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Unpaved forest road quality assessment using airborne LiDAR data

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Academic Dissertation

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ABSTRACT

This study creates new methods for assessing unpaved forest road quality using airborne laser scanning (ALS) data. The low and high pulse density ALS data were first processed and digital elevation models (DEMs) created at several resolutions from 0.2 m to 1 m. Different interpolation methods such as IDW, NN, Spline and Kriging were compared in the first phase, and IDW was chosen for further calculations. The work focuses on road quality properties such as surface flatness, surface wear quality, road structure, ditch quality, road drying properties and water accumulation, and also the vegetation cover on and beside the road.

The roads were divided into three categories using the Metsäteho forest road quality assessment system. Active/deactivated road status was assessed on Vancouver Island, Canada. Linear discriminant analysis was used to find the best predictors of the road quality classes, the result being validated using confusion matrices, by k-fold cross-validation, and/or by calculating kappa values. A combination of surface indices, the topographic wetness index and soil information provided high precision (81.6-89.8%) information about unpaved forest road quality. Simultaneously, the indices individually showed promising results when applied to high pulse density data. The classification based on vegetation growth was up to 73% correct, while the presence of a ditch system and its status as mapped using the high resolution LiDAR data was up to 92% correct.

The findings indicate that the use of LiDAR data can help forest managers gain more information about the quality and status of forest roads in remote areas without spending extra resources (time, transportation costs, personnel) on checking the road network manually. Although the use of ALS data for road quality assessment cannot yet replace field visits, it opens up possibilities for further research and offer the option of combining these novel approaches with other road assessments.

Keywords: forest road, road quality, LiDAR, ASL, road classification, forestry

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With reference to the Vancouver Island study (Paper III), I would like to thank Professor Nicholas C. Coops of the University of British Columbia, Canada, for his invaluable guidance during the work and help in finalizing the paper. Secondly, I would like to thank Dr. Piotr Tompalski and the whole UBC crew for their help with the field work and data processing, and thirdly Joanne C. White and Michael Wulder from the Canadian Forest Service for their time and suggestions, and WFP for the data and for access to their harvesting sites.

My thanks also go to all my fellow PhD students and friends, especially to Radu, Andrei and Anja, who were cheering each other on, providing support when needed, or simply going off skiing together somewhere in the beautiful Finnish countryside.

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Rovaniemi, 19th January 2021
Katalin Waga

LIST OF ABBREVIATIONS

ALS	*Airborne Laser Scanning*
DCP	*Dynamic Cone Penetrometer*
DEM	*Digital Elevation Model*
DTM	*Digital Terrain Model*
HCT	*High Capacity Transport*
FWD	*Falling Weight Deflectometer*
LDA	*Linear Discriminant Analysis*
LFWD	*Light Falling Weight Deflectometer*
LiDAR	*Light Detection and Ranging*
LOOCV	*Leave-One-Out Cross-Validation*
MALS	*Multispectral Airborne Laser Scanning*
SE	*Standardised Elevation*
SQI	*Surface Quality Index*
TPI	*Topographic Position Index*
TWI	*Topographic Wetness Index*

LIST OF ORIGINAL PUBLICATIONS

This PhD thesis consists of an introductory review followed by five research papers which are referred to in the review by their Roman numerals. These papers are reproduced with the permission of the publishers.

I Kiss K., Malinen J., Tokola T. 2015. Forest road quality control using ALS data. Canadian Journal of Forest Research, 45(11): 1636-1642, https://doi.org/10.1139/cjfr-2015-0067.

II Kiss K., Malinen J., Tokola T. 2016. Comparison of High and Low Density Airborne Lidar Data for Forest Road Quality Assessment. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., III-8, 167-172, 2016 https://doi.org/10.5194/isprs-annals-III-8-167-2016

III Waga K., Tompalski P., Coops N.C., White J.C., Wulder M.A., Malinen J., Tokola T. 2020. Forest Road Status Assessment Using Airborne Laser Scanning, Forest Science, 66(4), 501–508, https://doi.org/10.1093/forsci/fxz053

IV Waga K., Malinen J., Tokola T. 2020 A Topographic Wetness Index for Forest Road Quality Assessment: An Application in the Lakeland Region of Finland. Forests, 11(11), 1165. https://doi.org/10.3390/f11111165

V Waga K., Malinen J., Tokola T. 2021. Locally invariant analysis of forest road quality using two different pulse density airborne laser scanning datasets. Silva Fennica, 55(1), 10371. https://doi.org/10.14214/sf.10371

Katalin Waga was the primary author of all five papers with the main responsibility for the research design and realization, analysis and reporting of the results, *and is fully responsible for the summary part of the doctoral thesis "Unpaved forest road quality assessment using airborne LiDAR data".* As the primary author, she prepared the data, conducted most of the analyses and implemented the required modelling routines. The field work was carried out with the help of some of the co-authors, and the writing of the papers involved collaboration between all the authors, although the first author was responsible for formulating the first draft, for submitting the paper and for correspondence with journal editors, with the exception of Paper III, where Professor Nicholas Coops was the corresponding author and assisted immensely in finalizing the paper.

CONTENTS

1 INTRODUCTION

1.1 Forest road quality

The quality of forest roads is an essential consideration for maintaining reliable wood supplies for industry and guaranteeing smooth forestry operations. Especially in countries with huge areas of forest, manual road quality check-ups are laborious and expensive to carry out regularly, but quality checks and road maintenance are essential not only for forest management and timber harvesting (the harvesting machines need access to the forest sites), but also for ensuring access for emergency vehicles such as fire engines, for wildlife protection operations and for visitors seeking recreation in the forests. These groups often use the same ageing road network.

There is an even greater need for road quality control and maintenance in Finland than in the rest of Europe. The size and the weight of the truck increased significantly during the last decades (Table 1). Finland has the highest permitted weight of heavy transport vehicles in Europe, 76 tonnes, and even larger vechicles, so called HCT (High Capacity Transport) vehicles, 34.5 m long and weighing 104 tonnes, were tested between 2015 and 2019 to reduce fuel consumption per unit volume of timber transported (Yle.fi 2019; Boholm 2019) and their current use are bind to special permits (Metsäteho 2020). With the increased weight, the length of the trucks increased as well, since 2019 it is 34.5 m (instead of 25.25 m) (Valtioneuvosto 2019). It is important to note, that the maximum permissible weight depends on the number of the axles, and the current 76 tons applies to vehicles with 9 axles (Korpilahti 2013).

Table 1. The change of maximum permitted weight of the trucks operating on public roads in Finland, based on Korpilahti and Koskinen (2012) and Valtioneuvosto (2019)

Date	Max allowed weight (t)
04.02.1938	10.5
01.06.1948	16.5
17.06.1955	20.1
01.12.1957	24
01.07.1961	30
01.08.1966	32
10.09.1971	35
01.07.1975	42
01.04.1982	48
01.01.1990	56
01.01.1990 in winter	60
01.07.1993	60
01.10.2013	76

Although these weight limits are valid for paved roads, the timber trucks often need to drive on unpaved forest roads too, where weren’t constucted to sustain even similar load (Malinen et al. 2014), however, the Finnish Transport and Infratructure Agency (Väylävirasto 2021) may impose weight limits for short periods of times on certain unpaved forest roads too if the conditions, for example, spring thaw, hinders save transportation and driving conditions or to prevent serious road damage. As has been seen as the result of the rapid changes in vehicle sizes, the current Finnish system of forest roads was built for far smaller vehicles and these increments have had a serious impact on the unpaved forest roads too, so that the extent of their deteoriation now needs to be monitored.

Although these HCT vehicles may affect road quality negatively, other, positive outcomes motivates these trials. In an assessment when the vehicle size was increased from 60 to 74 tonnes, the fuel consumption decreased by 10% (Anttila et al. 2012). The use of even bigger HCT truck means not only the transport costs of timber and by-product chips would decrease by EUR 17.8–82.7 million € per year, but fuel consumption would also decrease by 5.6–20.1%, therefore CO2 emissions would be reduced significantly as well (Metsäteho 2020), therefore the economic and environmental motivations are notable.

In addition to unpaved forest road quality and maintenance, it is important to find a balance between optimising and maintaining the road network while reducing the environmental importance of roads and operations connected with them, as roads have a long-term impact on the forest ecosystem. Forest roads modify the hydrological cycle: they create a barrier and their compact surface reduces infiltration, changes water flows and interferes with wildllife (Grayson et al. 1993; Rummer et al. 1997; Forsyth et al. 2006; Jordán and Martínez-Zavala 2008; Boston 2016). Road consructions also cause substantial environmental damage to forests (Kan 2013). Stream crossings, usually culverts in British Columbia, can negatively affect fish and aquatic ecosystems (BC Ministry of Environment 2007) Several studies have addressed forest road construction and maintenance (Coulter et al. 2006; Gjahar et al. 2013) with the idea of reducing costs and leaving more profit for the forest owners (Ross et al. 2018).

Trafficability and bearing capacity are two important characteristics of unpaved forest roads. Bearing capacity means the roads' ability to sustain traffic without damage to their structure, while trafficability includes driveability elements as well, although it is often used as a synonym for bearing capacity. Driveability defines how fast you can drive or how much you have to steer to avoid obstacles on the road surface. For example, good drivability means if the allowed speed is 80km/h on a certain road section, is it possible to drive without extra attention and without too much steering or slowing down due to holes. Good trafficability also includes that the road body would not get damaged from the ongoing traffic Thus driveability factors are closely connected with road condition factors such as vegetation or surface conditions (Uusitalo et al. 2012; Kaakkurivaara et al. 2018).

Road trafficability can be classified according to whether the road is trafficable during the spring thaw, summer, dry summer, or wintertime (Venäläinen et al. 2009; Kaakkurivaara 2018) Spring thaw trafficability means that the road is trafficable at any time of the year, as the period after the snow has melted in spring is the most crucial time. Roads having trafficability only during the summer or only in a dry summer are less trafficable, while wintertime trafficability refers to roads that can be driven on only during the period when the ground is frozen. Road trafficability not only changes seasonally, but shows more rapid variations as well. Daily road conditions (so called ‘dynamic factors’) include the prevention of skidding, snow clearing, and frosting (increasing bearing capacity). These can be inventoried by means of smartphones, crowd sourcing, and machine vision, for example (Vaisala RoadAI 2020).

Forest roads can be divided into three classes based on their carrying capacity, driving speed, seasonal availability and expected lifespan (Pulkki 2003; Uusitalo 2010). Primary roads are built for continuous, -year-round operation, and their role is to enable haulage from secondary and spur roads. Secondary roads should function well also in autumn and difficult wet seasons. The forest roads in the lowest category, often referred to as spur roads, have the primary aim of providing access to timber harvesting sites. In Eastern and Northern Finland where water bodies freeze efficiently, winter roads are prepared to access harvesting sites as well, these are so called temporary ice roads (Metsähallitus 2021).

The biggest challenges of unpaved forest road maintenance is similar, yet, different in certain aspects in Canada and Finland (Table 2). First, I introduce the situation in Finland then Canada.

Finland's forest road network is huge, and most of these unpaved roads were built 30-50 years ago and will require maintenance in the coming years. Current inventory procedures require visiting the roads, even in remote locations. The yearly cost of cleaning drainage ditches and basic road maintenance for about 3800 km of unpaved forest roads is about 60 million euros (Finnish Statistical Yearbook of Forestry 2013). Airborne laser scanning data could efficiently help to locate these problematic road sections and reduce the time spent on inventories of road quality, as the data collected in this way cover vast areas.

The National Resources Institute Finland (2019) analysed numerous aspects of timber harvesting and transportation in Finland to explore new ways of saving costs and opening up new business opportunities for small and medium-sized enterprises. This consisted of analysing environmental factors and soil properties (including soil moisture, tire track-soil interference, bearing capacity and soil deformation) in order to increase the efficiency of forest operations and reduce their environmental effect and fuel consumption.

The problems related to timber transport in Finland include a number of road quality issues, some of the most pressing of which are winter maintenance, which includes the removal of snow and ice and slip prevention, the bearing capacity of roads, frost-damaged roads, including spring and autumn damage, road surface conditions and grading of the surface (Malinen et al. 2014).

Table 2. The biggest challenges regarding the maintenance of unpaved forest roads in Finland and Canada

Finland	Canada
aging forest road network	aging forest road network
dense forest road network	remoteness of forest roads
increasing vehicle sizes	quality of existing road network (and status deactivated roads)
determining the roads that require the most urgent maintenance	road safety concerns

Another financial aspect of forest road maintenance is connected to their remoteness. The forest areas in Finland and Canada are extensive and the majority of them are located far away from settlements, so that a lot of resources, including time and money, are required to verify the quality of all the roads. Whereas the remote location in Finland is challenging, it is even more of a challenge in British Columbia where there are over 800 000 km of roads in British Columbia alone, and 74% of them are connected with the forest industry: mainly roads in felling areas and hauling roads (Forest Practices Board 2015). Half of the road network is over 30 years old and will require more maintenance in the coming decade, even though currently the focus is on building new hauling roads.

In order to reduce maintenance costs, moderate the influence of roads on wildlife and stimulate forest regeneration where roads are no longer needed for harvesting or other purposes, such as fire safety, roads may be left without maintenance, "deactivated" (Forest Practices Code of British Columbia 2002), but this should only be done after a thorough analysis of the area as the deactivation of roads can cause slope failures and extensive environmental damage, especially in steep terrain (Clay 2004). The need for deactivation can also be approached from financial angle, as the optimization of logging routes, minimization of transport distances, and reduction of the costs of keeping roads active can lead to significant savings: in one area studied in British Columbia it was found that optimization of the forest road network could lead to savings of CAN$ 0.24 for every m^3 of timber logged (Anderson et al. 2006).

The deactivated roads in British Columbia can be divided into three categories: temporary, semi-permanent, or permanent deactivation (Forest Practices Code of British Columbia 2002). Temporary deactivation (or winterization) is the term for a procedure in which regular inspections are still carried out but no other maintenance activities. A road can be temporarily deactivated for up to 3 years. Semi-permanent deactivation is for a period of over three years, when the road is left in a self-sustaining status, without regular inspections. Permanent deactivation, as its name suggests, is a long-term strategical change in road function which includes removing culverts and bridges and recontouring the roadbed in order to encourage the vegetation and wildlife to reclaim the area.

Road safety is a major concern in BC, Canada (Resource Roads 2021). One aspect is their quality for harvesting timber, another aspect concerns other road users. The resource roads neither built using the same standards as paved roads or public highways, nor have the same maintenance priority. Loose gravel surfaces are common, the roads are often only one lane wide, and there are no traffic signs indicating road hazards such as potholes, sharp turns, steep sections or road blocks. Recently deactivated roads may have vegetation over the road body or shoulders, further hinder visibility and trafficability. Besides informing road users of these hazards (BC Forest Safety 2021), regular road quality assessments would help creating a database of these road conditions and deactivation status.

1.2 Forest road inventories

Forest road inventories are primarily carried out by means of field assessments, often using guidelines that give space for personal judgements, too. Although some parameters can be measured, others can only be estimated.

The trafficability of forest roads can be estimated by assessing their bearing capacity by means of penetrometers or a falling weight device (Kaakkurivaara et al. 2015). Some of the most frequently used devices are the light falling weight deflectometer (LFWD), dynamic cone penetrometer (DCP) and conventional falling weight deflectometer (FWD). Based on four-year sampling in springtime, Kaakkurivaara (2015) found that the cheaper hand-held devices can assess forest roads with great precision. One such LFWD device is the Finnish-made Loadman (AL-Engineering 2020), which is a reliable tool for assessing trafficability if there is no need to consider the quality of the subgrade. There are also other alternative and more experimental methods for measuring bearing capacity, such as those for analysing the geometrical properties of sand and gravel and the percentage of shells in coarse aggregates, or for measuring bearing capacity and compaction levels with a light drop weight that was used on a Latvian test site (Berg and Talbot 2019).

Approaches to the automation of road extraction and associated features such as road width or road surface have primarily focused on the use of terrestrial laser scanning in urban areas (see Goulette et al. 2006; Kumar et al. 2013; Fernandez et al. 2014), but these have been tested mainly for forest inventory purposes (Bauwens et al. 2016) and to some extent also for forest road assesment (Beck et al. 2020). The inventory methods currently in use in Finland for forest road quality require visits to the road sites and the inventory is often based on the subjective classification of visible road conditions using the Metsäteho criteria as introduced in the Materials section (Korpilahti 2008). According to this highly empirical assessment, good quality roads may be defined by reference to several different quality standards that take road structure, visibility and water transportation into consideration. A good quality road will have its surface and its immediate surroundings clear of vegetation, which means that the road body can dry out well. The ditch system will transport a sufficient amount of the water away so that it will not accumulate and cause structural damage. The wearing layer and the road surface should be smooth, and there should be no ruts and potholes to restrict driving speeds or alter driving patterns. Roads in the satisfactory and bad quality classes can be expected to slow transportation down and possibly damage vehicles (Haavisto et al. 2011). Both LiDAR and photogrammetry have been used in pilot projects to assess rut depth (Nevalainen 2017; Salmivaara 2017), with varying success.

The rapid development of laser scanning techniques has revealed a potential for deriving quality information from data on forest roads obtained using remote sensing techniques. Laser scanners can be mounted on a variety of vehicles: airplanes, helicopters, drones, or cars. Unmanned Aerial Vehicles (UAVs), or drones, are being used more and more frequently to examine roads when the sole interest lies in the roads themselves and quality information is not merely a by-product of a forest inventory (Buğday 2018).

UAVs has been studied during the last decade as platforms for the collection of road data with the aim of developing methods and processes for constructing forest roads (Buğday 2018) and for quantifying surface conditions on unpaved roads as well as for forest inventories (Wallace et at. 2012). This has led to the identification of "surface distress" by means of the 3D reconstruction and analysis of rural roads (Zhang 2008). Wearing layer damage was predicted by UAVs with a precision of up to 2 cm on a 500 m stretch of heavily damaged road in the Czech Republic (Hrůza et al. 2016).

Car-mounted laser scanner devices (Mobile Mapping 2020) can provide high-pulse density point clouds, too, and there have been novel approaches to Hand-Held Mobile Laser Scanning (HMLS), too (Kaartinen 2012; Ryding et al. 2015, Bauwens et al. 2016, Balenović 2021) not only to forest inventories, but enabling this to be used as an alternative tool for road assessments. Mobile Laser Scanning (MLS) offers opportunities for road research using both UAV and car-mounted sensors (Jaakkola 2015). Other alternatives include crowd-sourced road data (Venäläinen 2018) such as timber trucks and other vehicles collecting quality related information from lower rank roads using mobile phones while driving on them. These collected data via the RoadAI pilot project can then be processed through machine vision to obtain information about road conditions, such as roadblocks, snow cover or surface condition (Forests.fi, 2018; Metsäteho.fi. 2020).

However, all the currently available methods still require field visits (Metsäteidenkuntokatselmus 2017) – whether the road quality reports are filled in on paper or online - but there is an urging need for a solely remote sensing based way to inventory forest roads.

1.3 Airborne laser scanning-based road quality assessment

The forestry application of Airborne Laser Scanning (ALS), which in turn is a type of Light Detection and Ranging (LiDAR), is primarily used world-wide to collect data for forest resource inventories where the main tasks are species recognition and forest stock estimates (Maltamo et al. 2014; Næsset 2015), in addition to which there are now increasing numbers of research projects aiming to provide additional data for forest managers using these laser point clouds. Although ALS and other remote sensing data-based forest inventories are now commonly used to predict stand characteristics (Næsset 2002), some cases have been reported, for example, in which inventories of seedling stands are not accurate enough (Imangholiloo et al. 2019). Nonetheless, the data collection usually takes place when the forest management plans are being carried out, so that information about the quality of forest roads can be retrieved from this source as well.

The different road detection methods that are available vary greatly in their precision. In a comparative assessment of close range photogrammetry, terrestrial laser scanning, mobile laser scanning and airborne laser scanning, close range photogrammetry was found to perform best, with an RMSE of 0.0110 m, while that for terrestrial laser scanning was 0.0243 m and that for airborne laser scanning 0.1392 m (Hrůza et al. 2018). However, besides precision, the time required to collect the data for a certain area and the costs of doing so are also important factors in large-scale road quality assessments. The technology available in this field is also developing rapidly, one of the most promising new areas being that of multispectral sensors (Teledyne Optech 2019).

Depending on the canopy cover, the basic road geometry can usually be extracted best from low pulse density LiDAR data (Craven and Wing 2014). Azizi et al. (2014) used such data to interpolate DTM, DSM, and DNTM layers at resolutions of 1 metre in order to extract road locations. Their results achieved 63% correctness, but 95% of the LiDAR-derived road length was digitized to within 1.3 m of the roads in the field inventory. A heavy canopy cover will often hinder road detection, but multi-resolution segmentation can greatly increase its precision (Sherba et al. 2014).

High pulse density data can provide even more details. White et al. (2010) in the United States used a 12 pulse per m^2 point cloud to generate a DEM with 1 m resolution using ground points, and then to extract the positions of the roads, analyse their gradients and calculate the total length of forest haul roads. In steeper terrain in the French mountains, ALS data with 2-4 points per m^2 were used to extract forest roads with 80% detection success. The roads were detected by their morphological properties, and filters and supervised Random Forest classifications were employed to fill in the gaps in the road network (Ferraz et al. 2016). Road surface analysis using high and low pulse density ALS data was used to determine the quality of unpaved forest roads in the Lakeland region of Finland. Similarly a 11.6 points per m^2 ALS dataset was used to classify forest roads in Northern Vancouver Island, Canada, based on their vegetation status, the main being was to help forest managers verify the status of the more remote forest roads (active or deactivated). In this case 73% of the roads were assigned correctly to one of the four categories.

Having a clear and up to date inventory and overview of active forest roads is an important financial asset as well. A route-finding algorithm (Ross et al. 2018) that calculated least-cost hauling routes for the Upper Clearwater River Area in Washington, US, led to a decrease of 14.5% in the length of active forest roads and afforestation in those areas meant an increase in forest value of over half a million USD.

The Topographic Position Index and Standardised Elevation Index are surface indices used for analysing slopes and terrain morphology (Jenness Enterprises 2013). Their main areas of application are geomorphology and hydrology. Wetness Indices derived from Digital Elevation Models were originally used in hydrological modelling and have also been applied in forestry to assess the effects of topography on soil moisture (Gessler et al. 2000). Numerous methods exist for calculating the index, and Sørensenet et al. (2006) found that there is no single best algorithm in the case of Fennoscandian boreal forests, as the TWI values are site-specific. Topographical wetness models are used to assess and predict forest growth, as was the case when Byun et al. (2013) created a regression model to explain autocorrelation between forest growth and, topographic and climatic factors. The application of TWIs to the assessment of forest road quality was a novel approach.

1.4 Research gaps

The quality assessment of unpaved forest roads is mostly carried out by manual work and based on subjective evaluations both in Finland and Canada. There is a need to make the assessment more qualitative and automated, as covering large and remote areas and dense forest road networks takes time and requires resources due to the field visits, and therefore only occasionally updated databases are available.

1.5 Objectives of this thesis

Forest road quality control is a time-consuming task, but it can help reduce road management costs and allocate resources to the most urgent renovation needs. While in Finland the aging forest road network requires extent maintenance in the upcoming year, in Canada one of the biggest challenges to assess the existing road network system before building new forest roads.

Although bearing capacity cannot be assessed without field measurements, other trafficability criteria can be derived and assessed from remote sensing data. The quickly developing technology enables new tools, such as ALS to use for unpaved forest road quality assessments, and this thesis presents methods how this can be carried out.

The ALS data is usually collected when forest management plans are prepared, although they have not yet replaced field inventories, as inventories of seedling stands, for example, are not yet accurate enough. Road quality maps can be byproducts that forest managers could receive alongside an ALS-based forest inventory. Also, depending on the future cost structure, drone-based data collection systems might also provide a feasible alternative source of data for these techniques,

The present doctoral research was aimed at developing a method for determining the quality properties of unpaved forest roads and providing forest managers with information to meet the resulting renovation needs or information about the success of road deactivation, and with these, introduce methods that can be used to quantify forest road quality and automate the assessment. The road quality properties assessed here include the vegetation cover, ditch system and road surface conditions. Both in Finland and in Canada the research made use of the same ALS dataset as had been acquired for forest inventory purposes.

The detailed objectives were:

- to test novel methods for using surface quality indices to evaluate unpaved forest road quality properties such as surface wear, flatness, structural condition and ditch systems using high-density ALS data (Papers I and II),
- to compare low and high pulse density ALS datasets when used for unpaved forest road quality assessment (Papers II and V),
- to identify and categorise active and deactivated forest roads on the basis of their vegetation cover (Paper III)
- to identify road quality issues regarding water accumulation using the Topographic Wetness Index and soil information (Paper IV) and
- to introduce reference surfaces to improve classification (Paper V).

2 MATERIALS

2.1 Areas studies

The research was carried out in three areas, two located in Eastern Finland (Figure 1) and one on Vancouver Island in Canada (Figure 2). Field data and both high and low pulse density LiDAR data were collected from all three areas.

The field data for the first site (Kiihtelysvaara, Finland), reported on in Papers I, II and V, were collected in August 2013 and the ALS data in June 2009. Finland's boreal forests are less diverse than the North American forest areas, for example, as there are only four coniferous species native to Finland and these account for 89% of the forest area (Hämet-Ahti et al. 1992). This shows well in the stand compositions, too, in that the forest areas surrounding the sites are mainly spruce forest (52%) with some pine (31%) and birch (13%). The most common species are Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and Silver birch (*Betula pendula*) (Tomppo et al. 2014).

The second site (Tuusniemi, also in Eastern Finland) is also referred to in Papers II, IV and V. This area had greater relative height differences than the Kiihtelysvaara site, but there were few road sections that reached a gradient of 20%. The boreal forests here consist predominantly of spruce (52%) with some stands of pine (34%) and birch (11%) (Tomppo et al. 2014). Both the field inventory and the ALS data collection took place in July 2014.

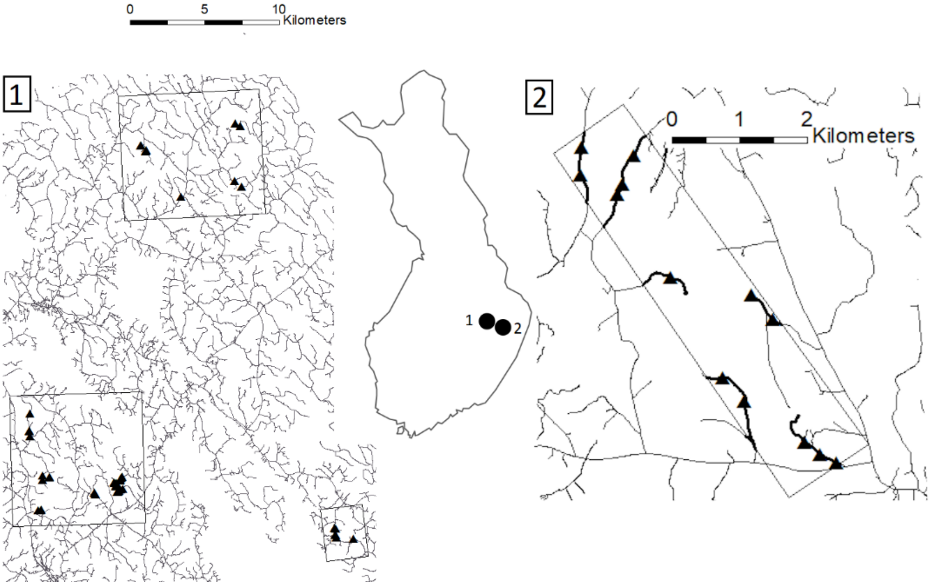


Figure 1. The two areas in Eastern Finland where the road quality assessments were carried out: Tuusniemi, 62°48.5′N, 028°29.5′E, and Kiihtelysvaara, 62°31'N, 30°11'E. Field data sampling points in both areas are marked with triangles.

The third site, located in the northern part of Vancouver Island, British Columbia, Canada, forms the subject of Paper III. This area belongs to the Coastal Western Hemlock biogeoclimatic zone (Meidinger and Pojar 1991), with an annual precipitation of 3000–5000 mm, mild winters (0°C–2°C) and cool summers (18°C–20°C). The area is a mountainous terrain with elevations from sea level to 1200 m. The main tree species in the 52,000 ha area are western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*) and amabilis fir (*Abies amabilis*). Other tree species such as Douglas fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), yellow cedar (*Chamaecyparis nootkatensis*), mountain hemlock (*Tsuga mertensiana*), and Sitka spruce (*Picea sitchensis*) are also observed at the site. The ALS data were collected in 2012 and the field inventory took place in September 2016.

2.2 Road databases

Spatial road databases and road centrelines were used to define the locations of the forest roads in the areas concerned and to provide more information for determining the road categories. These road centreline shapefiles were used for referencing the road network. In some cases, the overlap required manual corrections before further processing. Road centrelines for Finland were obtained from the Digiroad database of the Finnish Transport Agency (2013). The vector file also includes information on paved and unpaved roads. Since the research is focused on unpaved roads, the database was useful for locating these. The Tuusniemi area contained 356.8 km of unpaved forest roads, while the Kiihtelysvaara area had 9.7 km of unpaved forest roads. On neither area did the gradient of any unpaved forest road exceed 3%.

The Vancouver Island road database contained information on road locations, status and road class in a vector database provided by the area's forest licensee. The road class means the distinction between mainlines and spurs, while the road status refers to active and deactivated roads. It is important to note that the database did not distinguish between the various types of deactivation. Both the class and status information included roads of unknown class or status. The Vancouver Island area included 171 km of forest roads with variable slope conditions (up to 42%) that were used mainly for timber harvesting and transportation. Recreational traffic was of minor importance and was concentrated in the eastern part of the area. According to the road database, the network comprised 122.2 km of spur roads, 34.4 km of mainlines and 14.4 km of unclassified roads. In terms of status they were divided here into the categories of active (139.9 km), deactivated (26.6 km) and unknown status (4.5 km).

Due to the difference in the times of acquisition of the LiDAR data, the road databases and the field data in the case of Vancouver Island (field assessment: 2016, LiDAR: 2012, road data: 2009) and Kiihtelysvaara (field assessment: 2013, LiDAR & road data: 2009), some discrepancies between the datasets could be anticipated.

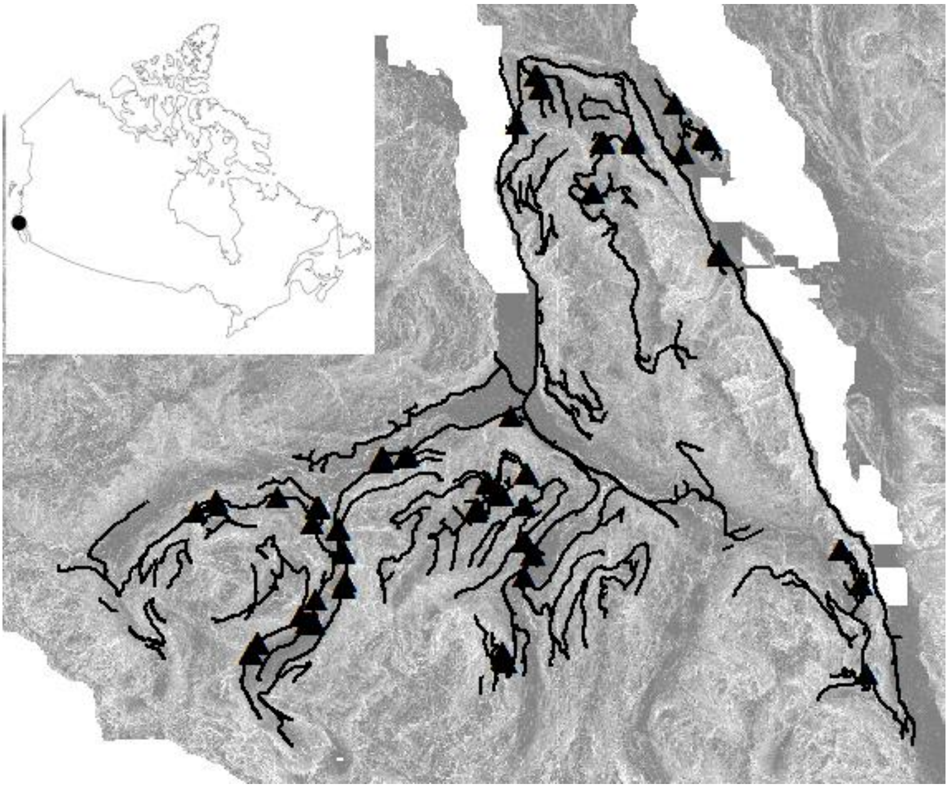


Figure 2. Distribution of field plots on unpaved forest roads on Vancouver Island, BC, Canada

Table 3. The classification of assessed road parameters and road quality classes applied on Finnish roads based on Korpilahti 2008.

Road Parameters Assessed	Road quality classes		
	Good	Satisfactory	Poor
Structural condition	The road surface is smooth. The driving speed does not need to be reduced.	Road quality problems are visible, driving lines must be chosen with care and speeds have to be slightly reduced.	There are clearly visible ruts. Driving lines must be chosen carefully, and speeds have to be significantly reduced.
Drying conditions	There is a drainage system (ditches, culverts) and it works well.	The drainage system works well in cases of high waterflow. At low water time the flow may be prevented by small obstructions (vegetation, sediment etc.).	No roadside drainage system exists or the system is blocked, so that water flow is prevented. The road body cannot dry out properly.
Surface wearing	The wear layer is sufficiently thick and of good quality.	The wear layer is too thin, or the material is either too fine or too coarse, hindering vehicle movement.	The wear layer has been worn away, or the material is too fine or to coarse, significantly hindering driving.
Vegetation cover	The vegetation beside the road is low and has small stem diameters (less than 2 cm). It does not obstruct the road drainage system or interfere with visibility. Coppices can be removed by normal maintenance measures.	The vegetation beside the road sometimes interferes with trafficability as it creates visual obstacles, especially in summertime. Coppices have not been cleared for several years, but can be removed by normal maintenance measures as the branches are less than 5 cm in diameter.	The roadway and/or its verges are overgrown with vegetation, with some branches over 5 cm in diameter. This prevents the side ditches from collecting water, narrows the width of the functional roadway, and limits visibility (a road safety concern). Coppices can be so robust that they cannot be removed by normal road maintenance measures.
Flatness	The road has an even surface, no risk or damage to vehicles, and drainage of the surface is good. Road conditions will not hinder transportation or daily movement.	The wear layer is uneven and the road has depressions, grooves and lateral bulges. There is visible damage. Lower speeds may be required in some places, but the risk of damage to a vehicle is quite small and will not hinder transportation or daily movement.	The road has depressions, grooves and lateral bulges, and/or drainage of its surface does not function well. The wear layer is defective, and driving conditions are obviously poor. It is necessary to reduce speed and to change the driving line frequently to avoid vehicle damage. The poor condition of the road hinders transportation and daily movement.

2.3 Road quality parameters

Both of the Finnish road inventories were carried out using the Finnish operational model as proposed by Metsäteho (Korpilahti 2008). This model is highly empirical and lacks exact measurement values at some points, but gives guidelines for assessing several aspects of the quality of forest roads with regard to their trafficability. The following categories were taken into account when conducting the inventory: structural condition, seasonal damage, wear, drying conditions, geometry, design and visibility, vegetation, bridges and flatness, and each observation was placed in one of three quality classes: good (3), satisfactory (2), or poor (1) (Table 3). Good quality roads do not hinder transportation and do not require the driver to reduce speed. Roads of satisfactory quality may require a lower driving speed or increased attention to driving conditions, while in the case of poor quality roads speeds must be significantly reduced, and driving lines need to be chosen carefully in order to avoid damage to the vehicle.

The term "structural condition" refers to the condition of the structural elements making up the road and is closely linked to bearing capacity. The visible signs of low bearing capacity can include road sections with damaged surfaces or tracks, in addition to which the report also assesses any signs of seasonal damage related to the melting of snow or the thawing of ground frost, such as potholes or collapsed road edges . The wearing layer refers to the top surface of the road and is especially concerned with the quality and quantity of the materials used to cope with wear. If this layer is too coarse or too soft it will cause drivability problems. Drying conditions refer to how well the road body can dry after precipitation, including the presence of ditches and their condition and the occurrence of lateral bulges which may prevent the water from flowing off the road surface. Geometry, design and visibility refer to problems related to sharp bends, steep uphill or downhill sections, locations where visibility is reduced by either vegetation or other objects in the terrain, and the provision of adequate places for overtaking or turning. For safety reasons, the gradient of a slope should not exceed 10% (or 12% over very short distances). It is also necessary to have passing places for heavy vehicles every 600 m or so, and turning places for long vehicles every one to two kilometres. The vegetation cover can be classified in terms of several factors: whether it is too close to the road and hinders visibility, whether it is blocking the drainage system, and what is the diameter of the stems or branches, which are acceptable if under 2 cm thick but constitute poor conditions if over 5 cm. Bridges must be assessed in terms of their physical condition, checking the presence of rust or severe structural damage and noting any restrictions on vehicle weight. In practice there were no bridges on the roads included in the inventories.

In addition, the basic road parameters (width of the road surface and shoulders, dimensions of the ditches) and details of the vegetation growing on the roadside and in the ditches (height, diameter and density) were recorded.

Thirteen field plots were surveyed in Kiihtelysvaara in 2013 (Table 4). The plots extended 20 metres along the centreline of the road in each case but varied in width due to the differing widths of the road elements. The observations and measurements included the quality of the road surface, the shoulders and the ditch systems.

The Tuusniemi field data were collected in July 2014, assessing 50 field plots in accordance with the Metsäteho road quality standards (Table 5). The parameters measured were the same as in Kiihtelysvaara.

The main emphasis in the acquisition of field data on Vancouver Island was to assess the spread of vegetation over and beside the roads in order to classify them as active or deactivated roads and to create an ALS-based updated database of their status for comparison with the exisisting field visit-based database.

The field data on Vancouver Island were collected in September 2016 on 55 field plots covering over 50 km of forest roads (Table 6). Each plot, of length 10 metres, was assessed in terms of road surface, shoulder, ditches and the vegetation cover on the surface, shoulders and roadside and overhanging the road. The widths of the plots depended on the road width in each case.

Table 4. The distribution of road quality classes (poor, satisfactory, and good) of three road quality parameters (structural condition, surface wearing, and flatness) that were recorded in Kiihtelysvaara, Finland.

Road quality class	Structural condition	Surface wearing	Flatness	Total number of observations in each road quality class
Satisfactory	3	7	6	16
Good	10	6	7	23
Poor	0	0	0	0
Total number of road sections	13	13	13	39

Table 5. The distribution of road quality classes (poor, satisfactory, and good) of three road quality parameters (structural condition, surface wearing, and flatness) that were recorded in Tuusniemi, Finland.

Road quality class	Structural condition	Surface wearing	Flatness	Total number of observations in each road quality class
Poor	3	6	3	12
Satisfactory	13	27	22	62
Good	33	16	24	73
Total number of road sections	49	49	49	147

Table 6. The status of assessed forest roads on Vancouver Island, Canada

Road Status	Length (km)
Active	139.9
Deactivated	26.6
No Status	4.5

Table 7. Properties of the LiDAR data collected in the three areas

	Kiihtelysvaara, Finland	Tuusniemi, Finland	Vancouver Island, Canada
Year of collection	2009	2014	2012
Scanning system	Optech ALTMGemini	Leica ALS50-II	Optech ALTM3100EA
Height above ground	600 m	2000 m	700 m
Width of swath	320 m		323 m
Angle of scan	26	20	12.5
Overlap	55%	20%	75%
Pulse repetition rate	100 kHz	114 kHz	70 kHz
Average density (points/m^2)	11.7	1.1	11.6

2.4 Acquisition and processing of LiDAR data

The high-density LiDAR dataset for Kiihtelysvaara area has a resolution of 11.7 pulses per m^2 and was been collected in June 2009 (Table 7) using an Optech ALTM Gemini scanning system at 100 kHz with a 50% overlap between swaths. The flight altitude was 600 m above the ground in a swath 320 m wide and at an angle of 26°

The LiDAR data for Tuusniemi were collected at the same time as the fieldwork was carried out, in July 2014, and have a sparse pulse density. The scanning was performed with a Leica ALS50-II system at 114 kHz from 2000 m above ground level. The angle of the swath was 20° and there was a 20% overlap. The average sampling density was 1.1 points per m^2.

The data for Vancouver Island, Canada, acquired in 2012 with an Optech ALTM3100EA laser scanning system, have an average point density of 11.6 points/m^2 with a pulse repetition rate of 70 kHz. The scanning was carried out from 700 m above ground level with a swath width of 323 m. The angle of the scan was 12.5° and the overlap was 75%.

Processing of the LiDAR datasets included filtering, ground classification and the creation of digital elevation models (DEMs) and digital terrain models (DTMs) for use in the subsequent analysis. Other DEMs created by the Topographic Database of the Finnish National Land Survey (2008) that were of lower resolution (10m and 25m) were also used in certain analyses.

Table 8. Soil and bedrock distribution of the field inventory plots in Tuusniemi, Finland

Soil Categories	Number of Plots
glacial till	22
sorted soil	1
organic soil	5
bedrock	15
mixed areas	6
Total	49

2.5 Soil data

Soil data for the Tuusniemi area were analysed in connection with water accumulation (Paper IV), the vector being soil information provided by the Geological Survey of Finland [25] at scales of 1:20 000/1:50 000. The soils of Finland were mapped between 1972 and 2007, using different soil samples and processing methods, interpolating the results with the aid of aerial images and GIS data processing. The area can be divided into five different categories (Table 8) using the Finnish soil classification system (Heiskanen et al. 2018): glacial tills, sorted soils, organic soils, bedrock and mixed areas. The sorted soil refer to alluvial or aeolian soils with narrow particle size distribution, while the glacial tills can further be divided into areas with coarse (1 plot), medium (19 plots) and fine-grained particles (2 plots). The only plot with sorted soil had fine-grained particles. The organic soils included sedge peats (4 plots) and Sphagnum peat (1 plot) areas, while the mixed areas had bedrock and glacial till (6 plots). There were 15 bedrock plots.

Soil trafficability is important in forest operations (harvesting, hauling and transportation of timber), and the trafficability of boreal soils has already been assessed based on soil types and wetness conditions (Natural Resources Institute Finland 2019). In general terms, the trafficability of a soil improves as the moisture content decreases. Some soils (such as peats and other organic soils) have low trafficability even under dry conditions, while others change to different extents throughout the year. The following trafficability ranking has been proposed, from worst to best: organic soils, fine-grained mineral soils with a thick organic layer, fine-grained mineral soils with a thin organic layer, sandy soils, medium-grained soils, and coarse-grained glacial till. The present field data were acquired during the driest time on the year in Finland, when the roads were in their best condition.

3 METHODS

3.1 The ALS-based road quality metrics

In order to develop the idea of predicting road quality parameters (Korpilahti 2008), various alternative ALS-based road quality indices based on the Topographic Position Index (TPI) and Standardised Elevation index (SE) (Jenness Enterprises 2013) were calculated and tested at various levels of resolution for both the areas studied in Finland (Papers I, II, IV and V).

The TPI (Eq. 1) was calculated by giving each cell a value in elevation units based on the difference between its elevation and the average elevation of the neighbouring cells, while for the Standardised Elevation Index (Eq. 2) the standard deviation of the neighbourhood elevation was incorporated into the value, so that 1 unit means that the cell is one standard deviation higher in elevation than its neighbourhood. Thus the indices themselves can indicate irregularities in the terrain.

$$TPI_i = x_i - \frac{\sum_{i=1}^{n} x_i}{n} \tag{1}$$

$$SE_i = \frac{x_i - \frac{\sum_{i=1}^{n} x_i}{n}}{\sigma} \tag{2}$$

It should be noted that these indices, which are usually applied at a lower resolution to large areas, were used here to map smaller surface differences: unevennesses in the road surface and the presence or absence of ditches at the roadsides.

Also, the index values are highly dependent on the size of the neighbourhood and the resolution of the DEM. In the final assessment a three-cell radius for the neighbourhood was chosen for use with DEM resolutions ranging from 0.1 m to 2 m (Papers I and II), although 10 m and 25 m resolutions were also tested in Paper V.

A variety of interpolation methods are available for use in road and forestry applications (Montealegre et al. 2015), of which four techniques were used here with the DEMs (Paper V): Kriging (Williams 1998), Natural Neighbours (Sibson 1981), Inverse Weighted Distance (Watson and Philip 1985) and Spline (Smith 1979). The aim of comparing interpolation methods was to find the best one to identify poor quality and good quality roads – since poor quality roads need urgent maintenance, while good quality ones do not. The main idea of the present work was to introduce reference surfaces with which to compare the LiDAR hits instead of using only surface indices, and to compare the surface quality indices calculated using different interpolations for the basic DEMs.

In mathematical terms, the Natural Neighbour and Inverse Distance Weighted interpolation techniques create surfaces with values that do not exceed the minimum and maximum values in the original data, while Spline and Kriging interpolation do not have this constraint. Considering that LiDAR pulses may not hit the highest or lowest points of the terrain (this is very likely in a sparse dataset), the latter two interpolation methods, Spline and Kriging, may be the best choices. On the other hand, it is better to have a smoother reference surface when attempting to identify poor quality roads, and it is the NN and IDW interpolation methods that calculate values that remain within the ranges of the original input data.

3.2 Ditch evaluations

Ditches of satisfactory depth and dimensions are necessary to allow the road body to dry out by transporting the water away. If the ditches are shallow or covered with dense vegetation they cannot function properly. The size and depth of a ditch are determined by its slope, the area to be drained, the estimated intensity, the volume of run-off and the amount of sediment that can be expected to be deposited in the ditch during periods of flow (FAO 1989). As our research in Finland was focused on rather small area without any significant differences in elevation, we examined the extent of the ditch system over the area that receives the same amount and intensity of precipitation.

Two methods were employed for ditch detection (Figure 3 Figure 4). The first used sink detection by means of the ArcMap hydrological tools (ArcGIS 2020), assuming that ditches are similar to rivers but on a smaller scale, while the second examined TPI values to find those that were significantly lower than their neighbourhood, taking values of 0.6 or 0.8 as indicative of ditches. Both methods yielded two site categories: ditches and no ditches. The plots considered for evaluation were corridors 3 m wide and 20 m long running parallel to the centerline of the roads on both sides. To differentiate between good and satisfactory ditches, we computed the number of cells identified as representing a ditch in each plot and analysed their proportions, on the assumption that larger and broader ditches are better, as they are not covered by vegetation.

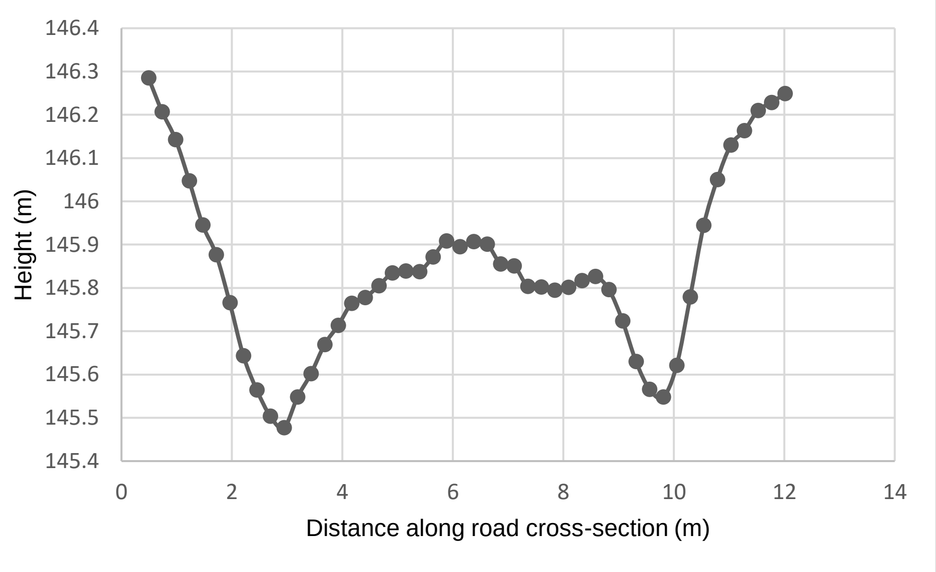


Figure 3. Cross-section of a road with good quality ditches at Kiihtelysvaara, Finland

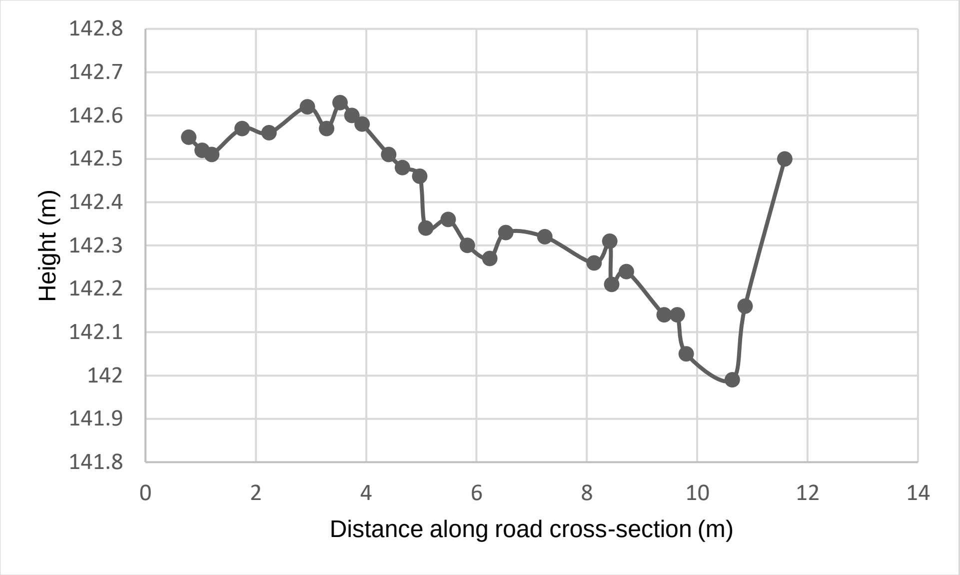


Figure 4. Cross-section of a road with ditches overgrown on the left side.

3.3 Calculating the Wetness Index and identifying water accumulation

The Topographic Wetness Index was calculated (in Paper IV) using the already available DEMs and those derived from the LiDAR data to identify places where water could accumulate close to the road body. The DEM model with 1 m resolution generated from the low pulse LiDAR data used IDW (Inverse Distance Weighted) interpolation (Watson 1985), and the pre-existing DEMs at resolutions of 10 m and 25 m were obtained from the Finnish National Land Survey (2008).

There are numerous methods for calculating the TWI which differ in the way the upslope area is calculated however, all the known methods are acceptable and no specific best method exists (Sørensen 2006), The workflow described in ArcGIS (Hydrology Tools 2000) with the D-infinity method (Tarboton 1997) was selected in this case. This is a dispersive method, in that the direction of flow is based on the steepest downward slope of a triangular facet on a block-centred grid. The direction is expressed by counting counter-clockwise from the east in radians between 0 and 2 π.

The Topographic Wetness Index is calculated as follows (Beven and Kirkby 1979):

$$TWI = \mathbf{ln}\left(\frac{\alpha}{\mathbf{tan}\,\beta}\right) \tag{3}$$

where:
α = Upstream contributing area in m^2
β = Slope value

Higher TWI values mean drainage or depressions, while lower values represent crests and ridges. The main aim of calculating wetness indices at different resolutions was to identify depressions in the area next to the forest roads and assess whether DEMs of a lower resolution would also provide reliable information for road quality purposes. Depressions where water can accumulate near the road body are assumed to be potential sources of road quality issues, as the whole road structure may deteriorate if the road body cannot dry properly.

3.4 Assessing vegetation cover near the road

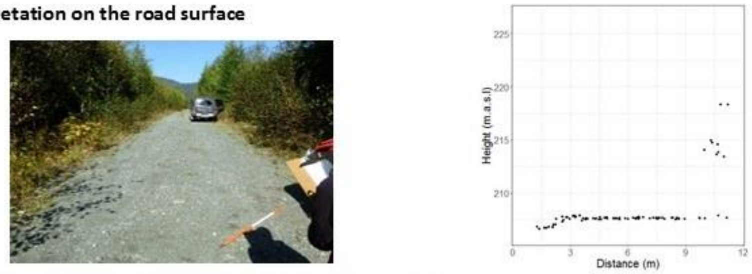
The vegetation cover was the main topic of Paper III. After basic data processing, the road vectors were first overlaid on the DEMs created from the LiDAR data and the vegetation status of 4x5-metre segments created along the centerlines the roads were assessed. The LiDAR point clouds were assessed in five height ranges: < 0.3 m, 0.3–1 m, 1–5 m, 5–10 m, > 10 m, and the proportions of these five ranges were calculated. The segments were then divided into four vegetation classes based on those proportion (Figure **5**): Class 1 - no vegetation on the road surface, Class 2 - minor vegetation on the road surface or roadside that does not hinder transportation, Class 3 - road covered with dense but short vegetation, Class 4 - dense and tall canopy cover. These four classes represent active roads (Class 1), recently deactivated or temporarily deactivated roads, or roads that are not in use (Class 2), deactivated roads (Class 3) and inactive or completely deactivated roads where the forest has re-invaded the area (Class 4). As the last step, a filtering algorithm was used to create uniform segments a minimum of 100 metres long to provide a better representation of the condition of the whole road section. A confusion matrix was used to validate the results against the field data.

3.5 Assessing trafficability

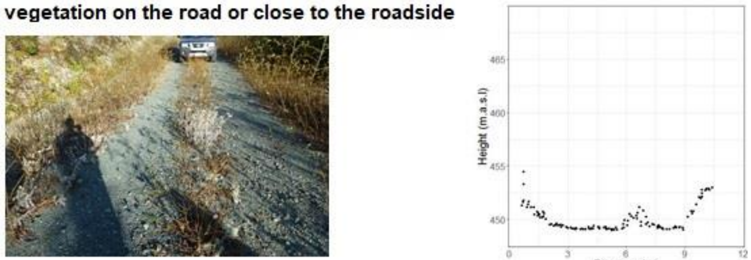
The Tuusniemi data were also used to assess trafficability based on soil types and their strengths (Paper IV), employing the trafficability classification for boreal soils set up by the Natural Resources Institute Finland (2019) and the soil maps produced by the Geological Survey of Finland (2015).

The trafficability criteria assessed in Paper IV were the Topographic Wetness Index, soil types and the TPI values used in the earlier work. The higher the wetness values or TPI values are, the less trafficable the area is.

Class 1: **No vegetation on the road surface**



Class 2: **Minor vegetation on the road or close to the roadside**



Class 3: **Dense vegetation**

Class 4: **Dense canopy**

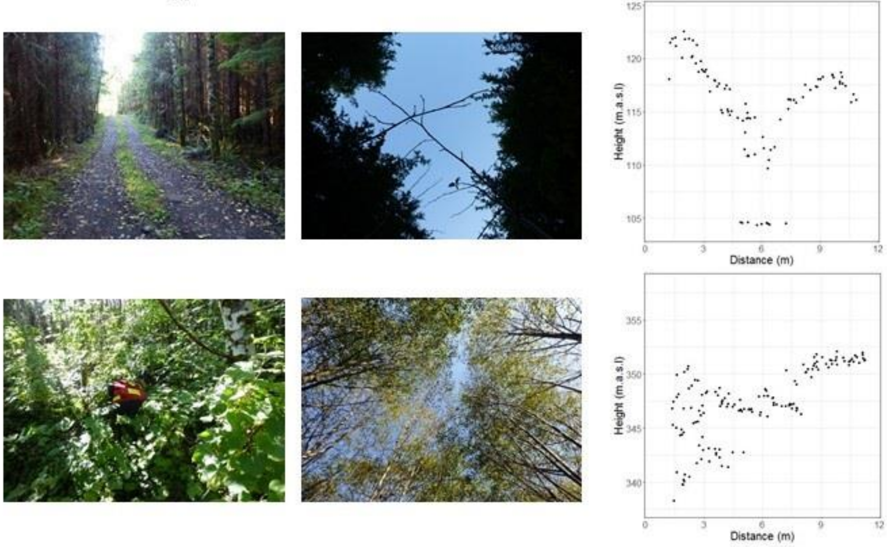


Figure 5. Road quality classes regarding vegetation cover on Vancouver Island, Canada

3.6 Classification and evaluation

The principal tools used in the classification were Linear Discriminant Analysis (LDA) (in Papers I, II, IV and V) and an algorithm for classifying LiDAR echoes (Paper III) (R Documentation, 2020).
LDA can be applied to find the best linear combination of features that will separate two or more classes from each other (Hastie et al. 2009), and in this case, it was used to identify features that would predict the three road quality classes (good, satisfactory, poor). In Paper III the vegetation growing on the road surface and its edges were analysed in terms of the height distribution of the ALS returns. K-fold evaluation (Paper V) and confusion matrices (Papers III and IV) were used to assess the accuracy of the classifications.

The general equation for road quality predictions is:

$$\text{RoadQuality} = x * \text{TPI} + y * \text{TWI} + z_1 * \text{Soil}_1 + z_2 * \text{Soil}_2 + \ldots + z_7 * \text{Soil}_7 \qquad (4)$$

where:
RoadQuality refers to prediction variables such as Flatness, Structural Condition, Drying and Surface Wear, and
TPI, TWI and SoilTypes are the GIS/ALS based predictors.

4 RESULTS

4.1 Categorizing vegetation growth and canopy cover (Paper III)

Paper III analysed the height distributions of the ALS returns of each road segment of the Vancouver Island study area. Four classes were set up based on the vegetation growing on the road surface and surrounding areas: Class 1 represented active roads without vegetation, and Class 3 deactivated roads with dense vegetation and most roads belonged to these two categories. The remainder was falling into Class 2 roads with minor vegetation and Class 4 roads with fully regrown vegetation. The classification results are shown on the map in Figure 6.

Altogether 73% of the roads were placed in the correct category as recorded in the field data. The proportions of correct classifications being 88% in Class 1, 62.5% in Class 2, 55.5% in Class 3, and 60% in Class 4.

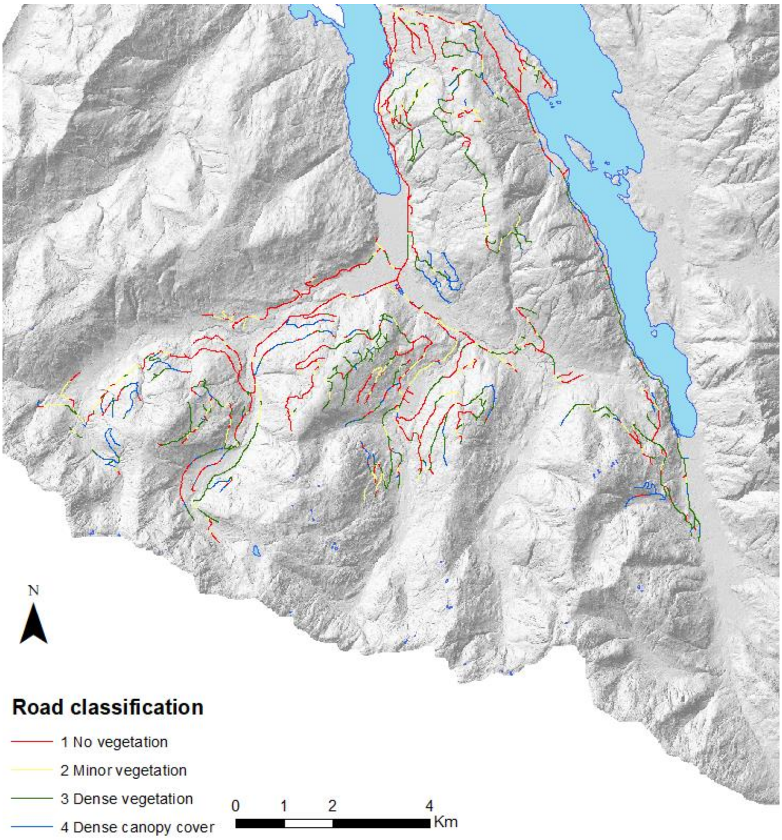


Figure 6. Forest roads on Vancouver Island as classified into the four vegetation classes

4.2 Road quality parameters obtained using the surface quality indices and the Wetness Index

4.2.1 Road surface quality indices (Papers I, II, IV, and V)

The two tested surface indices, TPI and SE, are highly dependant on neighborhood size. Not only the index values differ, but the time required for the computations also significantly increases with larger neighborhood sizes. 3-cell units were selected for further calculations (Papers I and II). The results showed that the SE index is less dependent on elevation differences than TPI. SE incorporates the area's standard deviation into the calculation and is more convenient to use in forested areas and on roads located on slopes.

Both high pulse and low pulse datasets were used and compared for assessing the relative suitability of the surface quality indices for road quality assessment (Paper II). The findings showed that the sparse dataset underperformed relative to the high-resolution one (Table 9 Table 10). Road flatness, surface wear, seasonal damage, and structural condition were also assessed in connection with the surface quality indices. The TPI index showed the best results at resolutions of 0.5 and 1 m. In comparison, the SE index performed best at resolutions of 0.25-0.5 m, as the success of the classification into the two categories was consistently above 69%.

Table 9. Classification success using TPI at resolutions of 0.1-1 metre by road quality categories and pulse densities.

Resolution (m)	Pulse density of dataset	Road quality categories Flatness	Structural condition	Surface wear
0.1	high	39%	39%	31%
0.25	high	46%	31%	46%
0.5	high	46%	69%	69%
1	high	62%	62%	69%
1	low	40%	30%	40%

Table 10. Classification success using the SE index at resolutions of 0.1-1 metre by road quality categories and pulse densities

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Resolution (m)	Pulse density of dataset	Road quality categories Flatness	Structural condition	Surface wear
0.1	high	54%	54%	46%
0.25	high	69%	92%	46%
0.5	high	77%	69%	69%
1	high	54%	31%	69%
1	low	25%	25%	25%

The low pulse density dataset had a classification success of only 25-40%, which is close to a random distribution for the three classes. Therefore, it did not give reliable information on road quality. Further studies have discussed other possibilities for using low pulse datasets.

4.2.2 The role of reference surfaces (Paper V)

In the case of the two Finnish areas, four interpolation methods were compared when creating the DEMs: natural neighbour (NN), kriging (KR), inverse distance weighted (IDW), and spline (SP), and the surface quality indices were also calculated using the same interpolation methods and variables derived from the LiDAR height data to determine road quality. Despite the earlier expectations, Spline interpolation of the reference surface performed best for both classifying the roads into three quality classes and identifying the poor quality classes. As interpolation for DEMs was used for calculating the surface quality indices, the difference between the interpolation techniques was not significant. Both IDW, Kriging, and Spline showed similar results, with 85% correctly identified poor quality road sections and 57% success when classifying the material into three quality classes. The introduction of the Spline reference surface significantly increased the precision of the classification.

4.2.3. Ditch detection (Papers I and II)

Ditch detection was carried out with the two Finnish datasets using both high pulse and low pulse LiDAR data. The presence of ditches was assessed at different resolutions from 0.1 metre to 2 metres using 3-cell neighbourhoods, and the classification was evaluated by comparing the areas classified as ditched versus those with no ditches. The sparse dataset did not perform well, as the laser often failed to hit the deepest part of the ditch system, causing the quality of the system to appear to be worse than it really was, while the high density dataset was suitable for determining ditch quality at several resolutions.

The TPI was used with a threshold value of 0.6, considering everything that was 0.6 m lower than its surroundings to be part of a ditch. The analysis showed that poor quality ditches at DEM resolutions of 0.2 m and 0.25 m could be separated from satisfactory and good ditches (Table 11). In the case of 1m resolution, the means of the values were different, but the standard deviation was high, and therefore the results are less reliable. Another tested approach was to detect sinks next to the centerlines of the roads using the Hydrology Tools (Table 12). Resolutions between 0.25 m and 1 m showed the best results. The classification success varied in the range of 60-80% with both methods.

Table 11. Ditch detection based on TPI values and assessments of the extent of ditching in the satisfactory and poor quality classes. Means and standard deviations (std dev) of the ditch areas (m^2) are shown in the table.

Resolution (m)	Satisfactory ditch system quality		Good ditch system quality		Statistically Significant Difference
	mean	std dev	mean	std dev	
0.1	7.4	1.8	7.8	1.6	
0.2	9.6	1.8	10.3	1.6	*
0.25	10.2	2.1	10.9	1.5	*
0.5	19.5	1.4	19.4	1.4	
1	14.4	10.6	18.9	13.7	

Table 12. Ditch detection based on Hydrological Tool analysis and assessments of the extent of ditching in the satisfactory and poor quality classes. Means and standard deviations (std dev) of the ditch areas (m^2) are shown in the table.

Resolution (m)	Satisfactory ditch system quality		Good ditch system quality		Statistically Significant Difference
	mean	std dev	mean	std dev	
0.1	3.2	1.3	3.2	1.0	
0.2	5.3	1.5	5.3	1.2	
0.25	5.0	1.1	6.0	1.7	*
0.5	3.9	1.8	7.3	3.6	*
1	6.0	6.2	12.2	3.7	*

Table 13. The correctness of classification of two quality classes of unpaved roads (poor and non-poor) using various combinations of predictors such as the Wetness Index, soil types, and Topographic Position Index (TPI) to predict flatness, drying conditions, and road structure.

	Predictors	TWI Index	TWI + Soil Type	TWI + TPI	TWI + Soil Type + TPI
Resolution	Predicted Variable	Agreement	Agreement	Agreement	Agreement
1 m	flatness	76%	90%	71%	84%
10 m	flatness	31%	90%	53%	86%
25 m	flatness	71%	90%	0%	90%
1 m	drying	78%	57%	82%	84%
10 m	drying	45%	57%	39%	59%
25 m	drying	39%	57%	37%	57%
1 m	structure	86%	86%	76%	84%
10 m	structure	80%	86%	80%	84%
25 m	structure	86%	84%	84%	82%

4.2.4 Wetness index and soil data for better road quality predictions (Paper IV)

In order to improve the performance of the analysis of the low pulse dataset and achieve higher precision when using the high pulse density LiDAR data for forest road quality assessment, other indices were introduced and tested.

The Topographic Wetness Index was assessed at three resolutions, 1m, 10m, and 25 m, both individually and combined with the soil type dataset and the surface quality indices introduced earlier.

Assessing the 356 km of roads in the area concerned, we found that only 7% of this distance, about 25 km, was shown by this method to be exposed to extremely wet conditions (Figure 7).

Regarding soil types, the roads on till soils were in good shape, an observation that aligns with the findings that these are the best trafficable soils under boreal conditions regardless of their wetness (Natural Resources Institute Finland 2019). Only one out of the five peat areas was shown in the road inventories to be of poor quality, even though these areas are known to be the least trafficable ones under boreal conditions. The high proportion of good roads can be explained by the extra attention paid to building long-lasting road structures with well-prepared foundations. On the other hand, numerous road sections in bedrock areas were in poor condition during the summer. Trafficability changes less during the year in bedrock areas, the accumulation of water during the thawing period and the rainy season has smaller effects, and the roads do not deteriorate much at those times.

The use of TWI alone showed the classification correctness of the three quality classes to be 22-70% (**Error! Reference source not found.**). Still, when TWI was combined with e ither soil data or surface quality indices, significant improvements took place, and the method performed the best when using all three. The determination of poor quality classes alone showed a higher precision, as was to be expected. In the case of poor vs. non-poor classification, the combination of TWI and soil data performed best for road flatness and structural quality, with 89.8% agreement for flatness and 85.7% for structure.

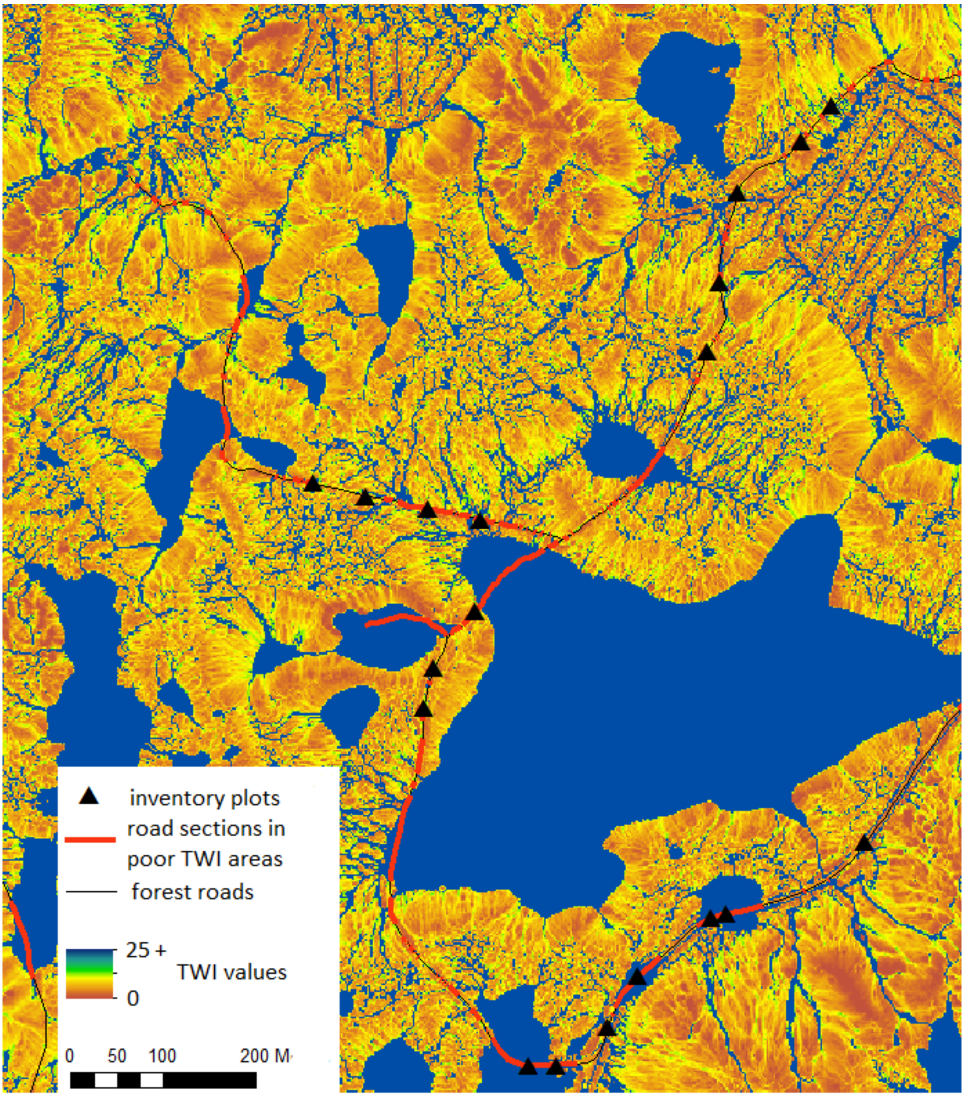

Figure 7. A sample map of Tuusniemi, Finland, highlighting roads in poor TWI areas.

5 DISCUSSION

General concept

This thesis evaluates the testing of methods for assessing unpaved road quality utilizing high and low pulse density airborne LiDAR data in three forested areas, two in Finland and one in Canada. It explores novel ways of doing this on both flat and sloping terrain that could be used alongside the other approaches that have already been proposed (Marinello 2017).

Information on the quality of unpaved forest roads obtained using ALS data can help forest managers to assess and decide which roads require urgent maintenance without time consuming visits. Providing reliable information about forest road quality is an important task, especially in forest areas that are remote and/or have an extensive road network. Various quality aspects, such as frost heave, bearing capacity, and surface conditions, are important issues for timber transport using the Finnish forest road system (Malinen et al. 2014) and the currently available methods to assess road quality are highly empirical or time-consuming (Korpilahti 2008, Kaakkurivaara 2018).

It is also the case that Finland's system of forest roads was designed for much smaller vehicles, which result in quicker deteoriation of the roads. The current situation is that heavy trucks up to 34.5 long and 76 tonnes in weight (tests have been carried out with 104-tonne trucks as well) can operate in the country, causing roads to deteriorate even faster (Korpilahti 2013; Yle.fi 2019; Boholm 2019). HCT vehicles were extensively researched and allowed on certain routes, and in the future these vehicles may operate on other routes too using special permits as they were found to be efficient: saving on fuel consumption is an economical and environmental benefit (Metsäteho 2020). The construction of new roads damage forest ecosystems (Grayson et al. 1993; Rummer et al. 1997; Forsyth et al. 2006; Jordán and Martínez-Zavala 2008; Daigle 2010; Kan 2013; Boston 2016) which a major concern especially in British Columbia, where the amount of newly built roads are fairly large: from 6000 km to 25 000 km roads were built annually in the last two decades in BC, Canada (Forest Practices Board 2015). Therefore, maintaining existing road network where possible is favorable over new constructions.

The Tuusniemi field inventory was carried out at the same time as the LiDAR data collection, but the other two datasets have a gap of several years between the field visit and the ALS sampling, which could affect the outcome of the analysis, as road conditions might have worsened in that time, or they might have improved due to scheduled road maintenance.

Road trafficability and drivability are essential as they ensure that harvesting machinery can reach the logging sites and that the timber can be transported out of the forest. Roads with a solid structure, high bearing capacity, and adequately trimmed vegetation are needed to avoid transport difficulties (O'Mahony et al. 2000; Malinen et al. 2014). Poor quality roads require slower driving speeds and mean higher fuel consumption for logging vehicles (Svenson and Fjeld 2016). Timely road maintenance is crucial for logging operations, but it can also benefit other aspects of the ecosystem. Meanwhile, a lack of road maintenance can negatively affect soil stability, the water regime, the quality of the landscape, and the area's game population (McCashion and Rice 1983). In order to repair the damage to unpaved roads caused by the spring thaw, records first need to be made of the locations of such roads. Hand-held devices can assist with quick measurements to determine the road surface damage (Vuorimies et al. 2015).

In BC, Canada, the road safety is an important issue too (BC Forest Safety 2021, Resource Roads 2021). These forest roads belongs to the reseource roads and are not maintained as freqently and throroughly as public roads are. It may lead to conflict between different types of road users, and also hard to follow the quality changes and the success of deactivation processes of the forest roads located in remote locations.

ALS and GIS-based road quality parameters

Paper I analysed only high pulse density ALS, while Papers II and V compared both this and the GIS approach's performance. The indices calculated in those papers evaluated which road quality category (surface wear, structural condition, flatness, drying, and ditching) can be predicted best using surface quality indices. The forest road inventories currently used in Finland are based on field visits (Korpilahti 2008, Metsäteiden kuntokatselmus 2017).

The road surface indices derived from high pulse ALS data performed well in Paper I. Still, these datasets are more expensive, and often it is only low pulse datasets that can be obtained for forest inventory purposes. Only good and satisfactory quality classes were recognized in that paper, and the 3-class classification was not tested with high pulse density ALS data. One of the main tasks in Papers IV and V was, therefore, to increase the precision of road quality classification using low pulse data. Although the TPI and SE indices both described surface wear and flatness best at 0.25 m resolution, they did provide some information about the structural condition of the unpaved roads at lower resolutions as well (Paper II).

Surface quality indices such as TPI and SE can be alternatives to the Terrain Ruggedness Index (Riley and Degloria 1999), which is another way to categorise and evaluate terrain features. Peuhkurinen and Puumalainen (2019) found in Southern Finland that road quality can be predicted using a machine learning algorithm with an accuracy of 64-78%, which is slightly lower than that achieved by the combined predictors used in Paper V. Their sample size was also more extensive, however. Ruts, as one of the leading quality problems after the spring thaw, have been the focus of other research, too. Both UAV and truck-mounted sensors have been tested at Finnish sites with varying success (Salmivaara 2017; Nevalainen 2017) in order to identify the biggest ruts, those over 20 cm deep, which approximately correspond to the poor quality class discussed here.

In the present ditch quality analysis, we tested two novel approaches to verifying the quality and presence of ditches. However, that good quality ditches do not depend only on physical aspects (such as their depth or extent) as some road sections don't require such a deep ditch system on account of their soil type or some geomorphological aspect brought about by a difference in sediment accumulation (FAO 1989).

The Topographic Wetness Index index's major strength in combination with soil data was the increase in classification performance achieved when using low-pulse ALS data. However, it is essential to note that the DEMs used in calculating the TWI were interpolated using the IDW method and that other methods could slightly alter the outcome.

The TWI performed well at low resolutions (10-25 m), especially when combined with other predictors such as the TPI discussed earlier. These results are comparable to those yielded by the high-resolution DEMs that were used to classify the roads in the Kiihtelysvaara area in Papers I and II, and to the findings of up to 78% correct classification reported by Peuhkurinen & Puumalainen (2019), as the road structure quality was classified correctly in over 80% of instances in the case of poor vs. non-poor quality.

Regarding soils, the roads built on glacial till were in good shape, an observation that concurs with findings that these are the best trafficable soils under boreal conditions regardless of their wetness (Natural Resources Institute Finland 2019). Fine-grained soils such as silt have a bearing capacity that depends on the level of moisture and particle sizes (Heiskanen 2018).

Analysis of the vegetation cover and identifying no longer used deactivated roads can also yield valuable information. The extracting of accurate road details from under a dense canopy cover using DTMs (Maguya et al. 2014) or assessing the vegetation cover accurately (Campbell et al. 2018) can be challenging tasks. The four categories established here gave more information than can be obtained by merely distinguishing between active and deactivated roads. The road sections under a vegetation canopy, where the ALS pulses are less likely to hit the road surface and the lack of sufficient data hinder classification, need a category their own, as they would require further field visits to reveal the quality of the road beneath the canopy.

Time is another crucial factor to consider when conducting road quality analyses that include the vegetation, as trees and bushes need time to invade deactivated roads. Also, the database had no information about whether all of these roads were permanently deactivated or whether some were being kept in a temporarily deactivated state, which could partly explain why 23% of the deactivated roads were included in class 1 (active roads). The method proposed here could reduce the number of roads to be checked, as verifying the success of deactivation, for example, would require field visits to the roads classified as active regardless of having been deactivated in the past in order to ensure that they had been adequately cut off from traffic.

Airborne scanners equipped with gamma-ray radiation spectrometers can further improve methods estimating soil properties combined with other spatial variables, in order to predicts clay content, organic matter and the depth of humus layer of the soils (Heiskanen et al. 2020). Weak connection were also identified between stoniness and the gamma-ray analysis in Finnish study areas, and further research could expand into this area as well, as Priori et al. (2014) found more significant predictions for soil structures as well as for stoniness in a reasearch carried out in the Netherlands.

Assessing dynamic trafficability is another approach gaining more attention as forestry operations are dependant on good trafficability of terrain and gravel roads. Currently static trafficability is assessed (Kaakkurivaara 2018) and classified according to the different seasons when roads can be used (spring thaw, summer, dry summer or wintertime trafficability). The dynamic approach would be more align with climate change and shifting seasons, and not only assess the roads' trafiicability at that moment, but would provide predictions as long as weather forecasts span and predict the local precipitation and temperature changes. These results can also be visualised (Salmivaara et al. 2020; HarvesterSeason 2021) to provide an easy overview for forest owners and managers. Similar applications for road renovation needs may be planned using the same laser scanning data.

Future research & applicability of the new data collection methods

Road quality assessments carried out on field visits require considerable resources. It involves a lot of time to drive along the dense forest road network to obtain information about its quality. With the help of ALS data and other remote sensing options, these field visits can be reduced significantly, leading to monetary savings. The cost of data collection is a highly critical factor not only in forestry. Existing ALS data (obtained during inventories for forest management planning purposes) can be used without extra costs. The current work on developing drone and car-mounted systems will further reduce ALS and TLS data collection costs. Although road quality can change rather rapidly, forest managegment plans may need revision and updates even in a five-year time frame. Therefore more frequent ALS data collection may be carried out of larger areas in the future, which would provide information for remote sensing-based road assessments at no extra costs. Also, rapid developments in technology have led to better methods of data collection and analysis for use with all types of space-borne, airborne or terrestrial sensors (Talbot et al. 2017).

There is an increasing need for collecting road quality data automatically and from larger areas. ALS data can be a good alternative for this purpose or used as an auxiliary source therefore present work can be used to develop a system for analysing the quality of unpaved forest roads. The Finnish pilot project known as the YTPA System (Venäläinen 2018) was created to collect and combine different sources of road data, including those maintained by the National Land Survey of Finland, the Finnish Transport Agency's Digiroad System, weather data, and to share these sources between the various stakeholders in the future. Machine learning and sensor analysis (Vaisala RoadAI 2020) is already being used to identify roadblocks, traffic signs, snow conditions, and in some cases, road surface quality problems (Forests.fi 2018; Metsäteho.fi 2020). Such projects also test different data collection systems, and LiDAR with both airborne and car-mounted sensors are included in these trials.

One future aspect of the ALS-based road quality method may also include the automatic delineation of forest roads and the manual modifications required to ensure their quality in the current project. These road centerline extractions and forms of automated road detection are already tested (White et al. 2010; Azizi et al. 2014; Hui et al. 2016). They can be integrated into the data processing to increase workflow automation and identify road width or non-paved roads.

According to the current Finnish operational ALS acquisition plan, a 5 pts/m2 data is being collected from majority of Finland during the years 2020-2025. There laser scanning inventories can open new possibilities about road quality analysis as well. Several projects already focus on these new datasets. The Access2Forest (2020) is a joint Finnish-Russian cooperation to develop advance planning methodology for forest road construction and maintenance planning to switch from traditional, often expensive, empirical data collection methods to cheaper and more accurate alternatives. Another ongoing project is Metsäteiden kuntokartoitus (MeTeiKu 2020), in English ‘condition survey of forest roads’. This joint Finnish pilot program is being carried out in 2020-21 and aims to collect more data and develop further methods using this high pulse density data to assess road trafficability and therefore benefit timber harvesting and long distance transportation in the forest industry.

The proposed methods of this thesis open the possibility of assessing unpaved forest roads using remote sensing data, in this case airborne laser scanning, which can lead to a more quantifiable, uniformed, and less subjective road quality assessment system to be introduced in the future.

6 CONCLUSIONS

Low and high-pulse density LiDAR-derived data were used here to determine various quality features of unpaved forest roads in both Finland and Canada. The research has shown that these airborne laser scanning data can classify roads in terms of various quality parameters and identify poor quality roads – the ones that will need maintenance the most in the coming year – with a reduced need for field visits. This can save time and resources when replaces even partially the manual road quality check-ups, furthermore, introduce a possibility to assess unpaved forest road quality in a more systematic way.

Automatic classification of the road network, whether in terms of vegetation cover or road surface quality, can help forest managers to obtain meaningful information applying to extensive areas. One possibility for improvement would be to incorporate the extraction of road features into the workflows in order to automate more processes (Craven and Wing 2014; White et al. 2010), but improvement of the tools and mapping technology can also offer future prospects.

Another option is to use multispectral ALS (MALS) data. Although commercial dual-wavelength ALS systems have already been used for coastline and shallow water mapping, the Optech Titan MALS system (Teledyne Optech 2019) can capture LiDAR data on three wavelengths: 532 nm (visible), 1064 nm and 1550 nm (intermediate infrared), with a topographic point density of over 45 pts/m^2 and a scan angle varying between 0° and 60°. Multispectral ALS would provide data on the vegetation cover that could be used to assess more precisely vegetation and canopy covering roads and occupying ditches, in order to provide a better picture of whether the ditch system is overgrown or missing, for example. If multispectral LiDAR inventories were to become more common in species-specific forest inventories (Kukkonen et al. 2019), these could be used for forest road research as well. Another option would be to use car mounted LiDAR devices (Salmivaara 2017; Mobile Mapping 2020) to collect data alongside manual road check-ups and in this way to gain more information regarding road quality than can be derived from empirical assessments alone.

Besides using improved sensors, multiple annual inventories could assist in mapping road quality changes better throughout the year. More bearing capacity measurements are needed in order to better understand seasonal changes in the quality of forest roads, not only at Finnish sites but also elsewhere (Kaakkurivaara 2015). Although the basic changes occurring in boreal soils and their effects on trafficability have been mapped (Natural Resources Institute Finland 2019), these areas require further research in order to derive the greatest benefit from ALS or other supplementary data (such as soil information, bearing capacity, MALS or aerial photos).

Aside from airplanes, UAVs such as drones can carry laser scannners too, which can lead to reduced costs (Zhu 2013). UAVs have already been used for mapping construction work in forests (Buğday 2018), and can easily become a popular tool for road quality assessments as well in the near future if their overall precision can be improved relative to other methods (Hrůza 2018). Tests have been carried out to identify rut depths exceding 20 cm using UAV photogrammetry (Nevalainen 2017), and Mobile Laser Scanning, including both car and UAV-mounted sensors, can currently achieve a precision RMSE of around 5.5 cm (Jaakkola 2015). Collecting road data by crowd-sourcing truck drivers' mobile phones, for example, is in the pilot phase in Finland as a means of automating and collecting road data more efficiently (Venäläinen 2018; Metsäteho.fi 2020; Vaisala RoadAI 2020), and this could well reduce the need for separate road quality inventory visits and thereby save time, money and resources.

Further research can help to derive more parameters affecting unpaved forest road quality, creating further methods integrating seasonal weather changes that highly affect trafficability of unpaved roads in both in Canada and Finland. Encorporating that with the new technologies, such as MALS (Teledyne Optech 2019), this work can be a solid foundation for further research concerning the quality assessment of unpaved forest roads.

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