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Producing information from airborne LiDAR data for peatland forest management

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Academic dissertation

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ABSTRACT

In Finland, peatland forests are significant for wood supply, although simultaneously, they are also important for biodiversity, carbon sequestration, water conservation, and recreation. In the 1960s and 1970s, peatland forests in Finland were extensively drained to increase tree growth and fulfil the needs of the forest sector. However, this extensive drainage has negatively impacted on the biodiversity of peatland ecosystems, and substantially increased nutrient and sediment emissions to lakes and rivers resulting in eutrophication, turbidity, and brownification of these water bodies.

This dissertation presents a number of approaches to move peatland forest management in a more environmentally sound direction, which may increase the general acceptability of peatland forestry. Airborne LiDAR (Light detection and ranging, i.e., laser scanning) derived 3D point cloud provides useful data, for example, to estimate forest biomass, to identify low-productive peatland forests, to model overland water flows, and to identify wet areas. The strength of airborne LiDAR is the ability of laser pulses to pass through tree canopies and obtain accurate observations from the ground level. The information derived from airborne LiDAR can enhance the planning of peatland forest management, as much of the planning can be done remotely, and supplementary field work can be implemented in areas of strategic need.

This study presented the novel idea of applying local binary patterns for the prediction of terrain trafficability, which should be considered in further studies and practice. The moisture index derived from the local neighborhood can reveal the small-scale variations in terrain moisture. This study also presented the novel idea to create spatial models to identify suitable locations for water protection structures, which may help forest managers to plan water protection of ditch network maintenance or peatland restoration operations. Overall, the utilization of airborne LiDAR-derived information for the development of peatland forestry practices shows great potential.

Keywords: Digital elevation model, Forest inventory, Overland flow modeling, Remote sensing, Terrain trafficability, Water protection

TIIVISTELMÄ

Suometsät muodostavat tärkeän puuvarannon suomalaiselle metsäteollisuudelle, mutta samaan aikaan suoekosysteemit ovat tärkeitä metsien monimuotoisuuden, hiilensidonnan, vesiensuojelun ja virkistyskäytön kannalta. Suometsiä ojitettiin laaja-alaisesti kasvavan metsäteollisuuden tarpeisiin 1960–70 -luvuilla, mikä lisäsi merkittävästi puuston kasvua turvemailla. Ojitukset heikensivät kuitenkin suometsien monimuotoisuutta ja lisäsivät huomattavasti vesistöjen kiintoaine- ja ravinnekuormitusta, mikä on aiheuttanut järvien ja jokien rehevöitymistä, samentumista ja tummentumista.

Tämä väitöskirja esittelee käytännönläheisiä mahdollisuuksia, joiden avulla suometsien hoidossa voidaan kustannustehokkaasti huomioida erityisesti metsien monimuotoisuus ja vesiensuojelu. Suometsien hakkuita ja ojituksia kritisoidaan laajasti, joten suometsänhoidon yleisen hyväksyttävyyden lisääminen ympäristöasioiden paremmalla huomioimisella on tarpeen. Lentolaserkeilauksen tuottama 3D-pistepilvi tarjoaa erinomaisen aineiston muun muassa biomassan määrän ja laadun arviointiin, heikkotuottoisten alueiden tunnistamiseen ja rajaamiseen, pintavesien virtauksen mallintamiseen sekä kosteiden maastonkohtien kartoittamiseen. Laserkeilauksen vahvuus muihin kaukokartoitusmenetelmiin verrattuna on sen kyky tuottaa maanpinnasta erittäin tarkka korkeusmalli, sillä keilaimen lähettämät pulssit pystyvät läpäisemään metsän latvuskerroksen.

Korkeusmallista laskettujen, kohteen lähiympäristöä kuvaavien tekstuuripiirteiden käyttö maaston kantavuuden ennustamisesta on uusi idea, joka kannattaa huomioida jatkotutkimuksissa ja käytännössä, koska tekstuuripiirteet kuvasivat lupaavasti hyvin pienialaista, leimikon sisäistä kantavuuden vaihtelua. Toinen uusi idea tässä väitöskirjassa on vesiensuojelurakenteiden automaattiseen sijoitteluun tähtäävä laskentamenetelmä, jonka on tarkoitus helpottaa ojituksen suunnittelijan työtä, koska etenkin pintavalutuskentille on yleisesti ollut vaikea löytää sopivia sijoituspaikkoja. Ylipäätään laserkeilausaineistoista voidaan johtaa paljon sellaista tietoa, joka auttaa merkittävästi suometsänhoidon ja ojien kunnostuksen suunnittelua. Paikkatiedon avulla valtaosa suunnittelusta voidaan jatkossa tehdä toimistotyönä, jolloin suunnittelun maastotyöt pystytään etukäteen kohdistamaan tärkeimpiin maastonkohtiin.

PREFACE

The first steps of this dissertation were taken in 2014, when my professor at the time, **Markus Holopainen**, took me on for a new project financed by Metsähallitus. Forest legislation in Finland had changed, and Metsähallitus was interested to see whether the peatland areas that were released from the obligation of forest regeneration could be detected by airborne LiDAR data. I tested the estimation accuracy of forest inventory attributes in low-productive peatland forests. **Mikko Vastaranta** (a lecturer in University of Helsinki at that time, and currently a professor in University of Eastern Finland) and **Jussi Peuhkurinen** (Arbonaut Oy) guided me to non-parametric, area-based predictions of forest attributes using airborne LiDAR data. Thanks to Markus, Mikko and Jussi, I managed to get my first article published in 2015. However, in those days, I had no real idea as to how my dissertation might develop, and my special interest towards peatland forestry was only aroused much later.

After the first research project, I was offered a fantastic opportunity to go to Nairobi, Kenya, for a three-month employment period funded by development aid. After the African trip, Markus employed me in the university, and I continued my research career in a project led by Mikko V. There was ongoing work trying to predict forest stand age using a time series of photogrammetrically derived surface models, and I provided the majority of the statistical analyses to that research. I also remember a field work trip to Ilomantsi, where I was alone, drilling trees in the middle of Finland’s most densely populated bear area, just before the bear hunting season started. This was a bit scary!

At that time, I also met my supervisor **Jari Vauhkonen**, who was working at the University of Helsinki. I worked part-time for Jari’s project, where we tested how textural features derived from digital surface models could improve area-based forest inventories. We published one interesting paper in the Remote Sensing journal, and I also utilized the same textural features in my further studies of terrain trafficability.

In 2016, my aim was to develop a dissertation related to terrain trafficability predictions, which was a topical question for the Finnish forest sector after a number of winters with difficult harvesting conditions. I received substantial funding from *Metsämiesten Säätiö*, under the guidance of Markus and Mikko V. The first study proceeded as planned, but I had no idea how the research of this topic could be continued. I lost my motivation and wanted to try something else. However, I pushed through the long and difficult peer review, such that the results were published in Scandinavian Journal of Forest Research in 2017.

In May 2017, I was employed as a forest resource expert for Tapio Oy, which is a state-owned forest consulting company. The work for Tapio has enabled me to enlarge my understanding of Finnish forestry and to network actively. At this point, I must mention one person from Tapio, who has had a significant impact on the final form of this dissertation: water conservation specialist **Samuli Joensuu**. Samuli has promoted the use of spatial data in ditch network maintenance and water protection for a number of years, and I was able to participate in his project in 2019, when we developed a story map about utilizing open spatial data for planning peatland forest management.

I had a three-year break from science. I got married to my wife, **Anna**, and we were blessed with the arrival of our lovely daughter, **Saga**. The daily work for Tapio was interesting, and it offered a lot of possibilities to learn new things. However, I knew that this dissertation was at the mid-way point, and that it would only need 1.5–2 years of full-time concentration to finish it. In March 2020, I contacted Markus and Jari to tell them that I wanted to take study leave to finish my dissertation. By a lucky coincidence, Jari, who had started a professorship in forest planning a few months earlier, had a suitable funding from the University of Helsinki to boost new research. He was willing to fund my work for a year so that I was able to plan the study leave without financial concerns. In addition, complementary funding from *Maa- ja Vesitekniikan tuki ry* at the time was very helpful.

In September 2020, I started my new co-operation with Jari. Following discussions with peatland researchers; **Paavo Ojanen**, **Harri Vasander**, and **Kari Minkkinen** from the University of Helsinki, we developed a plan to focus on water protection in peatland forestry. The aforementioned trio, strengthened by **Sakari Sarkkola** from Luke, were very open to discussions while I designed the studies **III** and **IV**. In addition, I managed to make useful contacts with water conservation specialists in ELY Pirkanmaa (Anne Mäkynen, especially), who supported my work and identified a suitable pilot area in Parkano.

In general, I like the models that we developed to predict terrain trafficability (study **II**) and those we developed to suggest water protection structures (study **IV**), and I really believe that those works may be useful. As the statistician George E. P. Box has said *"All models are wrong, but some are useful"*. None of these phenomena can be exactly modeled, but the models can still produce information that can clearly improve forest management practices. I also like study **III**, where I tried to determine the best practices to produce hydrologically conditioned elevation models and the subsequent overland flow networks by using high-density airborne LiDAR data. In my opinion, the weakness of this thesis is that the mapping of low-productive peatlands in study **I** is already a little outdated, as the technology and methods of LiDAR-based forest inventories have significantly developed in the last eight years. An equivalent study should give better results if it was repeated today.

Grateful thanks to Jari for making these last steps possible – I don't know whether I would ever have finished my PhD without his support. Also big thanks to Markus, Mikko, and Jussi, who guided me in the initial years. Thanks to Paavo, Harri, Kari, and Sakari for participating in the final paper – one highlight in the middle of strict Covid-19 restrictions was our great field trip to Parkano. Thanks to Samuli, **Raija Laiho** (Luke) and **Nuutti Kiljunen** (Finnish Forest Centre) for forming the thesis committee and for supporting my work.

Last but not least, grateful thanks to my wife **Anna** for all her help, team spirit, sympathy and encouragement. And thanks to our 4-year-old **Saga** for reminding me that there is something much more important than this thesis in the world – such as going to a sandpit or playing Paw Patrol figures with her. Thanks also to my parents, **Taina** and **Jukka**, for always encouraging me towards higher education.

Helsinki, November 2022

Mikko Niemi

LIST OF ORIGINAL ARTICLES

I. Niemi M, Vastaranta M, Peuhkurinen J, Holopainen M (2015) Forest inventory attribute prediction using airborne laser scanning in low-productive forestry-drained boreal peatlands. Silva Fenn 49(2), article id 1218. https://doi.org/10.14214/sf.1218

II. Niemi MT, Vastaranta M, Vauhkonen J, Melkas T, Holopainen M (2017) Airborne LiDAR-derived elevation data in terrain trafficability mapping. Scand J For Res 32(8): 726–773. https://doi.org/10.1080/02827581.2017.1296181

III. Niemi MT (2021) Improvements to stream extraction and soil wetness mapping within a forested catchment by increasing airborne LiDAR data density – A case study in Parkano, Western Finland. Silva Fenn 55(5), article id 10557. https://doi.org/10.14214/sf.10557

IV. Niemi MT, Ojanen P, Sarkkola S, Vasander H, Minkkinen K, Vauhkonen J (2022) Using digital terrain model for placing overland flow fields and uncleaned ditch sections for water protection in peatland forest management. Submitted manuscript.

AUTHOR CONTRIBUTION

Studies **I**, **II** and **IV** were designed together with all co-authors. Mikko Niemi wrote the first version of all the manuscripts and was responsible for data processing and statistical analyses in all the studies. In study **I**, Jussi Peuhkurinen was responsible for the field measurements. In study **II**, Mikko Niemi carried out all the field work. In study **IV**, Mikko Niemi organized the acquisition of expert evaluations. All co-authors participated in the revision of the published manuscripts (**I**–**II**).

TABLE OF CONTENTS

1. INTRODUCTION

1.1 The role of peatland forests in Finland

Finland is known as the land of forests, or the land of a thousand lakes, although the country could also be called the land of thousands of peatlands. Forestry land covers 86% of the total land area of Finland, and approximately one third of the forestry land is on peat soils. Drainage of pristine peatlands for increased tree growth was very intensive in the 1960s and 1970s, and currently 53% of the peatland area is drained (Korhonen et al. 2021).

The precondition for timber production in boreal peatlands is that the water table level is lower than 30 cm below the soil surface during the growing season (Vompersky and Sirin 1997; Sarkkola et al. 2012). Before an artificial drainage ditch network is constructed in boreal peatland forests, the water table level is typically near the soil surface, which significantly limits tree growth. Extensive soil drainage has clearly increased forest growth in Finland, as the area of productive forest land (determined as those forests with volumetric growth rates > 1 m^3 ha^{-1} $year^{-1}$) has increased from 18.7 million hectares (1960s) to 20.3 million hectares (2010s), mainly due to drainage of peatland forests (Korhonen et al. 2021).

Today, drainage of pristine peatlands is rare in Finland (Korhonen et al. 2021), although ditch network maintenance (DNM) i.e., clearing of ditches and/or complementary ditching, was carried out on an average 50,000 hectares per year in the 2010s (Vaahtera et al. 2021). The DNM operations are needed due to the gradual deterioration of the drainage ditches, which leads to a rise in the groundwater level in the peat between the ditches. Groundwater depth should be kept sufficiently low to maintain undisturbed tree growth (Heikurainen 1980), thus it is recommended that ditches are cleared to a depth of 0.6–1.1 m (Vanhatalo et al. 2019).

From a timber production perspective, drainage of peatlands has been successful, and a significant proportion of peatland forests are now reaching the phase of forest regeneration. Currently, 21% of available saw timber and 34% of pulp wood are located on peatlands, which makes peatland forests a considerable timber resource in Finland (Korhonen et al. 2021). However, peatland stands are more difficult to harvest than mineral soils due to their low load-bearing capacity (Uusitalo et al. 2015), shorter soil frost season (Kellomäki et al. 2010), and the typically long distances to the road network. Thus, improved and up-to-date data of the soil bearing capacity of peatlands and fine-grained mineral soils is needed to guarantee year-round timber harvesting for the forest sector.

However, 13% of drained peatlands are classified as poorly productive or as unproductive forests, determined by an average volume growth rate of < 1 m^3 ha^{-1} $year^{-1}$ during the rotation period (Korhonen et al. 2021). These low-productive drained peatlands (LPDP) are areas where ditch conditioning and forest regeneration are not profitable (Laiho et al. 2016). Finnish forest legislation was updated in 2014 and the requirement of forest regeneration was withdrawn for LPDP. Since then, the re-use of LPDP has been a topic of debate in peatland forestry (Tolvanen et al. 2018).

Peatland forestry faces several challenges, in addition to the problems associated with groundwater depth, difficult harvesting conditions, and the profitability of forest management. Drainage has increased the sediment and nutrient loads from peatlands to water bodies, which is harmful to aquatic ecosystems (Nieminen et al. 2018b; Finér et al. 2021). From a climatic perspective, the drainage of peatlands has had both positive and negative effects on the greenhouse gas balance (Ojanen et al. 2013). Therefore, water conservation and carbon sequestration must be carefully considered to guarantee social acceptability of peatland forest management in the future.

1.2 Information required in peatland forest management

1.2.1 Strategic and tactical planning

Various aspects, i.e., environmental, social and economic values, must be considered in multipurpose decision-making to achieve sustainable forest management (Hall 2001). Peatland areas can provide multiple ecosystem services, such as timber, peat, biodiversity conservation, carbon sequestration, flood risk control, water quality control, and recreational benefits. However, some of these ecosystem services are contradictory, and there are obvious trade-offs between the commercial use of peatlands and the other ecosystem services (Tolvanen et al. 2012). In addition, the climatic perspective adds further complexity: currently, peatland forests have a climate cooling impact via latent energy partitioning and tree growth, but DNM-based even-aged forest management can transform fertile peatland sites into greenhouse gas sources (Admiral et al. 2006; Ojanen et al. 2013).

A wide range of studies have attempted to optimize timber production on forestry-drained peatland stands (Miina 1996; Ahtikoski et al. 2012; Kojola et al. 2012; Hökkä et al. 2017; Ahtikoski and Hökkä 2019). Other studies have drawn up guidelines for optimal ditch depths in even-aged forest management, as refraining from DNM operations and the avoidance of unnecessarily deep ditches can move peatland forestry management practices in a more environmentally sound direction (Hökkä et al. 2021; Laurén et al. 2021). In addition, the negative environmental and climatic effects of DNM operations can be reduced by using continuous cover forestry, which is a feasible management alternative despite the decreased tree growth, as much less investment is needed for forest growth if regeneration cuttings are avoided (Nieminen et al. 2018a; Juutinen et al. 2021).

Decision-making in forestry-drained peatlands can be supported by the production of accurate data: forest inventory attributes (Brosofske et al. 2014), soil properties, wetness, flow accumulation, and ditch depth. Typically, peatland stands exhibit large within-stand variation, which should be considered in decision-making. Therefore, planning and management of peatland forests is now directed towards precision forestry, where treatments are instead implemented at the sub-stand or even individual tree-level (Holopainen et al. 2014; Melander 2021; Persson et al. 2022).

1.2.2 Harvesting planning

Harvesting operations are a challenge on peatlands and fine-grained mineral soils, where heavy forest logging and transport machines typically cause soil rutting and compaction due to the low load-bearing capacity of these soils (Sirén et al. 2019). Rut formation should be minimized during harvesting operations, because the recovery of soil microorganisms is strongly related to the level of soil compaction (Hartmann et al. 2014). On mineral soils, the decrease in water and oxygen supply to plants and microorganisms caused by compaction leads to a reduction in forest production and regeneration (Cambi et al. 2015). On peat soils, root production is decreased after disturbance, although boreal peatlands are rather resilient to soil compaction caused by forest machines (Lepilin et al. 2022). In thinning operations, the machines work within the growing tree stands where soil damage may reduce tree growth

5–10 years after thinning (Wästerlund 1992). In general, the degree of soil damage depends on the machinery used, site characteristics, terrain topography, and weather conditions (Saarilahti 2002; Nugent et al. 2003; Vega-Nieva et al. 2009; Hartmann et al. 2014; Cambi et al. 2015).

Harvesting conditions are determined using a concept of *terrain trafficability*, which describes the ability of the terrain to support the passage of vehicles (International Society for Terrain-Vehicle Systems Standardization Committee 1977). On fine-grained mineral soils, terrain trafficability depends on soil texture, dry density, moisture and stoniness, i.e., trafficability increases with increasing soil dry density and stoniness, or decreasing soil moisture and clay/peat content (Saarilahti 2002; Eliasson and Wästerlund 2007; Sirén et al. 2019). On course-grained mineral soils, terrain trafficability is more independent on soil moisture, thus the greater clay fraction results in a greater reduction in the soil load-bearing capacity under wet weather conditions (Elbanna and Whitney 1987). On peatlands, total tree biomass and the shear modulus of the topmost peat layers are the main factors influencing terrain trafficability (Uusitalo et al. 2015). Moreover, the amount of logging residues on strip roads leads to a significant decrease in soil rutting during forest operations (Sirén et al 2013).

Forest machinery should be used efficiently all year-round, although the seasonal variation in soil moisture makes that difficult in boreal forests. Wet conditions typically interrupt harvesting operations on peatlands and fine-grained mineral soils, which causes economical losses for the forest entrepreneurs. Improved and up-to-date information of terrain trafficability would enable more effective stand allocation and better forwarding route planning for timber procurement (Suvinen 2006; Mohtashami et al. 2017; Salmivaara et al. 2020).

1.2.3 Water protection

Overall, forest management contributes 17%, 35%, and 12% of annual nitrogen (N), phosphorus (P), and total organic carbon (TOC) emissions, respectively, to water bodies in Finland (Finér et al. 2021). Peatland forests are hotspots of sediment and nutrient loads from human-induced forestry and their serious impact on water quality has been addressed (Nieminen et al 2018b; Finér et al. 2021). Peatland forestry can harm ecologically sensitive streams, rivers, and lakes, because the sediment and nutrient loading may cause eutrophication, turbidity, and brownification of the water, and contribute to the loss of aquatic biodiversity (Tammi et al. 1999; Brönmark and Hansson 2002; Joensuu 2002; Schindler 2006; Holopainen and Lehikoinen 2022). Pressure to achieve sustainable and environmentally-sound land use management means that forest owners must consider water quality in peatland forest management (Nieminen et al. 2018c; Marttila et al. 2020, Miettinen et al. 2020).

The DNM operations aim to provide adequate drainage for tree growth by decreasing groundwater depth to below 0.30–0.35 cm during the growing season (Sarkkola et al. 2012; Hökkä et al. 2021). Nutrient and sediment export from DNM operations can be mitigated by avoiding unnecessary ditch cleaning or by adapting the minimum required ditch depth according to climatic conditions, stand volume, peat properties, and ditch spacing (Hökkä et al. 2021). In addition, nutrient and sediments loads can be reduced by constructing water protection structures, such as sedimentation ponds, peak runoff controls, buffer zones, and overland flow fields, and by leaving breaks in ditch cleaning operations (Väänänen et al. 2008; Marttila and Kløve 2010; Vikman et al. 2010; Finér et al. 2018; Haahti et al. 2018).

Typically, there are trade-offs between water quality control and the optimal drainage level for tree growth, which affects the choice of forest management and water protection alternatives (Miettinen et al. 2020). As forest managers are responsible for the selection of methods for water protection, in conjunction with harvesting and DNM planning, they therefore need improved tools to support their decision-making.

1.3 Utilizing airborne LiDAR in peatland forest management

1.3.1 Terrain modeling, overland flow routing and wetness mapping

Currently, airborne light detection and ranging (LiDAR) is a leading technology used to generate a digital elevation model (DEM, Kraus and Pfeifer 1998; Hodgson and Bresnahan 2004; Sharma et al. 2020). As LiDAR pulses have the capacity to pass through the forest canopy, airborne LiDAR is a significantly more accurate method for terrain modeling than photogrammetry (Kanostrevac et al. 2019).

In mineral soils, a high-resolution DEM is the primary data source for modeling hydrological properties, such as flow direction and flow accumulation, or mapping wet soils, flood risk areas or riverine topography (Wilson et al. 2008; Hohenthal et al. 2011; Muhadi et al. 2020). Overland flow routing is typically based on the multiple flow direction algorithm, which allows flow distribution to all possible downhill directions (Quinn et al. 1991; Holmgren 1994; Seibert and McGlynn 2007). However, in peatland soils water movement is often driven by hydraulic conductivity, thus it does not necessarily follow the matrix flow (Laurén et al. 2021). LiDAR-derived DEMs always contain local depressions that do not exhibit any downward direction, which can affect discontinuity in computational overland flow routing (Jenson and Domingue 1988; Lindsay and Creed 2005). Depressions must be either filled (O'Callaghan and Mark 1984) or breached through barriers (Martz and Garbrecht 1998; 1999) to manipulate hydrologically conditioned, depressionless DEM.

Soil wetness can be predicted using either the Topographic Wetness Index (TWI, Tarboton 1997) or the Depth-to-Water Index (DTW, Murphy et al. 2007), as both methods are reliable in boreal forests (Murphy et al. 2009; Ågren et al. 2014). Also, new machine learning algorithms may be useful for mapping wet soils (Lidberg et al. 2020; Ågren et al. 2021). Furthermore, improved flow routing and recognition of wet areas may support both peatland forest management (Launiainen et al. 2019) and terrain trafficability predictions (Salmivaara et al. 2020; Hoffmann et al. 2022).

1.3.2 Measuring forest attributes

At present, forest monitoring is increasingly carried out using remote sensing (RS). Of the various alternatives, airborne LiDAR has become the leading technology for the measurement of forest inventory attributes (Hyyppä et al. 2008; Maltamo et al. 2014). Stand-level forest inventories are often implemented using the area-based approach (ABA), where the prediction of different forest attributes is based on the statistical dependence between field-measured attributes and RS-derived metrics, and some non-parametric estimation method, such as *k*-nearest neighbor (Tomppo 1990; Næsset 2002; Maltamo et al. 2006).

The accuracy of an ABA-based forest inventory depends on the precision and the coverage of the field-measured sample plot data (Maltamo et al. 2011; White et al. 2013; Ruotsalainen et al. 2019). Moreover, the selection strategy of reference plots directly affects the value of the forest inventory data in decision-making (Ruotsalainen et al. 2019). Reference data of approximately 500 georeferenced field plots are collected in LiDAR-based Finnish forest inventory campaigns, although all field plots are typically placed on very productive forest lands and are therefore biased towards timber production. In non-parametric estimation methods, the reference data should cover the entire range of different forest stands because the predictions cannot be extrapolated (Maltamo and Packalen 2014), which is problematic when a decision-maker is interested, for example, in low-productive forests.

Nowadays, the pulse density used in airborne LiDAR inventory campaigns is rapidly increasing. In the 2010s, Finnish Forest Centre (FFC) used a pulse density of approximately 0.5 m^{-2} in their nationwide forest inventory campaigns, but since summer 2020, the pulse density has increased to approximately 5 m^{-2} (National Land Survey of Finland (NLS) 2022a), which enables forest inventory attributes to be predicted with improved accuracy (Jakubowski et al. 2013). In addition, new data processing methods, such as deep learning algorithms, can improve the prediction of forest inventory data from 3D point clouds (Ayrey and Hayes 2018; Hamedianfar et al. 2022).

1.4 Thesis scope and objectives

The aim of this dissertation is to produce useful information from airborne LiDAR data for peatland forest management, which may enhance precision forestry and multi-purpose decision-making in those areas. In study **I**, we tested the ABA inventory method on low-productive forestry-drained peatlands whose re-use is a topic of debate in the Finnish forestry sector. In study **II**, we developed terrain trafficability prediction models for forest soils, which may provide useful information for timber procurement on peatlands and other sensitive soils. In study **III**, I studied the added value of high-resolution airborne LiDAR data on overland flow routing and I proposed best practices to process hydrologically conditioned elevation model from LiDAR-derived point cloud data. Furthermore, the results in study **III** were used in study **IV**, where we developed spatial analysis for the placement of water protection structures within a catchment. The specific objectives of studies **I-IV** were as follows:

I. Current forest inventory practices are focused on productive forests with the strongest economic interest. However, since the changes in Finnish forest legislation in 2014, there has been growing national interest in low-productive forestry-drained peatlands (LPDP), where the growing tree stands are typically small, sparse and uneven in size. In this study, we evaluated how many field-measured reference plots would be needed to apply ABA to LPDP. The accuracy of forest inventory attributes was reported for total and species-specific stem volumes, stem number, and average stem volume.

II. Heavy off-road traffic may cause severe soil damage to peatlands and fine-grained mineral soils, which could be reduced if reliable terrain trafficability data were available. We investigated the best DEM-derived predictor variables of soil rutting and studied the potential of open-source spatial data for the generation of soil damage probability maps. The aim here was to produce useful terrain trafficability information for forest managers and entrepreneurs to assist in planning forwarding routes within harvesting areas.

III. Reliable information on water movement and flow accumulation is needed, especially in peatland forest management, where water management must be considered in every operation. In this study, I analyzed the current best practices to process hydrologically conditioned DEM from high-resolution airborne LiDAR data. This information is essential for the calculation of flow accumulation, wetness indices, and catchment boundaries in the area of interest.

IV. Peatland forestry is a key source of sediment and nutrient export to downstream waterways, which affects eutrophication, brownification, and loss of biodiversity in aquatic ecosystems. Overland flow fields and uncleaned ditch sections are cost-efficient methods to restrain the negative environmental effects of ditch network maintenance. We developed a spatial analysis workflow to place the above-mentioned water protection structures within the area of interest, which may help forest managers to plan environmentally sound operations on drained peatlands.

2. MATERIALS

2.1 Study areas and field data

2.1.1 Haapajärvi

Study **I** was implemented in the Haapajärvi municipality, which is in North Ostrobothnia, Finland (Fig. 1). The area belongs to the middle boreal vegetation zone, has a humid climate, and the mean annual volume increment of growing stock on forest land is rather small by Finnish standards: 4.2 m^3 ha^{-1} $year^{-1}$. Around 41% of the forest land is on peatlands, and 62% of peatlands on forestry land are drained (Vaahtera et al. 2021). In Haapajärvi, it is estimated that approximately 7–8% of drained peatlands are low-productive (Laiho et al. 2016).

Airborne LiDAR data was collected from the study area in 2012 and FFC measured 799 reference plots for a stand-level forest inventory in the same year. According to the FFC field sample design, the reference data were mainly allocated to productive forest stands. Thus, we measured 53 additional sample plots in 2013 from poorly growing peatland forests to augment the LPDP field data.

2.1.2 Uusimaa

Study **II** was carried out in the Uusimaa area, which is most populous region in Finland, covering 26 municipalities, including the national capital Helsinki (Fig. 1). The study area belongs to the southern boreal vegetation zone, and the mean annual tree volume growth is 7.4 m^3 ha^{-1} $year^{-1}$. In the Uusimaa region, only 11% of forest land is on peatlands (Vaahtera et al. 2021), although fine-grained sensitive forest soils are found extensively and are at risk of soil rutting during harvesting operations (Tamminen and Tomppo 2008).

An airborne LiDAR inventory was implemented for the Uusimaa region in summer 2015, and we used that data to predict the potential occurrence of soil rutting. Field data were collected from 19 harvesting stands after forwarding operations in autumn 2015. A total of 13 km of forwarding trails were mapped and assigned to three categories: undamaged (79%

of mapped trails), damaged (20%), and potential damage (1%). In addition, the following variables were either measured or estimated from 30 sample plots: 1) maximum rut depth, 2) amount of logging residues, 3) thickness of humus layer, 4) thickness of peat layer, 5) coverage of *Sphagnum* spp, 6) drainage status, 7) forest site type, and 8) soil stoniness.

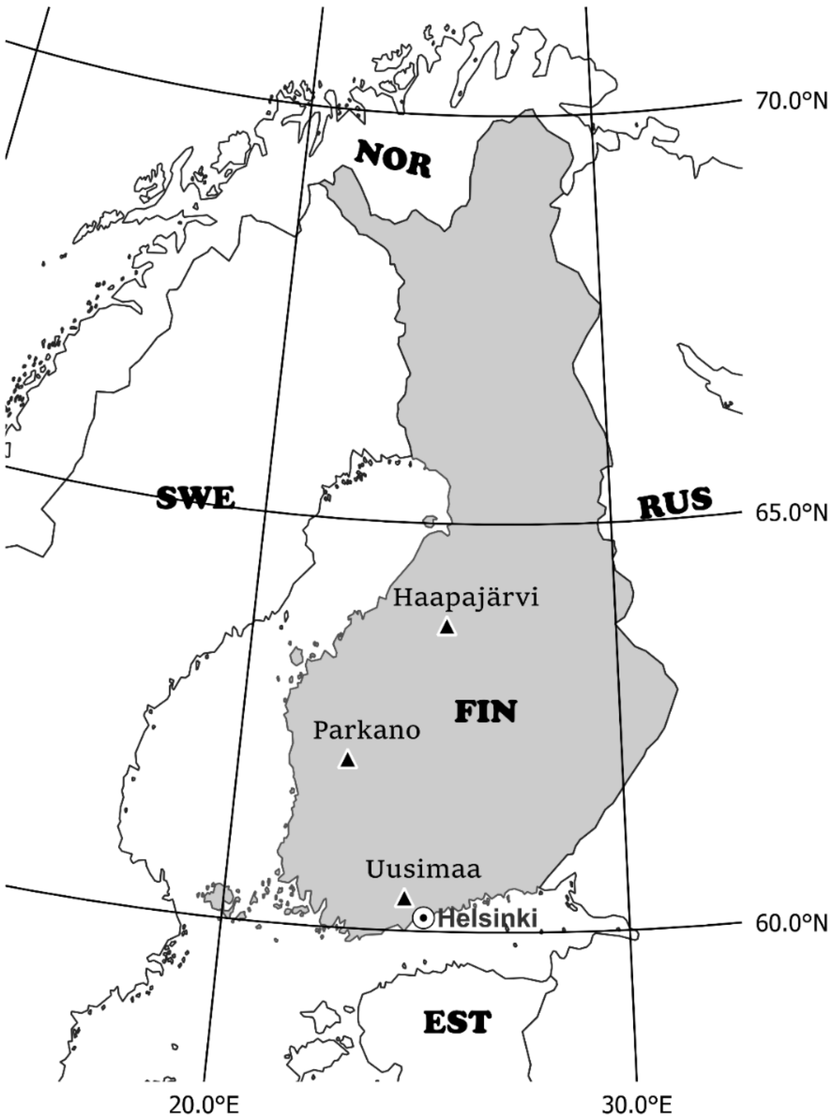

Figure 1. Map of Finland and location of the study areas: Haapajärvi, Uusimaa and Parkano. Copyright of the country shapefiles: EuroGeographics for the administrative boundaries, 2021.

2.1.3 Parkano

Studies **III–IV** were carried out in the catchment of Lake Kovesjärvi, situated in the Parkano municipality (Fig. 1). The area is located on the border of the southern and middle boreal vegetation zones. Drainage intensity is very high in this flat and peatland-dominated catchment, as approximately half of the forest stands grow on drained peatlands. Lake Kovesjärvi is classified as a water conservation hotspot area by the ELY Centre of Pirkanmaa (Alajoki et al. 2022).

The region was one of the first production areas covered by high-density airborne LiDAR data (5 m^{-2}) in June 2020. In study **III**, the topological database of Finland (NLS 2022b) was used as a reference data for stream extraction, and no field data was measured. In study **IV**, 10 suggested overland flow fields and 26 suggested uncleaned ditch sections were visited with peatland forest management professionals and researchers to see their characteristics and suitability to the suggested purpose.

2.2 Spatial data

2.2.1 LiDAR data

In Finland, the National Land Survey (NLS) is responsible for nationwide airborne LiDAR inventories and ground elevation modeling. Correspondingly, FFC is responsible for stand-level forest inventories, where airborne LiDAR has been utilized since 2010. Currently, LiDAR data are available for the whole country. In the 2010s, the pulse density of LiDAR inventories was approximately 0.5 m^{-2}. As a result of technical developments, the pulse density was increased to 5 m^{-2} in summer 2020, which will be the standard pulse density of Finnish nationwide LiDAR inventories in the 2020s (NLS 2022a). The former low-density airborne LiDAR data were used in studies **I–II**, and the high-density data were utilized in studies **III–IV** (Table 1).

2.2.2 Soil data

Information related to soil properties is typically determined by soil types (Aaltonen et al. 1949). In Finland, Geological Survey of Finland (GTK) has mapped soil types since 1972, and the data is freely available. Soil samples were drilled at a scale of 1:20000, and the soil stands were interpolated from these field measurements using terrain maps and aerial images (Haavisto 1983). However, this scale is too small to represent the considerable within stand variation in soil types, although the soil map can indicate the overall presence of fine-grained soils in the area of interest. In study **II**, the potential of the GTK soil data for terrain trafficability prediction was tested.

2.2.3 Topographic database

The topographic database is maintained by the NLS (2022b) to represent terrain properties for the whole of Finland. Elements, such as the road networks, buildings, and construction, administrative borders, geographic names, land use, waterways, and elevation, are freely available in digitized form. The road network and vectorized waterways were utilized in studies **III–IV**.

Table 1. Summary of the different airborne light detection and ranging (LiDAR) data sets. All data sets were acquired from the file service of National Land Survey of Finland (NLS).

Study	Area	Year	Pulse density	Data processing and software
I	Haapajärvi	2012	0.8 m^{-2}	Whole processing using TerraScan
II	Uusimaa	2015	0.5 m^{-2}	DEM prepared by NLS
III–IV	Parkano	2020	5 m^{-2}	Point classification by NLS, further processing using lidR and WhiteboxTools

3. THEORETICAL OVERVIEW OF THE METHODOLOGIES

3.1 Generating elevation models from airborne LiDAR data

The digital elevation model (DEM) is a representation of the ground surface, where surface objects, such as trees and buildings, are excluded, while a more specific digital terrain model (DTM) term to represent the earth’s surface also exists in the scientific literature (see Guth et al. 2021). In practice, the terminologies of DEM and DTM are used in a contradictory manner.

Airborne LiDAR data inventory produces a 3D point cloud of an environment. The subsequent DEM modeling starts with the classification of ground points from the point cloud, which is most often implemented using the slope-based filtering (Vosselman 2000). Next, the terrain model is interpolated from ground observations, and among different interpolation alternatives (triangulated irregular network (TIN), inverse-distance weighting (IDW), natural neighbor, spline, minimum curvature), universal kriging has proved to be the most accurate option for DEM interpolation (Heritage et al. 2009; Guo et al. 2010; Arun 2013).

Landscape representation and hydrological simulations are affected, in addition to the environment and terrain characteristics (e.g. slope) to be modeled, by the choices on how to classify ground points and interpolate the DEM to the chosen raster cell size, i.e., spatial resolution (Zhang and Montgomery 1994; Ariza-Villaverde et al. 2015). The spatial resolution refers to the area of land that is represented by a single grid cell. The smaller areas that are represented by a unique DEM value indicate a higher resolution. Also, higher resolution implies more detailed DEM and greater preservation of terrain features, such as artificial ditches, fallen trees, ericaceous shrubs, etc. On the other hand, a lower resolution smooths over terrain features and may give useful information of landscape topography on a larger scale (Lindsay et al. 2019).

3.2 DEM hydrologic conditioning and overland flow routing

Digital elevation models are widely used in hydrological analyses because the terrain topography significantly affects water movement in the landscape. Overland flow routing describes the process of computing water movements through the landscape, which provides information of flow accumulation in different areas (e.g., Wilson et al. 2008; López-Vicente et al. 2014). The multiple-flow-direction algorithm (Quinn et al. 1991; Holmgren 1994;

Seibert and McGlynn 2007) provides realistic information of water accumulation, soil wetness and stream network at the landscape-level (Murphy et al. 2008; 2009; Pei et al. 2010; Ågren et al. 2014).

Despite the data source, interpolation method, and spatial resolution, DEM rasters unavoidably contain depressions that affect the discontinuity in the computational flow accumulation (Jenson and Domingue 1988; Lindsay and Creed 2005). Thus, elevation models must be conditioned as "depressionless" to achieve continuous water flows though the digital landscape (Woodrow et al. 2016). Experience has shown that breaching algorithms (Martz and Garbrecht 1998; 1999) provide the most reliable model of stream networks, since it simulates culverts under bridges (Lindsay and Dhun 2015; Lidberg et al. 2017). In addition, the results can be improved if culvert locations are known, and they are burned onto the DEM raster prior to more robust DEM conditioning (Lidberg et al. 2017). Another strategy of DEM conditioning is filling (O'Callaghan and Mark 1984; Wang and Liu 2006), which may be used as a secondary option in DEM processing.

3.3 Extracting features from LiDAR data for further modeling

3.3.1 Height percentiles and density features

The use of RS-derived data in environmental modeling is based on predictor variables extracted from different data sources. There is a long tradition of extracting different features from aerial or satellite images and using them in forest inventories (Poso 1972; Tomppo 1990). Recently, airborne LiDAR has proven to be the superior data source compared to photogrammetry in forest inventories, because it is possible to measure height from ground level for all LiDAR returns (Næsset 2002; Maltamo et al. 2006). In addition, depending on the modeling purpose, predictor variables can be extracted from various different data sources, such as synthetic aperture radar (SAR, Yu et al. 2015), terrain topography, climatic data, traffic, population density or land use (e.g., Stahl et al. 2006; Hoek et al. 2008; Synes and Osborne 2011; Salmivaara et al. 2020; Frizzle et al. 2021).

The idea of extracting different height percentiles and density features from the first and the last pulses of airborne LiDAR and then applying them in forest attribute predictions was presented by Næsset (2002). Typically, two kind of predictor variables are used in practice: 1) height percentiles to indicate the height distribution of the growing trees, and 2) density features that indicate canopy closure. The set of geometric predictor variables tested in study **I** is shown in Table 2. Also, textural features extracted from a canopy surface model may contain additional information for the prediction of forest characteristics (Niemi and Vauhkonen 2016). More recently, full-waveform and radiometric features have shown potential to improve species-specific predictions of forest inventory attributes (Michałowska and Rapinski 2021).

3.3.2 Terrain topography-derived features

As terrain topography affects soil properties and soil wetness, it is reasonable to use topography-derived features for various modeling purposes, such as predicting soil vulnerability to erosion (Frizzle et al. 2021), terrain trafficability (Salmivaara et al. 2020) or augmenting forest growth models (Mohamedou et al. 2017). In general, the topography-derived features can be assigned to two classes: hydrological and textural features.

Hydrological features aim to explain water movement and flow accumulation in the landscape. The TWI and DTW indices are the most commonly used estimators of soil wetness, and they can also be used as predictor variables in environmental models, such as terrain trafficability mapping (Hoffmann et al. 2022). Also, hydrological features, such as flow direction, flow accumulation, channel length and watershed area have been tested for different environmental modeling purposes (e.g., Salmivaara et al. 2020; Frizzle et al. 2021).

Textural features are processed using the determined neighborhood of every DTM pixel. As comprehensively reviewed by Niemi and Vauhkonen (2016), there are numerous possible textural features that could characterize the texture of the most commonly used DTM statistics, such as the elevation, slope and aspect. In addition, DTM-derived terrain convexity (Iwahashi and Pike 2007) and local binary patterns (Ojala et al. 2002) are interesting options for further use that may contain useful information of terrain characteristics. In study **IV**, we presented a unique texture feature of terrain flatness perpendicular to flow direction, which was applied when placing overland flow fields.

Table 2. Predictor variables used in the study **I**.

Variable name	Variable description
$h10_f$ – $h100_f$	Point height at the *r* percentile of the first-echo points' height distribution (*r* = 10, 20... 100); ground points, i.e., points below the ground threshold (= 2 m), are excluded.
$h10_l$ – $h100_l$	Point height at the *r* percentile of the last-echo points' height distribution (*r* = 10, 20... 100); ground points are excluded.
$pene_f$	Penetration of first-echo points; calculated as the ratio of the number of ground points to the number of all points.
$pene_l$	Penetration of last-echo points.
HV_{mean}	Mean of the first-echo high-vegetation points, i.e., points above the high vegetation threshold (= 5 m).
HV_{sd}	Standard deviation of the Z coordinates for the high vegetation first-echo points.
$pc1_l$ – $pc8_l$	Ratio of the number of last-echo points with heights smaller or equal to h_{max} to the number of all last-echo points, where $h_{max} = hclass_{start} + i * hclass_{size}$ (i = 1, 2… 8; $hclass_{start} = 1.5\ m$; $hclass_{size} = 2.0\ m$).
$p8530_f$	Proportional canopy density at a height equaling 30% of the 85th percentile of first-echo points' height distribution; calculated as the ratio of the number of first-echo points below that height to the number of all first-echo points.
$p8580_f$	Proportional canopy density at a height equaling 80% of the 85th percentile of first-echo points' height distribution.
$p9030_f$	Proportional canopy density at a height equaling 30% of the 90th percentile of first-echo points' height distribution.
$p9080_f$	Proportional canopy density at a height equaling 80% of the 90th percentile of first-echo points' height distribution.
$p9530_f$	Proportional canopy density at a height equaling 30% of the 95th percentile of first-echo points' height distribution.
$p9580_f$	Proportional canopy density at a height equaling 80% of the 95th percentile of first-echo points' height distribution.

3.4 Area-based prediction of peatland forest attributes

The ABA is employed to predict forest inventory attributes using the predictor variables extracted from remote sensing (RS) data (Næsset 2002). It assumes that there is a statistical dependency between forest attributes and RS-derived features. The prediction is based on reference plots, where both forest inventory data and RS data are available. Furthermore, forest inventory data are predicted for grid cells or microsegments by searching the reference plots of the most similar predictor variables and calculating forest attributes based on the nearest neighbors (e.g., Maltamo et al. 2006). Among the alternative metrics to measure the neighborhood between the target inventory units and the reference plots, the random forest technique (RF, Breiman 2001) is a robust and flexible method for the selection of nearest neighbors (Hudak et al. 2008; Latifi and Koch 2012).

When the forest inventory attributes are predicted using the nearest neighbor method, there is typically a large set of candidate predictor variables, although the number of predictors should be significantly reduced to achieve a parsimonious subset of predictors. There should not be strong mutual correlation between any two selected predictors, thus autocorrelating variables need to be filtered out (Hudak et al. 2008; Millard and Richardson 2015). In practice, there are useful open-source tools for predictor variable selection and target variable prediction developed by Crookston and Finley (2008). In estimations, it is recommended that target variables are computed using the forest inventory attributes of the 3–5 nearest reference plots: the greater number of neighbors may improve estimation accuracy, but it decreases the variation associated with the estimated forest attributes (Tuominen et al. 2003).

Peatland forests may be a greater challenge for ABA inventories as the growing stocks are typically grouped, sparse, and uneven in size. Moreover, the ditch network divides the peatland stands into narrow strips such that there are completely different inventory units within forestry-drained peatland stands. In study **I**, we tested the prediction accuracy of forest inventory attributes in low-productive forestry-drained peatlands using a systematic grid consisting of 16 m × 16 m pixels as inventory units, which has proved to be a feasible inventory procedure when airborne LiDAR data are available (Tuominen and Haapanen 2011; White et al. 2013).

3.5 Logistic regression of terrain trafficability

Logistic regression is a common method to model the probability of a discrete outcome (Hosmer et al. 2013). In most cases, the outcome is a binary variable, i.e., something either happens or does not. In forest science, logistic regression process has been used, e.g., to model the susceptibility of forest stands to wind or snow damage (Jalkanen and Mattila 2000; Vastaranta et al. 2012; Saarinen et al. 2016). In study **II**, we used logistic regression to predict soil damage probability using DEM-derived features, with soil type and logging type as predictor variables. Another option would have been to model the scalar variable of rut depth using regression analysis as presented by Salmivaara et al. (2020).

In general, the severity of soil damage depends on the machinery used (e.g., tyre type, tyre pressure, chains), traffic load, number of passes on each track, harvesting method, placing of logging residues, and site characteristics (Sirén et al. 2013; 2019). On mineral soils, the bearing capacity increases when soil dry density or particle size increases or if soil moisture decreases (Saarilahti 2002). Also, soil stoniness and roots in the forest floor significantly increase the bearing capacity of mineral soils (Sirén et al. 2013; Rubio 2015). On peatland soils, peat shear modulus, which is a measure of soil stiffness (Ala-Ilomäki 2013) has been shown to explain terrain trafficability in combination with soil moisture and tree volume (Uusitalo et al. 2015).

As topography is the main factor that drives the spatial variation in soil moisture and its derivative variables, LiDAR-derived DEMs and flow analyses have great potential to predict the risk of severe soil damage. The review by Hoffmann et al. (2022) showed that TWI and DTW indices are widely used to produce terrain trafficability maps in several Northern and Central European countries. Currently, the development is moving towards dynamic terrain trafficability predictions where daily weather data is used to model up-to-date soil moisture conditions (Salmivaara et al. 2020). In addition, Controlled Area Network (CAN)-bus data, which measures the rolling resistance of forest machines, may be used as teaching data to predict terrain trafficability (Ala-Ilomäki et al. 2020).

4. RESULTS AND DISCUSSION

4.1 Planning the management of low-productive forestry-drained peatlands

In Finland, drainage of peatlands to increase tree growth was very intensive in the 1960s–70s, although the subsequent deterioration of the ditches has decreased their drying impact (Paavilainen and Päivänen 1995). Water management is essential in peatland forestry as the level of groundwater table significantly affects the growth of peatland forests and is a precondition for profitable forestry (Sarkkola et al. 2012). On fertile peatland sites, tree transpiration alone is sufficient to maintain a water table, but in infertile areas the water table rises when the ditch network deteriorates (Sarkkola et al. 2013). The simulations presented in Hökkä et al. (2017) have shown that the financial benefits of DNM are minimal on the poorest peatland sites, but negative environmental effects may be considerable. Thus, it is questionable how-to re-use LPDP when profitable timber production is not possible (Tolvanen et al. 2018).

In study **I**, we tested area-based forest inventories in LPDP. We suggested that allocating approximately 30 additional reference plots in LPDP, compared to field sample focused on productive forests, improved the prediction accuracy and reduced bias of forest inventory attributes in LPDP. Nevertheless, the influence of the considerably higher proportion of productive forest plots can be seen from the results and the representativeness of the field sample should be further analyzed considering possible design bias in its allocation. However, the reference data must cover the full range of vegetation variability, and study **I** proposes one way that may be refined for different areas. Furthermore, Laiho et al. (2016) provided the volume threshold required to classify peatlands as either productive or low-productive stands.

The LDPD are potential areas for restoration because their economic value is low, and they can offer important habitats, e.g., for grouse (Miettinen 2009). In peatland restoration, the objective is to return the natural hydrological functioning as much as possible (Similä et al. 2014). In study **III**, I studied methods to model water flow networks and flow accumulation within a peatland-dominated catchment. Korpela et al. (2009) concluded a high vertical accuracy for different peatland surfaces based on essentially similar workflow and data for ground classification and DEM at 1 m resolution. The results of study **III** can therefore be probably safely generalized to mineral and peatland soils similarly homogeneous for their microtopography. New tools to process hydrologically conditioned DEM and calculate water movements may enhance the planning of peatland restoration. Also, it is worth noting that peatland restoration may temporarily increase nutrient and sediment loading in aquatic ecosystems, although rewetting over the longer term is expected to prevent declines in water quality (Martin-Ortega et al. 2014; Shah and Nisbet 2019). In any case, the results reported in study **IV** can be applied when water quality is a consideration in peatland restoration projects.

4.2 Mapping within-stand soil wetness variation

Peatlands and fine-grained mineral soils are vulnerable to rutting and compaction during heavy off-road traffic. In study **II**, we tested the possibilities of using airborne LiDAR-derived DEM for mapping within-stand terrain trafficability variation, which is strongly dependent on soil wetness. In general, modeling water movements at the landscape-level is essential to identify wet forest soils. Furthermore, the impact of soil wetness on terrain trafficability strongly depends on soil type (Elbanna and Whitney 1987). All these responses must be considered when developing dynamic terrain trafficability maps (Salmivaara et al. 2020), which is a notable future research direction.

The novel finding of study **II** was the calculation of local binary patterns (LBP, Ojala et al. 2002) of DEM, and the application of the LBP-derived predictor variables to terrain trafficability predictions. Originally, a single LBP consisted of eight binary values computed from the circular neighborhood of the pixel of interest, and this approach has been used, e.g., for face recognition of image processing (Chan et al. 2007). The premise of using LBP-features in terrain trafficability predictions was to model the small-scale terrain variations that may explain the within-stand variation in soil damage, i.e., local sinks and peaks in the landscape can be automatically determined this way (Fig. 2). A similar approach for landform classification was presented in Jasiewicz and Stepinski (2013) and clearly illustrates the scale dependency of these patterns.

Study **II** was targeted at mineral soils, although the results can also benefit peatland forestry because forwarding routes (i.e. trails used for timber transport) typically lead from peatlands to forest roads via mineral soils. On mineral soils, route selection may affect the level of soil damage (Suvinen 2006). In previous studies, the TWI and DTW indices have been shown to be useful in terrain analyses (Murphy et al. 2009; 2011; Pei et al. 2010; Campbell et al. 2013; Ågren et al. 2014), and so it was assumed that both wetness indices would prove useful in study **II** too. Overall, a prediction accuracy of 85% was achieved in modeling soil vulnerability to rutting in study **II**. More recently, the DTW index in particular has been widely applied in terrain trafficability predictions (Hoffmann 2022), and Schönauer et al. (2021) have presented promising results of spatio-temporal soil moisture and soil strength predictions using this index. All the earlier studies could be improved using the findings of study **III**, as the overland flow routing and the derivative wetness indices were better modeled using the high-resolution LiDAR data.

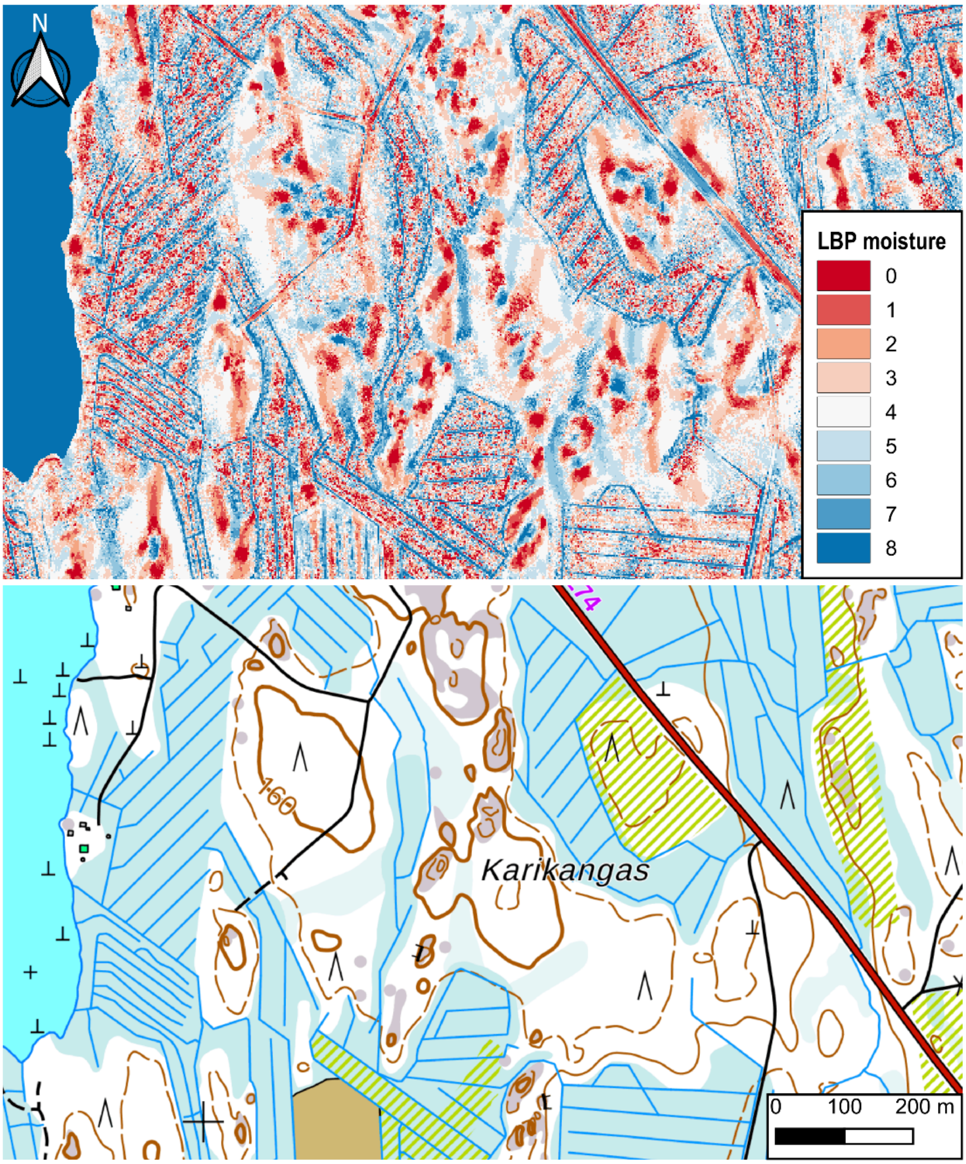

Figure 2. Illustration of the local binary pattern (LBP)-derived moisture index in the Parkano study area. The binary patterns were calculated using a radius of 20 m. The highest index values represent local depressions or valleys, and the lowest index values represent local uplands. A detailed description of this feature and speculations about the search radius are presented in study **II**. Copyright of the background map: National Land Survey of Finland, 2022.

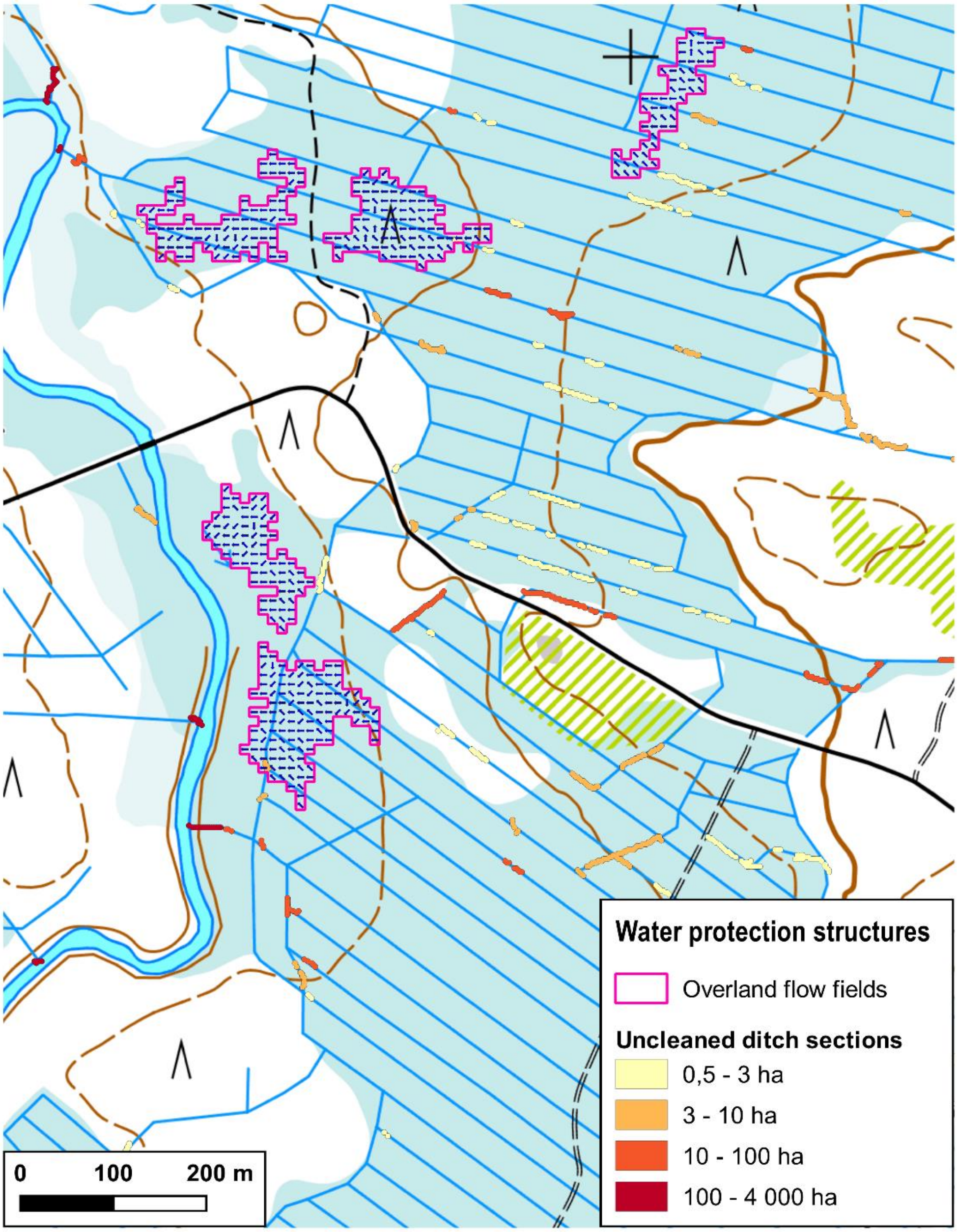

Figure 3. Example map of suggested overland flow fields and uncleaned ditch sections in North Ostrobothnia, Finland. The color ramp of uncleaned ditch sections represents the upslope flow accumulation area (in hectares). Copyright of the background map: National Land Survey of Finland, 2022.

4.3 Placing water protection structures within the landscape

Peatland forests are hotspots of sediment and nutrient loading (Finér et al. 2021), thus water protection must be carefully considered in DNM and restoration operations. In study **IV**, we developed spatial analyses to identify suitable locations for water protection structures within the forested catchment. In Finland, maps of wetness indices, flow accumulation, erosion risks etc. are freely available for forest managers planning operations on peatland sites, although the use of these maps and the success of water protection plans is highly dependent on the competence of the forest managers. To the best of our knowledge, our idea to automatically suggest locations for overland flow fields and uncleaned ditch sections is unique. The spatial analyses were developed in the study area of Parkano, but reasonable suggestions were later processed for the Tilanjoki catchment (64°58'N, 27°15'E) in North Ostrobothnia as well, using the same workflows presented in study **IV** (Fig. 3).

Study **III** was necessary prior to study **IV** as reliable modelling of overland flow routes was needed for further development of the algorithms employed to suggest water protection structures. Moreover, prior to study **III**, there was a lack of knowledge as to how high-density airborne LiDAR affects hydrological simulations. The main aim of study **III** was to determine good practices to process hydrologically conditioned DEM for overland flow routing and other hydrological purposes. In total, 85% of real flow channels were found when overland flow directions were automatically modelled from high-density airborne LiDAR data using IDW or kriging interpolation. Earlier knowledge supports my observations from study **III** that (a) kriging should be the preferred alternative in DEM interpolation (Heritage et al. 2009; Guo et al. 2010; Arun 2013; Chu et al. 2014), and (b) the breaching algorithm worked well in DEM conditioning (Woodrow et al. 2016; Lidberg et al. 2017).

Study **IV** proved that it is possible to develop an algorithm that automatically suggests water protection structures in a landscape. However, the pilot study was confined to the small catchment of Lake Kovesjärvi and we have no knowledge as to how these models would function in a different topography. Regardless, based on the field observations with peatland management experts and researchers, the results were promising but more testing and some developments are still needed, as explained in study **IV**. Of note, the idea of using median filtering (Huang et al. 1979) in DEM pre-processing worked well for this purpose, as the filtering made it possible to analyze the terrain topography at a larger scale while removing small-range characteristics from the DEM. In general, airborne LiDAR offers good and uniform quality data for analyzing terrain properties and for the development of new solutions that may be useful in forestry or other land uses.

5. CONCLUSIONS

This thesis covers a wide range of topics that are key questions in peatland forestry: production of information for forest inventories, peatland restoration, soil bearing capacity, ditch network maintenance, and water protection. However, continuous cover forestry and carbon sequestration are not defined in this study. Information of forest inventory attributes is needed for decision making, e.g., timing of harvesting operations and/or classifying peatland soils as either productive or non-productive stands from economic perspective. While numerous papers have focused on methods to develop airborne LiDAR based forest inventories, study **I** was justified as it targeted low-productive forestry-drained peatlands, which have considerable potential from a peatland restoration viewpoint. In retrospect, more general conclusions could have been made by analyzing the possible design bias of the field sample emphasized on productive forests. Adding a broader set of textural, full-waveform, and/or radiometric features, also those related to terrain and not only canopy surface, may further have improved forest inventory attribute prediction in low-productive peatland forests.

Study **II** focused on the question of terrain trafficability (i.e., soil load-bearing capacity), which will be one of the key challenges for the Finnish forest sector in the decades ahead as the average soil frost season shortens (climatic changes), and an increasing amount of timber supply will come from peatland forests. Study **II** was especially justified due to the novel idea of applying DEM-derived local binary patterns (that included additional information) to the conventionally used wetness indices in soil damage probability predictions. Overall, study **II** proved that within stand variation in soil load-bearing capacity can be predicted and mapped using LiDAR-derived DEM for mineral soils. The models are also applicable to forwarding from peatlands via mineral soils, but terrain trafficability should be further quantified on actual peatland surfaces.

The two first studies in this dissertation applied low-density airborne LiDAR data (i.e., pulse density of 0.5 m^{-2}), although high-density LiDAR data of 5 pulses per m^2 were available for the two later studies. Study **III** was justified as knowledge as to how LiDAR point density affects the hydrological derivatives of DEM was lacking. Study **III** presents good practice guidance for the processing of hydrologically conditioned DEM from the airborne LiDAR inventory 3D point cloud. Thus, the results can assist in environmental models where soil moisture is a consideration. Nevertheless, as overland flow routing does not necessarily follow the same pattern in both mineral and peatland soils, the treatment of hydraulic conductivity in DEMs for peatland soils should be studied more thoroughly in the future.

Water quality must be considered in peatland forestry. There is evidence that peatland forestry has caused eutrophication, turbidity, and brownification of water bodies, thus sediment and nutrient loading must be controlled. Downstream waters can be protected, e.g., by leaving uncleaned ditch sections wherever possible, or by placing water protection structures between the ditched area and the clean waterways. Study **IV** presented a novel way to automatically suggest water protection structures in a forested landscape. The weakness of study **IV** is the lack of quantitative evaluation, which would probably require developing new methodology to assess tradeoffs of the proposals from various economic, ecological, and e.g. hydrological aspects affecting sustainable peatland forest management.

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