbance studies (Fründ & Averdiek, 2016; Wei *et al.*, 2016; Ares *et al.*, 2005), and this was also the case 4–5 years after off-road traffic at site R and T (Paper II). The long-term effect was supported by the species composition, which through the Ellenberg indicator value for soil moisture, F, indicated higher VWC in the wheel tracks than in the other microsites (Table 2 in Paper II). Similarly, the measurements with the portable TDR in the vegetation survey plots indicated that the VWC was highest in wheel tracks and lowest between the tracks (Table 2 in Paper II). When studying the seasonal medians and mean for VWC at the permanent measuring points, no differences between microsites were significant in the statistical models. This is not surprising, given the high variation in VWC locally and the relatively low number of permanent TDRs (undisturbed soil: n=15, wheel track: n=8 and between-tracks: n=7) distributed across two sites and 3-4 locations.

At site T, in the upper parts of the slopes, the simulated pressure heads with Hydrus-1D were similar between the undisturbed soil and the wheel tracks, except for the top humus layer where it was drier on some occasions in the undisturbed soil (Figure 3 in Paper II). During the driest periods, the average root zone pressure head was also influenced by means of more negative pressure heads in the undisturbed soil (Figure 3 in Paper II). The groundwater level was lower in June 2018 than in June 2017, despite similar precipitation amounts during the two months, and as a consequence, the surface layer became even drier in the undisturbed soil, compared to the wheel tracks (Figure 3 in Paper II). However, no differences were found in water balance between the two microsites, which is not surprising given that the same weather data, plant descriptions and groundwater level data were used for both microsites. Despite small differences in pressure heads at the 8-cm depth, in the middle of the upper mineral soil layer, the simulations did corroborate a higher VWC in the wheel tracks than in the undisturbed soil (Figure 4 in Paper II), which can be explained by the water retention curves, where the wheel tracks will get a higher simulated VWC at water tensions higher (i.e., more negative) than -2 kPa (results from both sites together in Figure 5 in Paper I). Close to saturation, the VWC in the undisturbed soil will be higher than in the wheel tracks, due to the reduced macropore space in the wheel tracks (Figure 4 in Paper II).

The VWC at 20 cm reference depth beneath the disc-trenching treatment in Hagfors (Paper IV) was generally small (differences in seasonal means 0.01–0.04 $m^3 m^{-3}$ between the microsites). The maximum difference (May–October) was 0.06 $m^3 m^{-3}$ between the ridge and control microsites. In any event, there were significant differences between the treatments at 20 cm: during the first growing season, the VWC was lower beneath the furrows than below between furrows and ridges (similar to contents in the control), but increased over time (Figure 2, Table 3 in Hansson *et al.*, 2018b). After three summers, the VWC in the furrows was no longer significantly different from the VWC in the between furrows, and after the fifth seasons it did not differ from the VWC in the ridges. The soil beneath the ridges and between furrows never significantly differed with respect to VWC, while the 20 cm reference depth in the ridges was wetter than that in the furrows during all years, except the last. This could have been due to the additional mixed layer in the ridges hindering upward capillary movement and evaporation and the greater distance to the soil surface at the measuring points (Figure 1). However, the sensors in all microsites were at the same distance from the groundwater level, which probably contributed to the small differences in VWC between the microsites, especially as the porosity was similar in the different microsites (Table 2 in Paper IV).

## 5.3 Reducing severe rutting and soil compaction (Paper I, III)

The soil protection study at sites R and T (Paper III) indicated that logging residues (slash) or logging mats were efficient in preventing severe rutting and mineral soil exposure, especially in the lower parts of the slopes (Figure 8; Figure

10 in Paper III). In the plots with no soil protection, there was usually a distinguishable increase in rut depth somewhere along the slopes (Figures 8–10 in Paper III) and a slight decrease in rut depth at the end of the slopes. The decrease in rut depth at the very end of the slopes was probably due to the fact that only a part of the vehicle passed over it. The sharp increase in rut depth, especially at site T (20-50 m from the end of the slopes) could be due to a combination of changes in soil texture (an increase in silt content and decrease in gravel and stones) and an increase in VWC along the slope (Figures 7, 9 and 11 in Paper III; Figure 2 in Paper I). At site R, the soil texture was similar along the slopes, and the rut depths were more variable along the slopes, even though smaller rut depths were registered in the upper 40 m of slope A, and in the upper 35 m of slope B (Figure 8 and 10 in Paper III). The variable rut depth in the rest of the slope may be explained by the occurrence of boulders, stumps, and microtopographic differences along the slope causing differences in the local VWC. The smaller rut depth at the top of the slopes in site R is probably due to the high stone and boulder content (Paper I).

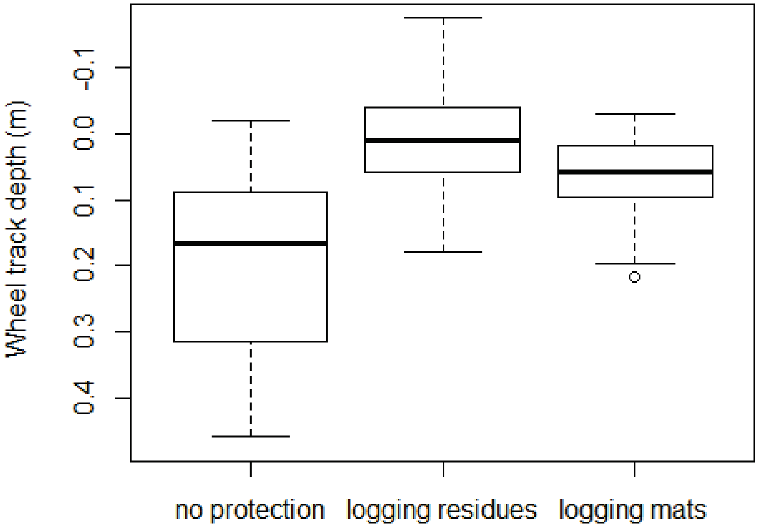

*Figure 8.* Boxplot of the variation in wheel track depths (both right and left). Each input value is a mean of the track depth in a 10 m segment of the slopes, in total 45 segments (90 input values) divided on four slopes for the treatment plots with no soil protection and logging residues, respectively, and 25 segments (two slopes, only site R) with driving on logging mats. The extra plots with driving without soil protection at site T are not included. The thick black lines are medians; the lower and upper limits of the box are the first and third quartile, the whiskers are 1.5 times the interquartile range from the top/bottom of the box to the furthest data point within that distance, and the circle is an outlier beyond that distance.

Logging residues both reduced rut depth and decreased the area of bare mineral soil after off-road traffic (Figure 8). However, logging residues were pressed into the ground. On average, 43 kg m$^{-2}$ logging residues were applied along the plots (Table 1 and Figure 3 in Paper III). When driving, the residues were compacted and probably partly pressed into the ground. The aboveground thickness of logging residues between the wheel tracks were on average 0.17 m at site R and 0.055 m at site T after driving (Paper III). The application of logging residues along the whole slopes also caused 10–20 additional passes in the top segment of the slopes. In operational forestry, however, the tops and branches from the harvested trees around the harvester are usually directly applied on the ground where the soil needs to be protected. At low-productive stands like site R and T, however, the trees around the harvester might not produce enough tops and branches to protect the soil, and thus, logging residues from other parts of the stand (with higher bearing capacity) may be transported to the sensitive areas. However, not as many additional passes with the forwarder will be needed, as in this study where all residues were transported to the plots from piles beside.

The use of logging mats was efficient in reducing deep ruts in the wet parts of the low slope positions. In this experiment, however, logging mats were applied along the whole slopes for comparison between treatments. Driving on logging mats in the upper parts of the slopes turned out to be a difficult job for the operator, especially when driving in reverse uphill. The mats did not stay in place due to the uneven microtopography, boulders and stumps. The humus layer was scraped and mineral soil was exposed when the mats moved during driving.

Even though severe rutting can be avoided by protection measures like using logging mats or harvest residues, the soil can still be compacted. Silty soils are known to be particularly sensitive to soil compaction (Steber *et al.*, 2007; Wästerlund, 1985), which was also found in Paper I, where silt was the only particle size class that was correlated with the degree of soil compaction. To avoid soil compaction, the most important tool is planning, both before and during the operation. Planning skid trails has become easier during recent years thanks to planning aids such as depth-to-water and soil type maps that can be used in the harvesters and forwarders (Mohtashami *et al.*, 2017; Ågren *et al.*, 2015). Another important step to minimize the impact of soil compaction over the whole clearcut is to concentrate the traffic to planned routes, which has been recommended and implemented, e.g., in Germany and Quebec, Canada (MNRQ 1994, described in Lorente *et al.*, 2012; Horn *et al.*, 2007; Vossbrink & Horn, 2004).

## 5.4 Consequences of soil disturbances for field vegetation, seedling establishment and growth (Paper I, II, IV)

### 5.4.1 Exceedance of thresholds for optimal seedling establishment

Restricted soil aeration 4–5 years after off-road traffic may have been a problem in the wheel tracks during several days in the growing season (82% of the days in site T and 29% of the days in site R, Table 3 in Paper II). Soil aeration in relation to soil compaction has been studied in more detail by others: e.g., Fründ and Averdiek (2016) found no recovery of soil aeration (12–24 cm depth) during the first three years after harvester and forwarder traffic on skid trails in Germany. An air-filled porosity of less than 0.10 $m^3 m^{-3}$ has been found to reduce growth of both Norway spruce and Scots pine in Finland (Wall & Heiskanen, 2009; 2003).

In the sub-xeric, coarse-textured soil in Hagfors, excessive soil water was not a problem in the topsoil (<20 cm depth), neither in the control nor in the disc-trenched microsites, and soil temperatures were not too high for optimal seedling growth (Table 4 in Paper IV). In general, the furrows (where the seedlings were planted) were warmer than the control area, which may have promoted root growth, allowing the roots to enter the nutrient rich ridges more quickly. However, the three chosen thresholds for too low temperatures (4, 5 and 8 °C) gave somewhat different results (Paper IV). The differences in results between two thresholds were enhanced by the higher seasonal amplitudes in the furrows and more pronounced if the thresholds were close to the mode of the normal distribution curve for the data.

After disc trenching, the number of days per season with assumed unfavourably dry conditions (threshold value equalling -0.1 MPa) was highest in the control (92), followed by the soil beneath the furrows (71), the between furrows (32), and the ridges (14) at the 20 cm reference depth (Table 4 in Paper IV). Thus, disc-trenching improved the soil water conditions at this dry site. Newly planted tree seedlings have been found to have >50% lower water uptake rates than established ones, and according to Örlander (1986), the reduction can persist for more than two years after planting.

After off-road traffic, the simulations of root-zone pressure head in the wheel tracks and in the undisturbed soil in the upper parts of the slopes at site T never resulted in an exceeded threshold for unfavourably dry conditions for seedling establishment (-0.10 MPa, Figure 3 in Paper II). However, in June 2017, the top of the humus layer became this dry on one occasion. The manual test process of tuning the model parameters and input values also indicated that the root zone pressure heads were more sensitive to the depth of the groundwater level than to differences in vegetation root up-take.

The specific site conditions and vegetation type determine whether or not field vegetation changes the soil water conditions for the seedlings. For example, Fleming *et al.* (1994) found that the removal of herbaceous vegetation caused by site preparation (including scalping) increased root zone water content down to 19 cm. Sutinen et al. (2007), on the other hand, found that transpiration by ground and field vegetation in northern Finland did not affect soil water content, and Nilsson and Örlander (1999) concluded that tree seedlings were not seriously affected by competition for water from grass-dominated field vegetation in southern Sweden. Self-seeded, as well as planted seedlings, benefitted from the slow development of field vegetation at the Hagfors site (Paper IV; Rappe George *et al.*, 2017).

### 5.4.2 Other consequences of changes in soil physical properties for plant establishment and growth

As discussed in the previous section, the lower porosity in the wheel tracks together with the higher water holding capacity (at water tensions equal to, or more negative than, -5 kPa) compared to the undisturbed soil may be beneficial during dry years. Soils with high porosity (in the topsoil), such as site R, may provide improved root/soil contact, water holding capacity, thermal regimes and/or nutrient uptake after moderate soil compaction (Steber et al., 2007, in combination with forest floor removal). However, at some point the compaction leads to bulk densities in the range where the soil may be too compact for optimal root growth. Norway spruce is found to be more sensitive to compaction than Scots pine (Wästerlund, 1985). According to Zhao *et al.* (2010), bulk densities of 1.3–1.5 g cm$^{-3}$ could start to impede growth of various conifer species after some years. In Paper I, all wheel track samples, except four, were within 1.3–1.7 g cm$^{-3}$. The areas at sites R and T with BD as high as 1.6–1.7 g cm$^{-3}$ in the wheel tracks were presumably too compact for optimal root growth, and this may be one of the explanations for why some areas in the upper parts of the slope still had bare soil in the wheel tracks 4–5 years after off-road traffic (Paper II). In mid-slope positions, both planted and self-seeded seedlings seemed to get a good start, especially in the between-tracks microsite, but this could not be detected with the statistical and experimental design used in Paper II (Hansson *et al.*, 2019). In the lower parts of the slopes, there were also areas with bare soil in the wheel tracks, and there, the slow establishment could be due to restricted aeration and periodically standing water at, for example, snowmelt or high precipitation events (Paper II). As discussed above, air-filled porosity below

0.10 $m^3$ $m^{-3}$ has been found to reduce seedling growth, but it may also severely limit microbial activity in soils (Brady & Weil, 2001). Mycorrhiza is found to be more sensitive to soil compaction than bacteria, and with a reduction in mycorrhizal fungi, water and nutrient uptake may be hampered (Hartmann *et al.*, 2012; Schnurr-Ptüz *et al.*, 2006).

Soil texture is always important, both for the severity and effect of intentional or unintentional soil disturbance. After soil scarification, Heiskanen and Rikala (1998) found that soil texture, in combination with VWC, was essential for root-soil interactions and the success of the establishment of containerized seedlings. The root-soil interaction of replanted seedlings develops over the first few seasons, and during this time sufficient water availability is particularly important (Örlander, 1986). During dry conditions, the risk of water and nutrient stress for newly planted containerized seedling was higher in fine-grained than in coarse-textured soils, according to Heiskanen and Rikala (1998), who explained this in relation to the high penetration resistance for roots in the dry fine-grained soil. They found no differences in root growth between the different textures during moist conditions. Generally, the fine fraction content (particles with diameters <0.06 mm) of the soil is an important predictor of the abiotic growing conditions for vegetation, because for example VWC and air-filled porosity at field capacity are closely related to the fine fraction content (Heiskanen *et al.*, 2018).

### 5.4.3 Vegetation response to soil disturbances

All three study sites included in this work are low-productivity boreal sites (Table 1) where the regeneration of trees and reestablishment of vegetation are slow processes. As discussed above, sites R and T had areas of bare soil, especially in the wheel tracks, four to five years after clearcutting and off-road traffic. The reestablishment of vegetation varied between microsites with less *Ericaceae* and mosses and more graminoides in the wheel tracks than in the undisturbed soil. This pattern was also found after stump harvest (another unintentional soil disturbance operation) in Fennoscandia (Andersson et al., 2017; Hyvönen et al., 2016). Less moss cover was also detected in the between-tracks than in the undisturbed soil in Paper II.

In Paper II, the total number of species was small (median 7, range 0–11) in each 0.4 $m^2$ plot, and no differences were detected between microsites, locations along the slopes and sites concerning the number of species present. Moreover, no differences were detected between the number or cover of self-seeded tree seedlings, diversity (Shannon DI), light tolerance (L), fertility (N), pH (R) or disturbance (D) between microsites (Table 2 in Paper II). The average height of planted seedlings was 29 cm in the wheel tracks and 31 cm between tracks. The plots in the undisturbed area were between two rows of planted seedlings, and thus, no planted seedlings were present in those plots (Paper II). However, other studies have been carried out, but not yet published, on the development and survival of the planted seedlings at sites R and T.

In Hagfors, disc trenching provided a head start for the seedlings, measured by seedling height, diameter, biomass and survival rate (Johansson *et al.*, 2013). One of the reasons for this was that the seedlings planted in the furrows were less affected by herbivory (mammals and pine weevils) compared to the seedlings planted without disc trenching (Johansson et al., 2013). Similarly to sites R and T, the field layer growth was rather slow at the Hagfors site, also in the areas with previous nitrogen fertilization (Rappe George et al., 2017). The modelling study from Hagfors by Rappe George *et al.* (2017) indicated that more nitrogen was accumulated in the pine seedlings than in the field layer in the disc-trenched areas, whereas the opposite conditions were found in the undisturbed areas.

## 5.5 Environmental consequences of soil disturbances (Paper I–IV)

As mentioned in the introduction, forestry operations may affect the surrounding ecosystems, and the changes in soil physical properties, water and temperature dynamics may affect element leaching and green-house gas emissions.

### 5.5.1 Consequences of changes in soil physical properties for element leaching

The following three results from Paper I-III may have implications for element or particulate transport to nearby streams.

First, the wheel tracks themselves may channel water and eroding particles from the exposed mineral soil to nearby streams. This will be enhanced by the lower $K_{sat}$ (and thus infiltration capacity) in the wheel tracks. In operational forestry, however, the wheel tracks commonly run across the slopes, in contrast to Paper I–III, and thus there are more possibilities for the runoff and eroded material to infiltrate or sediment before reaching the nearest stream.

Second, the compaction of the mineral soil may promote overland flow or lateral flow through the humus layer (if still present) in the wheel tracks. The latter may increase the amount of dissolved organic material in small streams, if they are hydrologically connected (Ledesma *et al.*, 2015; Bishop *et al.*, 2004), as the carbon-rich water within the humus layer is transported along the wheel tracks instead of infiltrating at an uphill position, where the transport time to the closest stream is years to decades (Grip & Rodhe, 2016).

Third, the higher number of days with insufficient soil aeration in the wheel tracks can promote methylation of mercury (Hg). When this occurs close to riparian areas, with short distances to streams, the methyl-Hg may reach the stream water, where it may contribute to the accumulation of Hg in fish (Eklöf *et al.*, 2018; Eklöf *et al.*, 2016). The methylation may be enhanced when logging residues are compacted and partly pressed into the soil (Blomgren, 2018). The branches and tops in the slash mats are a source of fresh organic carbon and may promote Hg methylation (Eklöf *et al.*, 2016).

The soil microclimate underneath the logging residues also changes towards a soil temperature regime with lower temperatures, less fluctuation and sometimes a higher VWC (Blomgren, 2018; Törmänen *et al.*, 2018; Ring *et al.*, 2015; Jansson, 1987). The use of logging residues as soil protection may also change the nitrogen fluxes, partly because the residues are concentrated in piles instead of being spread over the clearcut, and partly due to increased nitrogen mineralization, net nitrification and $NO_3$-N concentrations (Törmänen *et al.*, 2018; Stutz *et al.*, 2017). At the same time, however, logging residues diminish erosion and sediment export to nearby streams through less mineral soil exposure (Paper III). In future research, the potentially increased methylation caused by using logging residues as soil protection needs to be compared to the possibly increased methylation in the water-filled ruts, created when no soil protection is used, together with the increased hydrological connection between sites of Hg methylation and streams created by the ruts.

Soil scarification may also affect element leaching, and higher nitrogen concentrations in the soil water below ridges or mounds than below the control have been reported (Ring *et al.*, 2013; Piirainen *et al.*, 2007; Nohrstedt, 2000; Smolander *et al.*, 2000), which may be explained by the double amount of humus in that microsite. Nohrstedt (2000) suggested that this may be compensated in a larger scale by lower leakage below furrows. However, the modelling study from the Hagfors site, based on the same soil physical properties, soil water and temperature data as in Paper IV, did not find that the leaching of inorganic nitrogen from the ridges was counteracted by lower leaching below furrows, compared to the areas without disc trenching (Rappe George *et al.*, 2017). When the field vegetation is reestablished and the tree seedlings are beginning to form a closed stand, the nitrogen uptake by vegetation will diminish the nitrogen leaching (Bergholm *et al.*, 2015; Hedwall *et al.*, 2014; Gärdenäs *et al.*, 2003). The 6-year period following planting was not long enough for this to happen at the Hagfors site (Rappe George *et al.*, 2017).

### 5.5.2 Consequences of changes in soil physical properties for green-house gas emissions

The changes in soil physical properties by soil compaction increases the risk of poor gas-exchange and water logging, as discussed above. This leads to an altered balance of gases in the soil and shifts the bacteria community towards those adopted to low oxygen concentrations, for example methanogens and denitrifiers (Frey *et al.*, 2011; Frey, 2010; Schnurr-Ptüz *et al.*, 2006; Teepe *et al.*, 2004). If a new soil layer is created by the slipping of wheels (with a mix of humus and mineral soil), it may further reduce gas-exchange between the soil and atmosphere, resulting in increased anaerobic conditions (Teepe *et al.*, 2004). After off-road traffic, methane consumption has been found to decrease in the wheel tracks and thus, well-aerated forest soils may turn into net methane sources (Strömgren *et al.*, 2016; Frey *et al.*, 2011). Two passes with a 16 Mg forwarder in a Beech forest in Germany, were enough to cause a 40-fold increase in nitrous oxide emission from the wheel tracks (Teepe *et al.*, 2004). However, if traffic is concentrated to planned tracks, the cumulative effect of the increased green-house gas emissions to the atmosphere is small, if total emissions are considered (Teepe *et al.*, 2004). In central Sweden, Strömgren *et al.* (2016) did not find increased nitrous oxide emissions from wheel tracks at mesic sites (C/N-ratios 14-20). On drained organic soils, however, the risk of nitrous oxide emissions is probably higher (Ernfors *et al.*, 2007).

Changes in soil temperature and water content dynamics may explain the variation in carbon dioxide efflux from the soil after off-road traffic (Goutal *et al.*, 2012b; Fleming *et al.*, 2006). In addition, the destruction of pore continuity by soil compaction, obvious in Paper I, may lead to an accumulation of carbon dioxide in the soil through the reduced gas-exchange. Carbon dioxide concentration is suggested as a better indicator of soil damage than both bulk density and penetrometer resistance – when studying soils with initially elevated compaction levels (Ampoorter *et al.*, 2010). The increased anaerobic conditions in the wheel tracks reduces the decomposition of organic material, and very low carbon dioxide emissions have been measured (Strömgren *et al.*, 2017), despite the high concentration within the soil.

Increased soil temperature and more optimal soil water conditions for microorganisms may potentially increase green-house gas emissions after soil scarification (Fleming *et al.*, 2006; Johansson, 1994). However, only small or no differences in carbon dioxide efflux among different soil scarification treatments and undisturbed soil have been noted (Strömgren *et al.*, 2017; Mjöfors *et al.*, 2015; Strömgren & Mjöfors, 2012). The long-term effect of soil scarification on tree growth may even decrease total carbon dioxide emissions due to a higher proportion of carbon allocated to the standing biomass (Mjöfors *et al.*, 2017).

# 6 Other experiences gained through the PhD project

This PhD project has included many different methods and measuring techniques. In the following sections, I will discuss some of the pros and cons of these techniques and summarize what I have learned by using them.

## 6.1 Image analysis versus traditional soil physical analyses in the laboratory (Paper I)

In Paper I, two methods were used and compared for estimating the physical properties of soil samples: soil physical analyses in the laboratory and X-ray image analysis. The two methods showed good agreement when it came to structural porosity (Figure 8 and Table 3 in Paper I). The good agreement for pores >60 μm ($R^2$: 0.70) and >150 μm ($R^2$: 0.83, Figure 8, Paper I) suggests that the image analysis approach used in Paper I was sufficient for the types of soil samples used in that study. The logarithmically transformed $K_{sat}$ (measured in the laboratory) had significant linear relationships with the following variables derived from the image analyses (in order of significance): porosity, Euler characteristics, total number of pores clusters, and pore cluster orientation, but not for any of the pore thickness variables (Table 3 in Paper I). The relationships with $K_{sat}$ and image analysis derived variables have been tested by others, e.g., Anderson (2014) who found that the number of pore clusters was the best predictor of $K_{sat}$ ($R^2$=0.69). In Paper I, the relationship with numbers of pores (>14 voxels) was significant, but with a lower $R^2$ (0.29). One difference between Paper I and the study by Anderson (2014) is that the smallest pores included in the analysis were 60 μm and 200 μm in the two studies, respectively. This implies that there is a threshold diameter for the pores at which they become more important for predicting $K_{sat}$, as the larger pores channel most of the water.

There are advantages and disadvantages associated with both the laboratory and the image analysis methods as regards analysing soil samples. The laboratory method requires a soil physics lab with suction plates, etc., and the image analysis method requires an X-ray scanner with sufficient resolution and powerful computers. The cost of acquiring the VWC at five tension steps and $K_{sat}$, is at the moment ca. 1,000 SEK/sample at the soil physical laboratory at the Swedish University of Agricultural Sciences, Uppsala. The time required for X-ray scanning is ca. one hour per sample and the cost of using the X-ray scanner is 7,500 SEK/day at the moment (for an employee at the department). The image analysis of one single sample may take weeks to months. However, once an automatized routine is set up, the steps can proceed much quicker, and maybe 2–3 h are needed from the image reconstruction to the feature extraction (where the data are acquired and analyses of the results can begin), depending on computation power, reading and saving times, etc. The total cost for acquiring analyse-ready data from the X-ray tomography will thus be higher than the traditional soil physical analyses in the laboratory.

The final choice between the two methods depends on which results are most desirable. Using image analysis, one can explain why some of the samples have different properties than others, for example as in Figure 9, where there was no clue from the outside that the whole cylinder was filled by one big stone. On the other hand, this was evident when doing the “loss on ignition” on the whole sample (Figure 9). Other differences in soil structure are not as easily detected

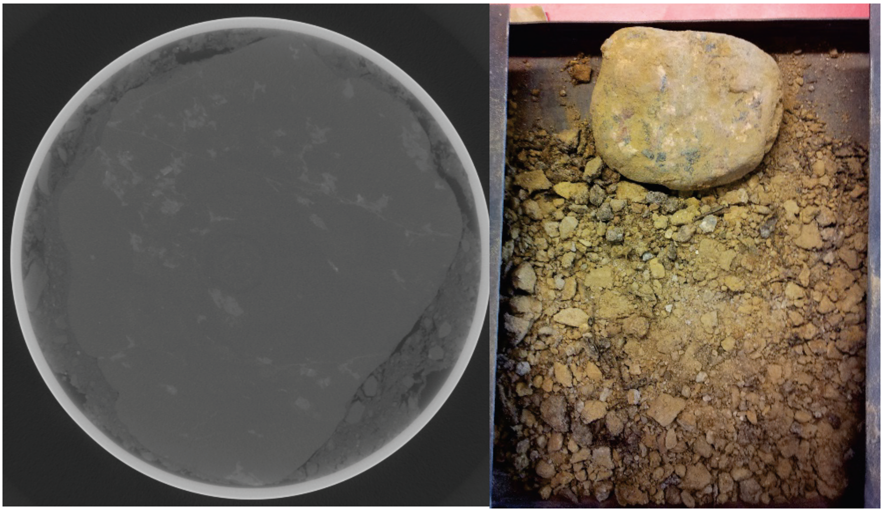

*Figure 9.* One of the three samples collected in the wheel track at site R, *top3*. Bulk density 1.73 g cm$^{-3}$. The stone was not visible from the top or the bottom of the cylinder and the field note from the sampling point states: *Very easy sampling, like butter.* The image to the left is one of the centre slices of the X-ray scanned cylinder. The photo to the right is of all soil material within the same cylinder before “loss on ignition”.

by destroying the sample, and the image analyses can also indicate how the sampling itself effects the structure of the sample (Pires *et al.*, 2004). With image analysis, $K_{sat}$ of the centre of the sample can be estimated (Koestel *et al.*, 2018), even though there is a gap between the cylinder wall and the soil. In the laboratory, this gap would give an erroneously high $K_{sat}$. With image analysis, it is also possible to analyse samples in other shapes than traditional cylinders: aggregates can be scanned directly without a container. However, there are many disadvantages as well, such as beam hardening artefacts and other artefacts caused by the different minerals in the soil and the difficulty of classifying partly decomposed roots as either pores or solid material. In stone-free soils, plastic or aluminium cylinders are preferable to steel, as they cause fewer artefacts. In Paper I, however, steel was needed for the sampling in the stone-rich soil. The advantage of traditional, laboratory soil physical analyses is that many analyses can be performed on the same samples at a low additional cost. To truly understand the studied soil and its properties, combining the two methods is optimal.

To conclude, the soil physical property results from the two methods were in good agreement, and choice of the most suitable method depends on objectives, soil type and resources.

## 6.2 Sensor installation and calibration (Paper II, IV)

Here follows a short evaluation of the methods used for sensor installation and calibration, both in the field and the laboratory as well as a summary of what I have learnt by testing the different approaches.

### 6.2.1 Sensor installation

In Hagfors (Paper IV), the sensors were installed in 2006 at 20 and 45 cm depth below the original surface of the mineral soil to capture the dynamics in the root zone and the soil below. The 45-cm depth was also chosen as lysimeters (used in other studies) were placed at this depth in the experimental plots of the clear-cut. It was important that the sensors were placed at a presumably equal distance from the groundwater level. However, if the sensors had been placed with the only objective to evaluate the soil microclimate for plants, a set-up as in Figure 10 would have been preferable. The advantage of the suggested set-up in Figure 10, from a planting spot perspective, is that all microsites could be compared both at 10 and 20 cm depth from the new ground surface (atmospheric interface). In addition, all microsites could be compared at a reference depth of 20 cm (from the original soil surface before disc trenching), which would be at the same distance from the groundwater level, and probably would have similar original bulk

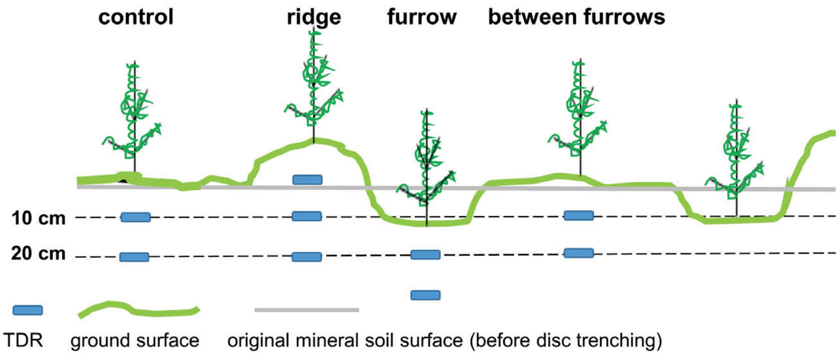

*Figure 10.* Alternative sensor installation in Paper IV, to improve comparisons of the microsites from a seedling perspective.

density. For all microsites except the furrows, this comparison would also be possible at a reference depth of 10 cm. Additional sensors in the ridges, 10 cm from the ground surface, would be located above the original humus layer, within the mixture of humus and mineral soil (brown in Figure 1). In that way, the ridges would also be possible to evaluate as planting spots, which was beyond the scope of Paper IV, where only the furrows and the control were evaluated as microsites for planting. However, for the experimental set-up used here, the 45-cm sensors were also needed for modelling purposes, as in Rappe George et al. (2017) and the total number of sensors is limited by project budgets, and trade-offs have to be made.

Another improvement of the experimental design would have been to have a control area, without disc trenching, in the other end of the transect, allowing installation of sensors in the control microsites farther apart from each other, which would have been preferable from a statistical standpoint.

A long and deep ditch, dug to install the sensors, can be problematic from a hydrological perspective, especially if the groundwater level is shallower than the ditch. In Hagfors, the groundwater level was deeper than 1 m most of the time, and the ditch was ca. 70 cm deep before refilling. It should be noted that the sensors were underneath the undisturbed soil, as they were pushed 30 cm into the undisturbed wall. The advantages of this installation method are that the sensors can be installed horizontally with ease (depending on the stone content of the soil) and that the cables will be buried in the soil and protected from rodents and other animals who like to nibble on them.

At sites R and T (Paper II), it was not possible to dig ditches, and vertical sensor installation was chosen. The sensors were pushed into the ground from the surface of the humus layer. In this way, the hydrology was minimally disturbed and the sampling points could be chosen more freely, with only the length of the cables as constraints. However, there were other problems: the cables laid on the ground, covered with tarpaulin, as protection for rodents. This was very time consuming, but effective, as none of the cables broke during the 1.5 years in the field. However, during snow-melt, a couple of sensors in the silt rich lower part of site T were frost heaved, and in the end of the second season, one or two of the sensors were partly pulled out by passing mammals (elk or bear). Another disadvantage of the vertical installation from the top of the humus layer is that the depth of the humus layer may vary between the microsites and thus influence the water content differently. Calibration of the sensors was performed on mineral soil, but the signal of the TDRs spreads differently in the humus layer (Pumpanen & Ilvesniemi, 2005; Schaap *et al.*, 1997). An installation from the top of the mineral soil could prevent the various impacts of the organic layer. However, this would mean more disturbances of the microsites, especially at stony sites where it takes several tries before a point is found where the complete rod length can be inserted. The humus layer cannot be removed after the installation point is found: once inserted to full length, the TDR cannot be removed and installed again at the same place without causing gaps of air close to the TDR rods, with underestimation of the VWC as a consequence.

### 6.2.2 Sensor calibration

Three types of sensor calibration were tested for the permanent TDRs in this work. In Hagfors (Paper IV), the standard quadratic calibration was used with temperature correction of the time signal, which is described in the manual (Campbell Scientific, 2016) and valid for soils with bulk densities less than 1.55 g $cm^{-3}$, and VWC 0–0.50 $m^3$ $m^{-3}$. The temperature correction is tested for temperatures of 10–40 °C. However, according to Campbell (Nigel Wills, Senior Technical Support Engineer, 2018-01-16), the same correction can be used down to 4 °C. Below 4 °C, the results of TDRs are not reliable. The advantage of this method is that the manufacturer has systematically tested it on many soils and conditions.

In Hagfors, a site-specific calibration was also tested, described in Paper IV, Appendix B. There, the VWC of the soil physical samples collected in 2011 (at the end of the experiment) that were sampled close (less than 5 cm horizontally and 3 cm vertically, n=12) to a TDR were compared with the VWC based on the standard calibration of the time signal of the TDRs. It seemed as if the Campbell function underestimated the VWC compared to the water content of the soil samples. Thus, we also tested a calibration based on the regression between the VWC from the soil samples and the VWC measured by the TDRs (see Figure B.1 in Appendix B of Paper IV). The soil sampling in 2011 aimed at describing the soil physical properties in the different soil layers and microsites. If the only purpose had been sensor calibration, however, all samples would have been taken more closely to the rods of the TDRs. An improvement would be to take additional samples around the TDR rods that would only be used for analysing VWC (and still sample the other depths for all soil physical properties). In any event, I prefer a general calibration of all the sensors together (based on all collected soil samples) to calibrating each sensor separately. My reasons for this are: the TDRs are very exact (precision and resolution <0.1%) and the between-sensor difference in the same medium at the same VWC is between ± 0.5–1.5%, depending on the water content (Campbell Scientific, 2016). The uncertainty in the soil sampling is not negligible: partial compaction around the cylinder walls occurs, and cutting the cylinders straight at the top and bottom is difficult, especially when there is a high rock fragment content. This influences the calculated BD of the sample and, thus, the calculated VWC from the gravimetrically derived water content. However, with a regression of all sensors and water contents around them, the uncertainty in the soil sampling will be less important, as the bulk density can be both over- and underestimated.

The third, most thorough, calibration method (Paper II) was carried out in the laboratory with mixed soil from two pits at each site and following the calibration guide given in the manual (Campbell Scientific, 2016). This method was necessary, as half of the TDRs were shortened to 15 cm, which completely alters the time signal and the standard calibration is not valid. The importance of being very exact when cutting the soil at the tops and the bottoms of the cylinder samples cannot be stressed enough, something also pointed out by Pumpanen and Ilvesniemi (2005), who stated that an accurate determination of sample volume was the main source of variation in the calibration. The greatest disadvantage of performing a calibration in the laboratory, compared to a field-based calibration, is that the soil structure is not the same as in the field, and thus a silty soil will “slack” (float out) with an increasing water content, rendering a higher bulk density. In the field, the roots and the structure of the dead organic material probably partly prevents this slacking. In the laboratory, it was not possible to keep the dry bulk density in the silty soil below 1.5 g cm$^{-3}$ if the VWC was raised above 0.3 cm$^3$ cm$^{-3}$, which adds uncertainty to the calibration at higher water contents, as the bulk densities in the field are not this high in the undisturbed soil.

To conclude, when there are no time or budget constraints, a calibration in the laboratory could be combined with extensive soil sampling (for only VWC, derived gravimetrically) around the TDR rods at the time of demounting of sensors.

# 7 Summary of main results and conclusions

The findings relevant to the aims and objectives of this thesis are summarized below:

Off-road traffic and soil scarification affected the soil, its water content and temperature, which has implications for field vegetation, seedling establishment and the surrounding ecosystems.

- The soil physical properties in the top mineral soil were affected by off-road traffic, also in recharge areas on stony till soils. These changes may especially affect soil aeration caused by the decrease in total porosity (reduced air-filled pore space), increased water holding capacity (longer periods with high water content), and decreased pore connectivity (decreased oxygen diffusion and mass flow).
- Soil temperatures were affected by both off-road driving and soil scarification. Four to five years after off-road traffic, the soil temperatures between and in the wheel tracks were higher than in the undisturbed soil in the lower parts of the slopes. No significant differences were found in the upper parts of the slopes, where the wheel track depth was small. Disc trenching generally increased the mean soil temperature at the reference depth of 20 cm, especially in the furrows, which were warmer during most of the growing season, and the warming lasted at least six growing seasons.

  The soil water content was also affected by the forestry operations studied here. The VWC was generally highest in the wheel tracks and lowest between them. The model simulations indicated that the VWC results in the wheel tracks could partly be explained by the altered soil hydraulic properties. However, the average pressure heads in the root zone were similar between wheel tracks and the undisturbed soil in the upper parts of the slopes, and differences were only apparent during dry periods. After disc trenching, the differences in VWC were generally small between microsites at the reference depth of 20 cm. The VWC values in the furrows were similar to the control during the first three years, but improved (i.e., increased) in the end of the study period.

- Both logging residues and logging mats were efficient in preventing deep ruts during off-road traffic. The logging residues also reduced the area of bare mineral soil, whereas the logging mats tended to scrape the soil uphill. However, in operational forestry logging mats are not used in the upper parts of the slopes. Planning of the skid trails is an important tool to minimize the extent and effect of soil disturbances caused by off-road traffic.
- The field vegetation was affected by off-road traffic, 4–5 years after the treatment, with less *Ericaceae* and mosses and more species with grass-like morphology in the wheel tracks than in the undisturbed soil.

  The growth conditions in the wheel tracks after off-road traffic in the lower parts of the slopes were not optimal, due to the high number of days during the growing season when aeration may have been restricted by a high VWC. In the upper parts of the slopes, the soil compaction was within a range where seedling growth could be affected, and these parts still had areas with bare soil 4–5 years after off-road traffic, mainly in the wheel tracks. After disc trenching, the root growth conditions for planted seedlings were generally improved in the furrows compared to the control at the Hagfors site, and thus, the roots could reach adjacent microsites more quickly, where the nutrient and water conditions were even better.
- After off-road traffic, the lower saturated hydraulic conductivity in the wheel tracks may increase the risk of surface runoff and element leaching. Bare mineral soil increases the risk of sediment loads to nearby streams but the risk is reduced by driving on logging residues. The changed soil physical properties leading to insufficient aeration may also increase the risk of greenhouse gas emissions, especially methane.

# 8 Recommendations and future research

To estimate how a certain forestry operation will affect the soil and its ecosystem services, one has to know something about the inherent soil properties at the site, as these will determine the effect and extent of the soil disturbances. Moist and silt-rich soils should always be treated with caution, as they are easily disturbed by forestry operations. A very dense and compact soil will not have a high increase in BD by off-road traffic, but, depending on the initial compaction level, the additional increase can still be adverse for plants (Page-Dumroese et al., 2006). A dry and loose soil can improve at medium compaction levels, as the water retention during dry periods improves, whereas a moist fine-grained soil can be too wet (too little oxygen available). However, intermediate soil compaction may promote regeneration, and the rutting in some parts of the slopes may act as a thorough soil scarification. As pointed out by previous research, severe soil compaction should be avoided or minimized to avoid impaired regeneration. It is important not to exceed the compaction levels where root penetration is reduced or inhibited, or to reach compaction levels where the air-filled porosity often falls below 0.10 $m^3$ $m^{-3}$. This is especially important on naturally acid podzols in the boreal region, where root and mycorrhizal growth is a key factor for soil structure recovery, as worms and other soil mixing fauna may not thrive, and an early and thick snow cover may inhibit soil frost, thus inhibiting extensive structural changes caused by frost heaving. However, about 12–30% of a clear-cut is normally affected by off-road traffic (Mohtashami et al., 2017; Eliasson, 2005; Brais, 2001), and for the future stand, reduced soil aeration in some parts may be of little concern, especially if soil scarification is carried out. However, more studies are needed on the loosening effect of soil scarification on soils that are compacted by off-road traffic and on how tree growth is affected both in the short term (including establishment of seedlings) and long term (over the rotation period).

Off-road traffic on forest soils occurs under all kinds of soil water conditions, as there is a year-round demand for fresh wood from the industry. To transport timber over forest soils and at the same time minimize the soil disturbances caused by traffic, careful planning of the skid trail system is needed, both before the operation and in the forwarder. Logging mats can preferably be used in the lower parts of the slopes and in riparian areas to reduce rutting and wheel tracks that frequently will be ponded. The use of logging residues close to streams needs to be studied more, as these could be potential hotspots for methyl mercury production, especially when the residues are compacted by traffic. However, logging residues are suitable for soil protection at a distance to the streams, where the potential methyl mercury production will not be directly transported to a stream. More research is needed to evaluate the consequences of driving on logging residues in riparian areas compared to using no soil protection, with deep ruts as a result, and to evaluate what method will most affect the methyl mercury levels of soil and stream water.

Inherent soil physical properties, especially soil texture, are also important when choosing soil scarification method and the microsite for planting. Generally, soil scarification aims to increase the soil water availability on dry soils and decrease the soil water content and increase the temperature on wet and cold sites. In the boreal, sub-xeric Hagfors site, the furrows were suitable planting spots, and planting in furrows could be recommended on other forest clearcuts with field layers dominated by *Vaccinium vitis-idaea*. However, at sites with wet or mesic, fine-textured soils, more elevated plantings spots would be preferable. To fully benefit from the improved soil temperature conditions in the furrows, planting soon after disc trenching is recommended. This is also beneficial from a species competition perspective, especially at sites where the field vegetation reestablishes quickly and will help diminish nitrogen leaching because the plants are more quickly established.

Solutions for promoting profitable forestry and at the same time diminishing the environmental consequences of forestry operations are continuously developing, and the new methods needs to be evaluated from both productivity and conservation perspectives.

# References

Alexandersson, H. & Eggertsson Karlström, C. (2001). *Temperaturen och nederbörden i Sverige 1961–1990: Referensnormaler-utgåva 2 [Temperature and percipitation in Sweden 1961-1990].* (Swedish Meteorological and Hydrological Institute (SMHI) Rapport. Meteorologi 99, 99). Norrköping.

Alvarez-Uria, P. & Körner, C. (2007). Low temperature limits of root growth in deciduous and evergreen temperate tree species. *Functional Ecology,* 21(2), pp. 211-218.

Ampoorter, E., de Schrijver, A., van Nevel, L., Hermy, M. & Verheyen, K. (2012). Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. *Annals of Forest Science,* 69(5), pp. 533-542.

Ampoorter, E., Van Nevel, L., De Vos, B., Hermy, M. & Verheyen, K. (2010). Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction. *Forest Ecology and Management,* 260(10), pp. 1664-1676.

Anderson, S.H. (2014). Tomography-measured macropore parameters to estimate hydraulic properties of porous media. *Procedia Computer Science,* 36, pp. 649-654.

Andersson, J., Dynesius, M. & Hjältén, J. (2017). Short-term response to stump harvesting by the ground flora in boreal clearcuts. *Scandinavian Journal of Forest Research,* 32(3), pp. 239-245.

Andersson, S. (1955). Markfysikaliska undersökningar i odlad jord [Soil physical studies in cultivated soils]: VIII. En experimentell metod [Methodology for characterizing physical properties of soils]. *Grundförbättring [Journal of Agricultural Land Improvement].* 8(2), pp. 1-98.

Ares, A., Terry, T.A., Miller, R.E., Anderson, H.W. & Flaming, B.L. (2005). Ground-based forest harvesting effects on soil physical properties and Douglas-Fir growth. *Soil Science Society of America Journal,* 69(6), pp. 1822-1832.

Aust, W.M. & Blinn, C. (2004). Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years (1982–2002). *Water, Air and Soil Pollution: Focus,* 4(1), pp. 5-36.

Bagheri, I., Kalhori, S.B., Akef, M. & Khormali, F. (2012). Effect of compaction on physical and micromorphological properties of forest soils. *American Journal of Plant Sciences,* 3(1), pp. 159-163.

Balisky, A.C. & Burton, P.J. (1995). Root-zone soil temperature variation associated with microsite characteristics in high-elevation forest openings in the interior of British Columbia. *Agricultural and Forest Meteorology,* 77(1-2), pp. 31-54.

Balisky, A.C. & Burton, P.J. (1997). Planted conifer seedling growth under two soil thermal regimes in high-elevation forest openings in interior British Columbia. *New Forests,* 14(1), pp. 63-82.

Bansal, S., Hallsby, G., Löfvenius, M.O. & Nilsson, M.-C. (2013). Synergistic, additive and antagonistic impacts of drought and herbivory on *Pinus sylvestris*: leaf, tissue and whole-plant responses and recovery. *Tree Physiology,* 33(5), pp. 451–463.

Bartelheimer, M. & Poschlod, P. (2016). Functional characterizations of Ellenberg indicator values – a review on ecophysiological determinants. *Functional Ecology,* 30(4), pp. 506-516.

Batey, T. (2009). Soil compaction and soil management - a review. *Soil Use and Management,* 25(4), pp. 335-345.

Ben-Noah, I. & Friedman, S.P. (2018). Review and evaluation of root respiration and of natural and agricultural processes of soil aeration. *Vadose Zone Journal,* 17(1), pp. 1-47.

Bergholm, J., A. Olsson, B., Vegerfors, B. & Persson, T. (2015). Nitrogen fluxes after clear-cutting. Ground vegetation uptake and stump/root immobilisation reduce N leaching after experimental liming, acidification and N fertilisation. *Forest Ecology and Management,* 342, pp. 64-75.

Bergstedt, J., Hagner, M. & Milberg, P. (2008). Effects on vegetation composition of a modified forest harvesting and propagation method compared with clear-cutting, scarification and planting. *Applied Vegetation Science,* 11(2), pp. 159-168.

Bhatti, J.S., Fleming, R.L., Foster, N.W., Meng, F.R., Bourque, C.P.A. & Arp, P.A. (2000). Simulations of pre- and post-harvest soil temperature, soil moisture, and snowpack for jack pine: comparison with field observations. *Forest Ecology and Management,* 138, pp. 413-426.

Bishop, K., Seibert, J., Köhler, S. & Laudon, H. (2004). Resolving the double paradox of rapidly mobilized old water with highly variable responses in runoff chemistry. *Hydrological Processes,* 18(1), pp. 185-189.

Block, R., Van Rees, K.C.J. & Pennock, D.J. (2002). Quantifying harvesting impacts using soil compaction and disturbance regimes at a landscape scale. *Soil Science Society of America Journal,* 66(5), pp. 1669-1676.

Blomgren, A. (2018). *Influence of logging residues on MeHg accumulation in soil.* Diss. Stockholm: Royal Institute of Technology, KTH.

Boateng, J.O., Heineman, J.L., Bedford, L. & Nemec, A.F.L. (2010). Twenty-year effects of mechanical site preparation and windrow burning treatments on soil properties and *Pinus contorta* var. *latifolia* nutrition in sub-boreal British Columbia. *Scandinavian Journal of Forest Research,* 25(6), pp. 515-533.

Booth, M., Stark, J. & Hart, S. (2006). Soil-mixing effects on inorganic nitrogen production and consumption in forest and shrubland soils. *Plant and Soil,* 289(1-2), pp. 5-15.

Bottinelli, N., Hallaire, V., Goutal, N., Bonnaud, P. & Ranger, J. (2014). Impact of heavy traffic on soil macroporosity of two silty forest soils: Initial effect and short-term recovery. *Geoderma,* 217, pp. 10-17.

Brady, N.C. & Weil, R.R. (2001). *The nature and properties of soils.* 13. ed. New Jersey: Pearson Education, Inc.

Brais, S. (2001). Persistence of soil compaction and effects on seedling growth in northwestern Quebec. *Soil Science Society of America Journal,* 65(4), pp. 1263-1271.

Buitrago, M., Paquette, A., Thiffault, N., Bélanger, N. & Messier, C. (2015). Early performance of planted hybrid larch: effects of mechanical site preparation and planting depth. *New Forests,* 46(3), pp. 319-337.

Burton, P., Bedford, L., Goldstein, M. & Osberg, M. (2000). Effects of disk trench orientation and planting spot position on the ten-year performance of lodgepole pine. *New Forests,* 20(1), pp. 23-44.

Cajander, A.K. (1949). Forest types and their significance. *Acta Forestalia Fennica,* 56(5).

Cambi, M., Certini, G., Fabiano, F., Foderi, C., Laschi, A. & Picchio, R. (2016). Impact of wheeled and tracked tractors on soil physical properties in a mixed conifer stand. *iForest - Biogeosciences and Forestry,* 9(1), pp. 89-94.

Cambi, M., Certini, G., Neri, F. & Marchi, E. (2015). The impact of heavy traffic on forest soils: A review. *Forest Ecology and Management,* 338, pp. 124-138.

Campbell Scientific (2016). *CS616 and CS625 water content reflectometers instruction manual* Loughborough, United Kingdom: Campbell Scientific Ltd.

Chen, J., Franklin, J.F. & Spies, T.A. (1993). Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. *Agricultural and Forest Meteorology,* 63(3–4), pp. 219-237.

Devine, W.D. & Harrington, C.A. (2007). Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. *Agricultural and Forest Meteorology,* 145(1-2), pp. 125-138.

Domisch, T., Finér, L. & Lehto, T. (2001). Effects of soil temperature on biomass and carbohydrate allocation in Scots pine (*Pinus sylvestris*) seedlings at the beginning of the growing season. *Tree Physiology,* 21(7), pp. 465-472.

Domisch, T., Finér, L., Lehto, T. & Smolander, A. (2002). Effect of soil temperature on nutrient allocation and mycorrhizas in Scots pine seedlings. *Plant and Soil,* 239(2), pp. 173-185.

Doube, M., Kłosowski, M.M., Arganda-Carreras, I., Cordelières, F.P., Dougherty, R.P., Jackson, J.S., Schmid, B., Hutchinson, J.R. & Shefelbine, S.J. (2010). BoneJ: Free and extensible bone image analysis in ImageJ. *Bone,* 47(6), pp. 1076-1079.

Duguid, M.C. & Ashton, M.S. (2013). A meta-analysis of the effect of forest management for timber on understory plant species diversity in temperate forests. *Forest Ecology and Management,* 303, pp. 81-90.

Ebeling, C., Lang, F. & Gaertig, T. (2016). Structural recovery in three selected forest soils after compaction by forest machines in Lower Saxony, Germany. *Forest Ecology and Management,* 359, pp. 74-82.

Egnell, G., Jurevics, A. & Peichl, M. (2015). Negative effects of stem and stump harvest and deep soil cultivation on the soil carbon and nitrogen pools are mitigated by enhanced tree growth. *Forest Ecology and Management,* 338, pp. 57-67.

Eklöf, K., Bishop, K., Bertilsson, S., Björn, E., Buck, M., Skyllberg, U., Osman, O.A., Kronberg, R.M. & Bravo, A.G. (2018). Formation of mercury methylation hotspots as a consequence of forestry operations. *Science of The Total Environment,* 613-614, pp. 1069-1078.

Eklöf, K., Lidskog, R. & Bishop, K. (2016). Managing Swedish forestry's impact on mercury in fish: Defining the impact and mitigation measures. *Ambio,* 45(2), pp. 163-174.

Eliasson, L. (2005). Effects of forwarder tyre pressure on rut formation and soil compaction. *Silva Fennica,* 39(4), pp. 549-557.

Eliasson, L. & Wästerlund, I. (2007). Effects of slash reinforcement of strip roads on rutting and soil compaction on a moist fine-grained soil. *Forest Ecology and Management,* 252(1-3), pp. 118-123.

Ellenberg, H., Weber, H., Düll, R., Wirth, V., Werner, W. & Paulissen, D. (1991). Zeigerwerte von Pflanzen in MittelEuropa. *Scripta Geobotanica,* 18, p. 248.

Ernfors, M., von Arnold, K., Stendahl, J., Olsson, M. & Klemedtsson, L. (2007). Nitrous oxide emissions from drained organic forest soils - an up-scaling based on C:N ratios. *Biogeochemistry,* 84, pp. 219-231.

Ezzati, S., Najafi, A., Rab, M.A. & Zenner, E.K. (2012). Recovery of soil bulk density, porosity and rutting from ground skidding over a 20-year period after timber harvesting in Iran. *Silva Fennica,* 46(4), pp. 521-538.

Finér, L., Mannerkoski, H., Piirainen, S. & Starr, M. (2003). Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting. *Forest Ecology and Management,* 174(1–3), pp. 51-63.

Fleming, R.L., Black, T.A. & Eldridge, N.R. (1994). Effects of site preparation on root-zone soil-water regimes in high-elevation forest clearcuts. *Forest Ecology and Management,* 68(2-3), pp. 173-188.

Fleming, R.L., Laporte, M.F., Hogan, G.D. & Hazlett, P.W. (2006). Effects of harvesting and soil disturbance on soil $CO_2$ efflux from a jack pine forest. *Canadian Journal of Forest Research,* 36(3), pp. 589-600.

Frey, B. (2010). Evaluation of machine-induced soil compaction in forest soils by means of changes in soil bacteria populations. *Schweizerische Zeitschrift fur Forstwesen,* 161(12), pp. 498-503.

Frey, B., Kremer, J., Rüdt, A., Sciacca, S., Matthies, D. & Lüscher, P. (2009). Compaction of forest soils with heavy logging machinery affects soil bacterial community structure. *European Journal of Soil Biology,* 45(4), pp. 312-320.

Frey, B., Niklaus, P.A., Kremer, J., Luescher, P. & Zimmermann, S. (2011). Heavy-machinery traffic impacts methane emissions as well as methanogen abundance and community structure in oxic forest soils. *Applied and Environmental Microbiology,* 77(17), pp. 6060-6068.

Fridman, J. & Wulff, S. (2018). *Skogsdata 2018 [Forest statisitics 2018].* (Sveriges Officiella Statistik [The official statistics of Sweden]). Umeå: Swedish University of Agricultural Sciences.

Fründ, H.C. & Averdiek, A. (2016). Soil aeration and soil water tension in skidding trails during three years after trafficking. *Forest Ecology and Management,* 380, pp. 224-231.

Gaertig, T., Schack-Kirchner, H., Hildebrand, E.E. & Wilpert, K.v. (2002). The impact of soil aeration on oak decline in southwestern Germany. *Forest Ecology and Management,* 159(1), pp. 15-25.

Gayoso, J. & Iroume, A. (1991). Compaction and soil disturbances from logging in southern Chile. *Annales Des Sciences Forestieres,* 48(1), pp. 63-71.

Goutal, N., Boivin, P. & Ranger, J. (2012a). Assessment of the natural recovery rate of soil specific volume following forest soil compaction. *Soil Science Society of America Journal,* 76(4), pp. 1426-1435.

Goutal, N., Parent, F., Bonnaud, P., Demaison, J., Nourrisson, G., Epron, D. & Ranger, J. (2012b). Soil $CO_2$ concentration and efflux as affected by heavy traffic in forest in northeast France. *European Journal of Soil Science,* 63(2), pp. 261-271.

Grigal, D.F. (2000). Effects of extensive forest management on soil productivity. *Forest Ecology and Management,* 138(1-3), pp. 167-185.

Grip, H. & Rodhe, A. (2016). *Vattnets väg från regn till bäck [The way of water from rain to stream].* 4. ed. Uppsala: Uppsala universitet.

Grossnickle, S.C. (2012). Why seedlings survive: influence of plant attributes. *New Forests,* 43(5), pp. 711-738.

Grossnickle, S.C. & El-Kassaby, Y.A. (2016). Bareroot versus container stocktypes: a performance comparison. *New Forests,* 47(1), pp. 1-51.

Gärdenäs, A., Lillemägi, M. & Eckersten, H. (2003). *Modeling long-term effects of N fertilization and N deposition on the N balances of forest stands in Sweden*. (Emergo - Studies in the biogeophysical environment, 2003:3). Uppsala: Swedish University of Agricultural Sciences.

Han, H.S., Page-Dumroese, D., Han, S.K. & Tirocke, J. (2006). Effects of slash, machine passes, and soil moisture on penetration resistance in a cut-to-length harvesting. *International Journal of Forest Engineering,* 17(2), pp. 11-24.

Hansson, L., Šimůnek, J., Ring, E., Bishop, K. & Gärdenäs, A. (2019). Soil compaction effects on root-zone hydrology and vegetation in boreal forest clearcuts *Soil Science Society of America Journal,* 83(S1).

Hansson, L.J., Koestel, J., Ring, E. & Gärdenäs, A.I. (2018a). Impacts of off-road traffic on soil physical properties of forest clear-cuts: X-ray and laboratory analysis. *Scandinavian Journal of Forest Research,* 33(2), pp. 166-177.

Hansson, L.J., Ring, E., Franko, M.A. & Gärdenäs, A.I. (2018b). Soil temperature and water content dynamics after disc trenching a sub-xeric Scots pine clearcut in central Sweden. *Geoderma,* 327, pp. 85-96.

Hartmann, M., Howes, C.G., VanInsberghe, D., Yu, H., Bachar, D., Christen, R., Nilsson, R.H., Hallam, S.J. & Mohn, W.W. (2012). Significant and persistent impact of timber harvesting on soil microbial communities in Northern coniferous forests. *Isme Journal,* 6(12), pp. 2199-2218.

Hartmann, M., Niklaus, P.A., Zimmermann, S., Schmutz, S., Kremer, J., Abarenkov, K., Luescher, P., Widmer, F. & Frey, B. (2014). Resistance and resilience of the forest soil microbiome to logging-associated compaction. *Isme Journal,* 8(1), pp. 226-244.

Hébert, F., Boucher, J.F., Walsh, D., Tremblay, P., Côté, D. & Lord, D. (2014). Black spruce growth and survival in boreal open woodlands 10 years following mechanical site preparation and planting. *Forestry,* 87(2), pp. 277-286.

Hedwall, P.-O., Bergh, J. & Nordin, A. (2014). Nitrogen-retention capacity in a fertilized forest after clear-cutting — the effect of forest-floor vegetation. *Canadian Journal of Forest Research,* 45(1), pp. 130-134.

Heiskanen, J., Hallikainen, V., Uusitalo, J. & Ilvesniemi, H. (2018). Co-variation relations of physical soil properties and site characteristics of Finnish upland forests. *Silva Fennica,* 52(3), pp. 1-18.

Heiskanen, J. & Rikala, R. (1998). Influence of different nursery container media on rooting of Scots pine and silver birch seedlings after transplanting. *New Forests,* 16(1), pp. 27-42.

Hillel, D. (2003). *Introduction to environmental soil physics*. Amsterdam: Elsevier Academic Press.

Horn, R., Vossbrink, J. & Becker, S. (2004). Modern forestry vehicles and their impacts on soil physical properties. *Soil & Tillage Research,* 79(2), pp. 207-219.

Horn, R., Vossbrink, J., Peth, S. & Becker, S. (2007). Impact of modern forest vehicles on soil physical properties. *Forest Ecology and Management,* 248(1-2), pp. 56-63.

Hyvönen, R., Kaarakka, L., Leppälammi-Kujansuu, J., Olsson, B.A., Palviainen, M., Vegerfors-Persson, B. & Helmisaari, H.-S. (2016). Effects of stump harvesting on soil C and N stocks and vegetation 8–13 years after clear-cutting. *Forest Ecology and Management,* 371, pp. 23-32.

Håkansson, I., Voorhees, W.B. & Riley, H. (1988). Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. *Soil & Tillage Research,* 11(3-4), pp. 239-282.

Hägglund, B. & Lundmark, J. (1987). *Handledning i bonitering med Skogshögsskolans boniteringssystem del 1: Definitioner och anvisningar.* Jönköping: Skogsstyrelsen [In Swedish].

ISO11274 (1998). Soil quality -- Determination of the water-retention characteristic -- Laboratory methods. International Organization for Standardization.

ISO11277 (2009). Soil quality -- Determination of particle size distribution in mineral soil material -- Method by sieving and sedimentation. International Organization for Standardization.

Jansson, P.E. (1987). Simulated soil temperature and moisture at a clearcutting in central Sweden. *Scandinavian Journal of Forest Research,* 2(1-4), pp. 127-140.

Jarvis, P.G. & Jarvis, M.S. (1963). The water relations of tree seedlings II. Transpiration in relation to soil water potential. *Physiologia Plantarum,* 16(1), pp. 236-253.

Johansson, K., Ring, E. & Högbom, L. (2013). Effects of pre-harvest fertilization and subsequent soil scarification on the growth of planted *Pinus sylvestris* seedlings and ground vegetation after clear-felling. *Silva Fennica,* 47(4).

Johansson, M.B. (1994). The influence of soil scarification on the turn-over rate of slash needles and nutrient release. *Scandinavian Journal of Forest Research,* 9(2), pp. 170-179.

Jourgholami, M., Labelle, E.R. & Feghhi, J. (2017). Response of runoffand sediment on skid trails of varying gradient and traffic intensity over a two-year period. *Forests,* 8(12), pp. 1-13.

Jourgholami, M. & Majnounian, B. (2011). Soil compaction and disturbance from logging with a wheeled skidder (case study: in Kheyrud forest). *Iranian Journal of Forest,* 2(4), pp. 287-298.

Kabzems, R. (2012). Aspen and white spruce productivity is reduced by organic matter removal and soil compaction. *Forestry Chronicle,* 88(3), pp. 306-316.

Kamaluddin, M., Chang, S.X., Curran, M.P. & Zwiazek, J.J. (2005). Soil compaction and forest floor removal affect early growth and physiology of lodgepole pine and Douglas-fir in British Columbia. *Forest Science,* 51(6), pp. 513-521.

Kataja-aho, S., Smolander, A., Fritze, H., Norrgård, S. & Haimi, J. (2012). Responses of soil carbon and nitrogen transformations to stump removal. *Silva Fennica,* 46(2), pp. 169-179.

Klaes, B., Struck, J., Schneider, R. & Schüler, G. (2016). Middle-term effects after timber harvesting with heavy machinery on a fine-textured forest soil. *European Journal of Forest Research,* 135(6), pp. 1083-1095.

Knapp, B.O., Wang, G.G. & Walker, J.L. (2008). Relating the survival and growth of planted longleaf pine seedlings to microsite conditions altered by site preparation treatments. *Forest Ecology and Management,* 255(11), pp. 3768-3777.

Koestel, J. (2018). SoilJ: an ImageJ plugin for the semiautomatic processing of three-dimensional X-ray images of soils. *Vadose Zone Journal,* 17(1).

Koestel, J., Dathe, A., H. Skaggs, T., Klakegg, O., Ahmad, M., Babko, M., Giménez, D., Farkas, C., Nemes, A. & Jarvis, N. (2018). Estimating the permeability of naturally structured soil from percolation theory and pore space characteristics imaged by X-ray. *Water Resources Research,* 54(11), pp. 9255-9263.

Kranabetter, J.M. & Chapman, B.K. (1999). Effects of forest soil compaction and organic matter removal on leaf litter decomposition in central British Columbia. *Canadian Journal of Soil Science,* 79(4), pp. 543-550.

Krekula, B., Bergqvist, J., Fries, C., Gällerspång, J., Reisek, J., Ringagård, J., Sollander, E., Svensson, L. & Wågström, K. (2018). *Föreskrifter för anläggning av skog - regeringsuppdrag*. (rapport, 2018/3). Jönköping.

Kubin, E. & Kemppainen, L. (1994). Effect of soil preparation of boreal spruce forest on air and soil temperature conditions in forest regeneration areas. *Acta Forestalia Fennica,* 244, pp. 1-56.

Labelle, E. & Jaeger, D. (2018). Management implications of using brush mats for soil protection on machine operating trails during mechanized cut-to-length forest operations. *Forests,* 10(1), p. 19.

Labelle, E.R. & Jaeger, D. (2011). Soil compaction caused by cut-to-length forest operations and possible short-term natural rehabilitation of soil density. *Soil Science Society of America Journal,* 75(6), pp. 2314-2329.

Laudon, H., Kuglerová, L., Sponseller, R.A., Futter, M., Nordin, A., Bishop, K., Lundmark, T., Egnell, G. & Ågren, A.M. (2016). The role of biogeochemical hotspots, landscape heterogeneity, and hydrological connectivity for minimizing forestry effects on water quality. *Ambio,* 45, pp. 152-162.

Ledesma, J.L.J., Grabs, T., Bishop, K.H., Schiff, S.L. & Köhler, S.J. (2015). Potential for long-term transfer of dissolved organic carbon from riparian zones to streams in boreal catchments. *Global Change Biology,* 21(8), pp. 2963-2979.

Li, Q., Allen, H.L. & Wilson, C.A. (2003). Nitrogen mineralization dynamics following the establishment of a loblolly pine plantation. *Canadian Journal of Forest Research,* 33(2), pp. 364-374.

Lindahl, K.B., Sténs, A., Sandström, C., Johansson, J., Lidskog, R., Ranius, T. & Roberge, J.-M. (2017). The Swedish forestry model: more of everything? *Forest Policy and Economics,* 77, pp. 44-55.

Linn, D.M. & Doran, J.W. (1984). Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Science Society of America Journal,* 48(6), pp. 1267-1272.

Lopes, E.d.S., Sampietro, J.A., Lombardi, K.C. & Dias, A.N. (2011). Evaluation of moisture content on compaction of soil submitted to forest harvesting machine traffic. *Revista Arvore,* 35(3, Supplement 1), pp. 659-667.

Lopushinsky, W. & Klock, G.O. (1974). Transpiration of conifer seedlings in relation to soil water potential. *Forest Science,* 20(2), pp. 181-186.

Lorente, M., Parsons, W.F.J., Bradley, R.L. & Munson, A.D. (2012). Soil and plant legacies associated with harvest trails in boreal black spruce forests. *Forest Ecology and Management,* 269, pp. 168-176.

Lundmark-Thelin, A. & Johansson, M.-B. (1997). Influence of mechanical site preparation on decomposition and nutrient dynamics of Norway spruce (*Picea abies* (L.) Karst.) needle litter and slash needles. *Forest Ecology and Management,* 96(1–2), pp. 101-110.

Löf, M. & Birkedal, M. (2009). Direct seeding of *Quercus robur* L. for reforestation: The influence of mechanical site preparation and sowing date on early growth of seedlings. *Forest Ecology and Management,* 258(5), pp. 704-711.

MacKenzie, M.D., Schmidt, M.G. & Bedford, L. (2005). Soil microclimate and nitrogen availability 10 years after mechanical site preparation in northern British Columbia. *Canadian Journal of Forest Research,* 35(8), pp. 1854-1866.

Makkonen, K. & Helmisaari, H.S. (1998). Seasonal and yearly variations of fine-root biomass and necromass in a Scots pine (*Pinus sylvestris* L.) stand. *Forest Ecology and Management,* 102(2-3), pp. 283-290.

Mallik, A.U. & Hu, D. (1997). Soil respiration following site preparation treatments in boreal mixedwood forest. *Forest Ecology and Management,* 97(3), pp. 265-275.

McMahon, S., Simcock, R., Dando, J. & Ross, C. (1999). A fresh look at operational soil compaction. *New Zealand Journal of Forestry,* 44(3), pp. 33-37.

Mellander, P.E., Bishop, K. & Lundmark, T. (2004). The influence of soil temperature on transpiration: a plot scale manipulation in a young Scots pine stand. *Forest Ecology and Management,* 195(1-2), pp. 15-28.

Meyer, C., Luescher, P. & Schulin, R. (2014). Recovery of forest soil from compaction in skid tracks planted with black alder *Alnus glutinosa* (L.) Gaertn.). *Soil & Tillage Research,* 143, pp. 7-16.

Mjöfors, K., Strömgren, M., Nohrstedt, H.O. & Gärdenäs, A.I. (2015). Impact of site-preparation on soil-surface $CO_2$ fluxes and litter decomposition in a clear-cut in Sweden. *Silva Fennica,* 49(5).

Mjöfors, K., Strömgren, M., Nohrstedt, H.Ö., Johansson, M.B. & Gärdenäs, A.I. (2017). Indications that site preparation increases forest ecosystem carbon stocks in the long term. *Scandinavian Journal of Forest Research,* 32(8), pp. 1-9.

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

Mohtashami, S., Nordlund, S., Krook, M., Bergkvist, I., Ring, E. & Högbom, L. (2016). *Körskador vid slutavverkning – En inventeringsstudie i Mälardalen. [Soil damage in final felling – An inventory of machine tracks in Mälardalen].* (Arbetsrapport 896–2016, 896). Uppsala: Skogforsk.

Monteith, J.L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology,* 19, pp. 205-34.

Mossadeghi-Björklund, M., Arvidsson, J., Keller, T., Koestel, J., Lamande, M., Larsbo, M. & Jarvis, N. (2016). Effects of subsoil compaction on hydraulic properties and preferential flow in a Swedish clay soil. *Soil & Tillage Research,* 156, pp. 91-98.

Murphy, G., Firth, J.G. & Skinner, M.F. (2004). Long-term impacts of forest harvesting related soil disturbance on log product yields and economic potential in a New Zealand forest. *Silva Fennica,* 38(3), pp. 279-289.

Mäkitalo, K. & Hyvönen, J. (2004). Late-summer soil water content on clear-cut reforestation areas two decades after site preparation in Finnish Lapland. *Forest Ecology and Management,* 189(1-3), pp. 57-75.

Naghdi, R., Solgi, A., Labelle, E.R. & Zenner, E.K. (2016). Influence of ground-based skidding on physical and chemical properties of forest soils and their effects on maple seedling growth. *European Journal of Forest Research,* 135(5), pp. 949-962.

Nilsson, U., Luoranen, J., Kolström, T., Örlander, G. & Puttonen, P. (2010). Reforestation with planting in northern Europe. *Scandinavian Journal of Forest Research,* 25(4), pp. 283-294.

Nilsson, U. & Örlander, G. (1999). Water uptake by planted *Picea abies* in relation to competing field vegetation and seedling rooting depth on two grass-dominated sites in southern Sweden. *Scandinavian Journal of Forest Research,* 14(4), pp. 312-319.

Nohrstedt, H.O. (2000). Effects of soil scarification and previous N fertilisation on pools of inorganic N in soil after clear-felling of a *Pinus sylvestris* (L.) stand. *Silva Fennica,* 34(3), pp. 195-204.

Nordlander, G., Hellqvist, C., Johansson, K. & Nordenhem, H. (2011). Regeneration of European boreal forests: Effectiveness of measures against seedling mortality caused by the pine weevil *Hylobius abietis*. *Forest Ecology and Management,* 262(12), pp. 2354-2363.

Page-Dumroese, D.S., Jurgensen, M.F., Tiarks, A.E., Ponder, F., Jr., Sanchez, F.G., Fleming, R.L., Kranabetter, J.M., Powers, R.F., Stone, D.M., Elioff, J.D. & Scott, D.A. (2006). Soil physical property changes at the North American Long-Term Soil Productivity study sites: 1 and 5 years after compaction. *Canadian Journal of Forest Research,* 36(3), pp. 551-564.

Pallardy, S.G. (2008). *Physiology of Woody Plants (Third Edition)*. San Diego: Academic Press.

Palviainen, M., Finer, L., Lauren, A., Mannerkoski, H., Piirainen, S. & Starr, M. (2007). Development of ground vegetation biomass and nutrient pools in a clear-cut disc-plowed boreal forest. *Plant and Soil,* 297(1-2), pp. 43-52.

Persson, H.Å. (1983). The distribution and productivity of fine roots in boreal forests. *Plant and Soil,* 71(1-3), pp. 87-101.

Piirainen, S., Finér, L., Mannerkoski, H. & Starr, M. (2007). Carbon, nitrogen and phosphorus leaching after site preparation at a boreal forest clear-cut area. *Forest Ecology and Management,* 243(1), pp. 10-18.

Pires, L.F., Bacchi, O.O.S. & Reichardt, K. (2004). Damage to soil physical properties caused by soil sampler devices as assessed by gamma ray computed tomography. *Australian Journal of Soil Research,* 42(7), pp. 857-863.

Pohtila, E. & Pohjola, T. (1985). Maan kunnostus mannyn viljelyssa Lapissa. [Soil preparation in reforestation of Scots pine in Lapland]. *Silva Fennica,* 19(3), pp. 245-270.

Poltorak, B.J., Labelle, E.R. & Jaeger, D. (2018). Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats. *Soil and Tillage Research,* 179, pp. 96-104.

Ponder, F., Jr., Fleming, R.L., Berch, S., Busse, M.D., Elioff, J.D., Hazlett, P.W., Kabzems, R.D., Kranabetter, J.M., Morris, D.M., Page-Dumroese, D., Palik, B.J., Powers, R.F., Sanchez, F.G., Scott, D.A., Stagg, R.H., Stone, D.M., Young, D.H., Zhang, J., Ludovici, K.H., McKenney, D.W., Mossa, D.S., Sanborn, P.T. & Voldseth, R.A. (2012). Effects of organic matter removal, soil compaction and vegetation control on 10th year biomass and foliar nutrition: LTSP continent-wide comparisons. *Forest Ecology and Management,* 278, pp. 35-54.

Pumpanen, J., Heinonsalo, J., Rasilo, T., Villemot, J. & Ilvesniemi, H. (2012). The effects of soil and air temperature on $CO_2$ exchange and net biomass accumulation in Norway spruce, Scots pine and silver birch seedlings. *Tree Physiology,* 32(6), pp. 724-736.

Pumpanen, J. & Ilvesniemi, H. (2005). Calibration of time domain reflectometry for forest soil humus layers. *Boreal Environment Research,* 10, pp. 589-495.

Pumpanen, J., Westman, C.J. & Ilvesniemi, H. (2004). Soil $CO_2$ efflux from a podzolic forest soil before and after forest clear-cutting and site preparation. *Boreal Environment Research,* 9(3), pp. 199-212.

Rappe George, M.O., Hansson, L.J., Ring, E., Jansson, P.E. & Gärdenäs, A.I. (2017). Nitrogen leaching following clear-cutting and soil scarification at a Scots pine site – A modelling study of a fertilization experiment. *Forest Ecology and Management,* 385, pp. 281-294.

Ring, E., Högbom, L., Hansson, L., Nordlund, S. & Andersson, M. (2019). Logging mats and logging residue as ground protection during forwarder traffic on till hillslopes. *Manuscript*.

Ring, E., Högbom, L. & Jansson, G. (2013). Effects of previous nitrogen fertilization on soil-solution chemistry after final felling and soil scarification at two nitrogen-limited forest sites. *Canadian Journal of Forest Research,* 43(4), pp. 396-404.

Ring, E., Högbom, L., Nohrstedt, H.-Ö. & Jacobson, S. (2015). Soil and soil-water chemistry below different amounts of logging residues at two harvested forest sites in Sweden. *Silva Fennica,* 49(4), pp. 1-19.

Ring, E., Jacobson, S. & Högbom, L. (2011). Long-term effects of nitrogen fertilization on soil chemistry in three Scots pine stands in Sweden. *Canadian Journal of Forest Research,* 41(2), pp. 279-288.

Schaap, M.G., de Lange, L. & Heimovaara, T.J. (1997). TDR calibration of organic forest floor media. *Soil Technology,* 11(2), pp. 205-217.

Schaeffer, B., Stauber, M., Mueller, R. & Schulin, R. (2007). Changes in the macro-pore structure of restored soil caused by compaction beneath heavy agricultural machinery: a morphometric study. *European Journal of Soil Science,* 58(5), pp. 1062-1073.

Schnurr-Ptüz, S., Bååth, E., Guggenberger, G., Drake, H.L. & Küsel, K. (2006). Compaction of forest soil by logging machinery favours occurrence of prokaryotes. *FEMS Microbiology Ecology,* 58(3), pp. 503-516.

Seyferth, U. (1998). Effects of soil temperature and moisture on carbon and nitrogen mineralisation in coniferous forests. *Licentiate Thesis, Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences.*

Simard, S.W., Jones, M.D., Durall, D.M., Hope, G.D., Stathers, R.J., Sorensen, N.S. & Zimonick, B.J. (2003). Chemical and mechanical site preparation: effects on *Pinus contorta* growth, physiology, and microsite quality on grassy, steep forest sites in British Columbia. *Canadian Journal of Forest Research,* 33(8), pp. 1495-1515.

Šimůnek, J., van Genuchten, M.T. & Šejna, M. (2008). Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal,* 7(2), pp. 587-600.

Šimůnek, J., Van Genuchten, M.T. & Šejna, M. (2016). Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal,* 15(7).

SMHI (2019). *Normal uppmätt årsnederbörd, medelvärde 1961-1990 [measured normal annual precipitation, mean for 1961-1990].* Available at: http://www.smhi.se/klimatdata/meteorologi/nederbord/normal-uppmatt-arsnederbord-medelvarde-1961-1990-1.4160 [16 January, 2019].

SMHI (2019). *Normal årsmedeltemperatur [normal annual mean temperature for 1961-1990].* Available at: http://www.smhi.se/klimatdata/meteorologi/temperatur/normal-arsmedeltemperatur-1.3973 [16 January, 2019].

Smolander, A., Paavolainen, L. & Mälkönen, E. (2000). C and N transformations in forest soil after mounding for regeneration. *Forest Ecology and Management,* 134(1-3), pp. 17-28.

Solgi, A., Naghdi, R., Labelle, E.R. & Zenner, E.K. (2018). The effects of using soil protective mats of varying compositions and amounts on the intensity of soil disturbances caused by machine traffic. *International Journal of Forest Engineering,* 29(3), pp. 199-207.

Solgi, A. & Najafi, A. (2014). The impacts of ground-based logging equipment on forest soil. *Journal of Forest Science (Prague),* 60(1), pp. 28-34.

Soudzilovskaia, N.A., Bodegom, P.M. & Cornelissen, J.H.C. (2013). Dominant bryophyte control over high-latitude soil temperature fluctuations predicted by heat transfer traits, field moisture regime and laws of thermal insulation. *Functional Ecology,* 27(6), pp. 1442-1454.

Startsev, A.D. & McNabb, D.H. (2009). Effects of compaction on aeration and morphology of boreal forest soils in Alberta, Canada. *Canadian Journal of Soil Science,* 89(1), pp. 45-56.

Steber, A., Brooks, K., Perry, C.H. & Kolka, R. (2007). Surface compaction estimates and soil sensitivity in aspen stands of the Great Lakes States. *Northern Journal of Applied Forestry,* 24(4), pp. 276-281.

Stendahl, J., Lundin, L. & Nilsson, T. (2009). The stone and boulder content of Swedish forest soils. *Catena,* 77(3), pp. 285-291.

Strömgren, M., Hedwall, P.-O. & Olsson, B.A. (2016). Effects of stump harvest and site preparation on $N_2O$ and $CH_4$ emissions from boreal forest soils after clear-cutting. *Forest Ecology and Management,* 371, pp. pp. 8-22.

Strömgren, M. & Mjöfors, K. (2012). Soil-$CO_2$ flux after patch scarification, harrowing and stump harvest in a hemi-boreal forest. *Scandinavian Journal of Forest Research,* 27(8), pp. 754-761.

Strömgren, M., Mjöfors, K. & Olsson, B.A. (2017). Soil-surface $CO_2$ flux during the first 2 years after stump harvesting and site preparation in 14 Swedish forests. *Scandinavian Journal of Forest Research,* 32(3), pp. 213-221.

Stutz, K., Schack-Kirchner, H., Kändler, G., Landes, L., Linz, M., Warlo, H. & Lang, F. (2017). Available nutrients can accumulate in permanent skid trails. *Forests,* 8(10), p. 358.

Sutinen, R., Middleton, M., Hänninen, P., Vartiainen, S., Venäläinen, A. & Sutinen, M.-L. (2007). Dielectric constant time stability of glacial till at a clear-cut site. *Geoderma,* 141(3–4), pp. 311-319.

Sutinen, R., Pänttäjä, M., Teirilä, A. & Sutinen, M.-L. (2006). Effect of mechanical site preparation on soil quality in former Norway spruce sites. *Geoderma,* 136(1–2), pp. 411-422.

Sutton, R.F. (1993). Mounding site preparation: A review of European and North American experience. *New Forests,* 7(2), pp. 151-192.

Swedish Forestry Agency (2016). *Statistical Reports: Silvicultural activites 2015*. Jönköping: Swedish Forestry Agency.

Tan, X., Chang, S.X. & Kabzems, R. (2005). Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. *Forest Ecology and Management,* 217(2-3), pp. 158-170.

Teepe, R., Brumme, R., Beese, F. & Ludwig, B. (2004). Nitrous oxide emission and methane consumption following compaction of forest soils. *Soil Science Society of America Journal,* 68(2), pp. 605-611.

Tiarks, A.E., Powers, R.F., Ragus, J.F., Page-Dumroese, D.S., Ponder, F., Jr. & Stone, D.M. (1997). *North American long-term soil productivity research program.* (General Technical Report, 238). Northeastern Forest Experiment Station.

Toivio, J., Helmisaari, H.-S., Palviainen, M., Lindeman, H., Ala-Ilomäki, J., Sirén, M. & Uusitalo, J. (2017). Impacts of timber forwarding on physical properties of forest soils in southern Finland. *Forest Ecology and Management,* 405, pp. 22-30.

Tracy, S.R., Black, C.R., Roberts, J.A., Sturrock, C., Mairhofer, S., Craigon, J. & Mooney, S.J. (2012). Quantifying the impact of soil compaction on root system architecture in tomato (Solanum lycopersicum) by X-ray micro-computed tomography. *Annals of Botany,* 110(2), pp. 511-519.

Törmänen, T., Kitunen, V., Lindroos, A.J., Heikkinen, J. & Smolander, A. (2018). How do logging residues of different tree species affect soil N cycling after final felling? *Forest Ecology and Management,* 427, pp. 182-189.

Wall, A. & Heiskanen, J. (2003). Effect of air-filled porosity and organic matter concentration of soil on growth of *Picea abies* seedlings after transplanting. *Scandinavian Journal of Forest Research,* 18(4), pp. 344-350.

Wall, A. & Heiskanen, J. (2009). Soil–water content and air-filled porosity affect height growth of Scots pine in afforested arable land in Finland. *Forest Ecology and Management,* 257(8), pp. 1751-1756.

van Genuchten, M.T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal,* 44(5), pp. 892-898.

van Genuchten, M.T. (1987). *A numerical model for water and solute movement in and below the root zone*: United States Department of Agriculture Agricultural Research Service U.S. Salinity Laboratory.

Wei, L., Hulin, F., Chevalier, R., Archaux, F. & Gosselin, F. (2016). Is plant diversity on tractor trails more influenced by disturbance than by soil characteristics? *Forest Ecology and Management,* 379, pp. 173-184.

Widenfalk, O. & Weslien, J. (2009). Plant species richness in managed boreal forests—Effects of stand succession and thinning. *Forest Ecology and Management,* 257(5), pp. 1386-1394.

Williamson, J.R. & Neilsen, W.A. (2000). The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. *Canadian Journal of Forest Research,* 30(8), pp. 1196-1205.

Vogel, T., van Genuchten, M.T. & Cislerova, M. (2001). Effect of the shape of the soil hydraulic functions near saturation on variably-saturated flow predictions. *Advances in Water Resources,* 24(2), pp. 133-144.

von Wilpert, K. & Schäffer, J. (2006). Ecological effects of soil compaction and initial recovery dynamics: a preliminary study. *European Journal of Forest Research,* 125(2), pp. 129-138.

Vossbrink, J. & Horn, R. (2004). Modern forestry vehicles and their impact on soil physical properties. *European Journal of Forest Research,* 123(4), pp. 259-267.

Wästerlund, I. (1983). Growth reduction of trees near strip roads resulting from soil compaction and damaged roots - a literature survey. *Sveriges Skogsvårdsförbunds Tidskrift,* 81(2), pp. 97-109.

Wästerlund, I. (1985). Compaction of till soils and growth tests with Norway spruce and Scots pine. *Forest Ecology and Management,* 11(3), pp. 171-189.

Xu, X., Nieber, J.L. & Gupta, S.C. (1992). Compaction effect on the gas-diffusion coefficient in soils. *Soil Science Society of America Journal,* 56(6), pp. 1743-1750.

Zenner, E.K., Fauskee, J.T., Berger, A.L. & Puettmann, K.J. (2007). Impacts of skidding traffic intensity on soil disturbance, soil recovery, and aspen regeneration in North Central Minnesota. *Northern Journal of Applied Forestry,* 24(3), pp. 177-183.

Zhao, Y., Krzic, M., Bulmer, C.E., Schmidt, M.G. & Simard, S.W. (2010). Relative bulk density as a measure of compaction and its influence on tree height. *Canadian Journal of Forest Research,* 40(9), pp. 1724-1735.

Ågren, A.M., Lidberg, W. & Ring, E. (2015). Mapping temporal dynamics in a forest stream network—implications for riparian forest management. *Forests,* 6(9), pp. 2982-3001.

Örlander, G. (1986). Effect of planting and scarification on the water relations in planted seedlings of Scots pine. *Studia Forestalia Suecica*(173), pp. 1-17.

Örlander, G. & Due, K. (1986). Water relations of seedlings of Scots pine grown in peat as a function of soil water potential and soil temperature. *Studia Forestalia Suecica*(175), pp. 1-13.

Örlander, G., Hallsby, G., Gemmel, P. & Wilhelmsson, C. (1998). Inverting improves establishment of *Pinus contorta* and *Picea abies* - 10-year results from a site preparation trial in northern Sweden. *Scandinavian Journal of Forest Research,* 13(2), pp. 160-168.

# Skogsbruksåtgärders inverkan på markens fysikaliska egenskaper, vatten- och temperaturdynamik

Fysikaliska markstörningar är en del av ett produktivt skogsbruk och görs både avsiktligt, t. ex. markberedning, och oavsiktligt i form av t. ex. markpackning och körskador vid terrängtransport och annan körning i samband med skogsbruksåtgärder. Alla störningar förändrar marken, och därmed kan även dess vatten- och temperaturdynamik ändras, med konsekvenser både för skogsproduktion och miljö.

Syftet med denna avhandling var att sammanfatta hur skogsbruksåtgärder (här terrängtransport och markberedning) påverkar marken, dess vatten- och temperaturdynamik samt vilka konsekvenser det kan få för t. ex. plantetablering, fältvegetation och de omgivande ekosystemen. Avhandlingen bygger på fyra studier, tre om körskador på två hyggen i Västerbotten och två om markberedning (harvning) på ett hygge i Värmland. Metoderna som användes var markfysikaliska analyser, röntgenskanning, bild- och laboratorieanalyser, fältmätningar av marktemperatur och vattenhalt, vegetationsinventering, utvärdering av abiotiska växtförhållanden och slutligen hydrologisk modellering.

De mest anmärkningsvärda resultaten var att körningen orsakade markpackning även på grova jordar i inströmningsområden, vilket särskilt påverkade den hydrauliska konduktiviteten som reducerades med 70 %. Markpackning kan leda till längre perioder med hög vattenhalt, ökad risk för ytavrinning och otillräcklig luftning av växtrötterna. Fem år efter körning var vattenhalten högre i körspåren, vilket bekräftades av artsammansättningen där. Modellsimuleringar med Hydrus-1D visade hur förändringarna i markens hydrologiska egenskaper påverkade vattenhaltsdynamiken. Otillräcklig luftning var vanligare i hjulspår och kunde förklara varför det fortfarande fanns fläckar av bar mark i de nedre delarna av sluttningarna. Användandet av stockmattor och grot (grenar och toppar) förhindrade djupa körspår, trots att det krävdes ytterligare körningar för att lägga ut (och ta bort) dem. Groten pressades dock in i marken, vilket kan ha resulterat i markpackning och även en förhöjd risk för ämnesutlakning under groten. Sammanfattningsvis bör man vara noga när man planerar skogsbruksåtgärder också på grova steniga marker, eftersom det översta markskiktet, där majoriteten av alla rötter finns, ändå kan vara känsligt för markpackning.

Efter markberedning var marktemperaturen under växtsäsongen högre i fårorna än i mark som inte var markberedd och temperatureffekten varade i minst sex år men minskade över tiden. Ingen mikromiljö hade tillräckligt hög vattenhalt för att hindra markluftningen efter markberedning. Sammanfattningsvis var mikroklimatet i fårorna lämpligt för plantering på det relativt torra hygget i Värmland.

# Impacts of large mammals on forest research equipment

*Ursus arctos* or *Alces alces*?

The logger station at Trågalidsberget before and after impact of a large mammal.
Left photo: Linnea Hansson (2017-05-28).
Right photo: Mikael Andersson (Skogforsk, 2018-10-10).

# Acknowledgements

There are a great number of people I would like to thank:

First of all my supervisors, who all in different ways have helped me during these years at SLU: **Annemieke**, thank you for supporting and coaching me through the complete process from the first ideas to the final product and always sharing your wide knowledge with me. I have especially appreciated our brainstorming meetings when we have found new creative ways of moving forward. You are an expert in seeing possibilities and can find great solutions despite limited budgets. I am very thankful for your ambitious and useful comments on my texts. **Eva**, thanks for inviting me to be part of the "off-road" project and for generously sharing your data and knowledge. You are a co-(or main) author of all the papers included in this thesis, and I have really appreciated working with you, with your quick responses and to-the-point feedback. **Per-Erik**, thank you for sharing your knowledge and outside-the-box ideas, and for encouraging me in the modelling work. **Iwan**, thank you for introducing me to soil compaction by off-road traffic with engaging lectures all those years ago during my graduate studies in Forestry at SLU in Umeå. During my PhD work, we have had nice discussions of soil disturbances, and thank you (and **Dianne**) for inviting me to your fabulous house, Olasgården, in Sävar. **Kevin,** thanks for always offering those nice encouraging comments at times when I have needed them the most. You have saved my day several times!

I would also like to thank my co-author **John**, who introduced me to the world of X-ray scanning and image analysis and did some great work on illumination correction on my cylinder samples of steel. In my image analysis work, I am also appreciative of my discussions with **Maria S** and **Francisco. Martin,** thank you for many interesting discussions and good work with the Hagfors data. I am very grateful that I got my first manuscript published through you! To my other co-authors, **Annemieke, Eva, Per-Erik, Kevin**, **Mikael A F, Jirka, Lasse, Sten** and **Mikael A,** thank you for good cooperation in the work with the different studies.

During the fieldwork and in the preparation for it, I have a number of people to thank: **Adrian**, **Erik**, **Viktor** and **Michael H** for good field assistance. **Maria B**, **Örjan, Johan** (Insitu AB) and **Mikael A** for help and suggestions for getting the logger stations to resurrect, work and communicate. **Ola** for helping me identify the species I did not recognize. You really have an impressive skill in identifying species, even when they are rotten or mouldy. I also would like to thank my dear friends in Umeå, **Amanda** and **Maria F**, who have hosted and charged both me and my logger batteries, and have supported me with positive comments during this journey.

Other skilful people I would like to thank for being involved in the work are: **Mikael A F.**, **Ulf** and **Claudia** (statistical advice), **Christina** and **Ana-Maria** (soil physical analysis), **Sebastian** (adapting and summarizing Ellenberg indicators to Swedish conditions), **Karen** (language editing), **Ragnar** and **Håkan** (IT support), and **Anna**, **Magnus** and **Mats** for helpful suggestions to improve the thesis summary. I would also like to thank all **my office mates**, some for very engaging scientific (and private) discussions and some for a calm working environment. I also would like to thank all **the people around the fika and lunch tables** for nice discussions, **Monika**, for being my support and partner in crime as a forest engineer in soil science at our department, and **Karin** for engaging discussions about mercury, logging residues and soil disturbances.

I would like to thank my **friends** and **family** for supporting me in this project. **Mamma, Pappa, Tilda** and **Jon**, you have all helped a lot with baby-sitting during courses, fieldwork and conferences, and of course, you have all contributed to the person I am today. Finally, I would like to acknowledge the best things that happened to me during my time as a PhD student: **Vide, Noel** and **Lykke**!!! You are the stars of my life and I am so happy that I have you!