

Dissertationes Forestales 120

Airborne laser scanning based identification and
interpretation on ecologically important old-growth
forest habitats in natural conservation areas

Mikko Vehmas
School of Forest Sciences
Faculty of Science and Forestry
University of Eastern Finland

Academic dissertation

To be presented, with the permission of the Faculty of Science and Forestry of the University of Eastern Finland, for public criticism in the auditorium N100 of the University of Eastern Finland, Yliopistokatu 7, Joensuu, on 13th May 2011, at 12 o'clock noon.

Title of dissertation: Airborne laser scanning based identification and interpretation on ecologically important old-growth forest habitats in natural conservation areas

Author: Mikko Vehmas

Dissertation Forestales 120

Thesis supervisors:

Prof. Matti Maltamo

School of Forest Sciences, University of Eastern Finland, Joensuu, Finland

Dr. Kalle Eerikäinen

Finnish Forest Research Institute, Joensuu Research Unit, Finland

Prof. Jari Kouki

School of Forest Sciences, University of Eastern Finland, Joensuu, Finland

Pre-examiners:

Prof. Svein Solberg

The Norwegian Forest and Landscape Institute, Ås, Norway

Dr. Jörg Müller

Nationalparkverwaltung Bayerischer Wald, Grafenau, Germany

Opponent:

Dr. Timo Kuuluvainen

Department of Forest Sciences, University of Helsinki, Finland.

ISSN: 1795-7389

ISBN: 978-951-651-332-7 (PDF)

(2011)

Publishers:

Finnish Society of Forest Science

Finnish Forest Research Institute

Faculty of Agriculture and Forestry of the University of Helsinki

School of Forest Sciences of the University of Eastern Finland

Editorial Office:

Finnish Society of Forest Science

P.O. Box 18, FI-10301 Vantaa, Finland

<http://www.metla.fi/dissertationes>

Vehmas, M. 2010. Airborne laser scanning based identification and interpretation on ecologically important old-growth forest habitats in natural conservation areas. *Dissertationes Forestales* 120. 44 p. Available at: <http://www.metla.fi/dissertationes/df120.htm>.

ABSTRACT

Over the last decades, accurate and cost efficient remote sensing techniques in large-scale forest inventories have developed rapidly. In particular, the airborne laser scanning (ALS) has provided new possibilities to quickly and accurately monitor forest ecosystems over large areas. ALS provides three-dimensional data on forest structure and basic forest characteristics (e.g. wood volume per hectare) with good accuracy. Currently, ALS is already applied in the stand level management inventory in many countries. However, the applicability of ALS to detect more rare items and forest characteristics has not yet been entirely assessed. My study focuses on these uncommon forest characteristics and tests the potential of ALS to facilitate biodiversity inventories. Boreal forest stands with high herbaceous plant species diversity, large European aspen (*Populus tremula* L.) individuals, and old-growth forest canopy gaps have been found to be important biodiversity characteristics in western taiga forests. The field inventories of these forest structures are often time-consuming and, therefore, the inventory methods in various scales should be developed to improve their conservation and management.

In this thesis I developed and evaluated ALS based methods to identify the old-growth forest characteristics. All the data were collected from Koli National Park (Koli NP) in eastern Finland. The data used in this thesis included 274 mature forest stands belonging to five different forest site types and varying in size. The spatial and temporal patterns of the chosen biodiversity characteristics were investigated. The longevity of aspen stands was studied based on multi-source data. About one-third of the old-growth forest areas of the Koli NP contained large aspen trees that persisted throughout the period between 1910 and 2004.

The results show that aspen can maintain long-term occurrence in old-growth forests and that the species is not only transient or confined to early successional stages. The ALS was used to identify herb-rich forest stands. ALS was capable of distinguishing herb-rich forests from less fertile site types with an accuracy of 88.9%. This was mainly based on the vertical vegetation profiles that characterize forests on high fertility sites. The best overall classification accuracy achieved for all the forest site types was 58.0%. As a basis on earlier studies canopy gaps can be located using ALS data. I found clear differences between the canopy gaps of natural forests and managed forests. In addition, both the density of vegetation and amount of coarse woody debris are utilizable characteristics in the ALS data-based identification of canopy gaps. In the large-scale forest inventories ALS-data proved to be a useful technology for the identification of several forest characteristics related to biodiversity in old-growth boreal sites. In particular, locating the herb-rich stands was found to be accurate.

Keywords: ALS, Boreal forest, Canopy gaps, Forest inventory, Herb-rich forests, *Populus tremula*, Remote sensing, Vegetation

ACKNOWLEDGEMENTS

My work with airborne laser scanning (ALS) data started in summer 2001 when I was establishing field sample plots in “legendary” Kalkkinen managed forest area, in southern Finland. Since then I have followed the development of ALS based methods relatively intensively. My PhD project started in 2005 after getting access to the ALS data from the Koli National Park, which has now become a really special place for me. Finally this long project has come to an end and new challenges await. First and foremost, I would like to thank my supervisors and co-authors Prof. Matti Maltamo and Prof. Jari Kouki for guiding and helping me through these years. There are no words to describe how much my third supervisor, Dr. Kalle Eerikäinen, has helped me through this work by co-authoring all my four articles included in this dissertation. Thank you, Kalle. Additionally, I want to thank Jussi Peuhkurinen, who gave valuable know-how to articles II and III, as well as Petteri Packalén who has been “the master of ALS data processing” here at our university. All these years it has been my pleasure to work with so many great colleagues. I would like to thank you all for your support. I would like to express my gratitude to the pre-examiners of this dissertation, Dr. Svein Solberg and Dr. Jörg Müller, for their valuable comments, which helped me to finalize my dissertation.

My project has been funded mainly by Maj & Tor Nessling foundation. Additionally the Finnish Ministry of the Environment, the Graduate School in Forest Sciences and the Niemi foundation (Niemi-säätiö) supported this dissertation. I am very grateful for these financial supporters.

Finally, I give my warmest thanks to all of my beloved friends who are part of our family. My mother and father deserve special attention and gratitude, because I am indebted to them for everything. It has been said that life without children would be easier. That might be true, but for myself, life with my children is a constant source of pure joy. I am really grateful to have four children - thank you mothers! Through these years there have been many people who I appreciate for supporting me in many ways and giving me valuable experiences and opportunities to have meaningful conversations and melodies to go forward in life. Last but not the least, I want to thank my wife Maaret for being my priceless half. My personal development, not only in the field of science but also in the field of service, is based on the Bahá’i Faith, and that has helped me to get through all the challenges I have faced while writing this dissertation. As ‘Abdu’l-Bahá describes: *“Religion and science are the two wings upon which man’s intelligence can soar into the heights, with which the human soul can progress. It is not possible to fly with one wing alone! Should a man try to fly with a wing of religion alone he would quickly fall into the quagmire of superstition, whilst on the other hand, with a wing of science alone he would also make no progress, but fall into the despairing slough of materialism.”*

Joensuu, April 2011

Mikko

LIST OF ORIGINAL ARTICLES

The thesis is based on the following papers, which are referred to in the text by the Roman numerals I-IV. The papers are reprinted with the kind permission of the publishers.

- I Vehmas, M., Kouki, J. and Eerikäinen, K. 2009. Long-term spatio-temporal dynamics and historical continuity of European aspen (*Populus tremula* L.) stands in the Koli National Park, Eastern Finland. *Forestry* 82(2), 135-148. <http://dx.doi.org/10.1093/forestry/cpn044>
- II Vehmas, M., Peuhkurinen, J., Eerikäinen, K., Packalén, P. and Maltamo, M. 2009. Identification of boreal forest stands with high herbaceous plant diversity using airborne laser scanning. *Forest Ecology and Management* 257, 46-53. <http://dx.doi.org/10.1016/j.foreco.2008.08.016>
- III Vehmas, M., Eerikäinen, K., Peuhkurinen, J., Packalén, P. and Maltamo, M. 2011. Airborne laser scanning for the site type identification of mature boreal forest stands. *Remote Sensing* 3, 100-116. <http://dx.doi.org/10.3390/rs3010100>
- IV Vehmas, M., Packalén, P., Maltamo, M. and Eerikäinen, K. 2011. Using airborne laser scanning data for detecting canopy gaps and their understorey type in mature boreal forest. *Annals of Forest Science*. In Press. <http://www.afs-journal.org/>

Mr. Mikko Vehmas is the principal author of all the articles. He is also the creator of the original ideas of the studies and mainly responsible for the data processing and analysis. Some of the calculations in article II and all k-NN calculations in article III were done by the co-author. The co-authors helped to develop the articles in all ways to achieve their final quality.

TABLE OF CONTENTS

ABSTRACT	3
ACKNOWLEDGEMENTS.....	4
LIST OF ORIGINAL ARTICLES	5
LIST OF ABBREVIATIONS.....	7
1 INTRODUCTION	9
1.1 General background.....	9
1.2 Forest inventories	9
1.2.1 National forest inventory in Finland	9
1.2.2 Inventory by compartments	10
1.3 Ecologically important biodiversity characteristics.....	11
1.3.1 Old-growth forests	11
1.3.2 Finnish forest site type system and the herb-rich forests	12
1.3.3 Aspen	13
1.3.4 Canopy gaps.....	14
1.4 Remote sensing in forest inventory	15
1.4.1 Optical imagery-based methods.....	15
1.4.2 Airborne laser scanning-based methods	15
1.5 Objectives.....	18
2 MATERIALS.....	19
2.1 Study area: the Koli National Park	19
2.2 Inventory data.....	20
2.2.1 Forest inventories.....	20
2.2.2 Additional field inventories	22
2.3 Laser data (II-IV).....	22
3 METHODS	23
3.1 Laser data metrics (II-IV).....	23
3.2 Logistic regression (II)	24
3.3 K-NN (II-III)	24
3.4 Spatial canopy gap characteristics (IV).....	26
3.5 Example calculations.....	27
3.6 Evaluation of the results and statistical tests	28
4 SUMMARY OF THE RESULTS.....	29
5 CONCLUSIONS	31
REFERENCES	35

ARTICLES I-IV

LIST OF ABBREVIATIONS

3D	Three-dimensional
ALS	Airborne laser scanning
CG-class	Canopy gap -class
CHM	Canopy height model
CWD	Coarse woody debris
DDW	Downed deadwood
DTM	Digital terrain model
ENN	Euclidean nearest neighbour
GPS	Global positioning system
GSCI	Gap shape complexity index
INS	Inertial navigation system
k-NN	k-nearest neighbour
Koli NP	Koli national park
LSI	Landscape shape index
MSFI	Multi-source forest inventory
NFI	National forest inventory
PD	Patch density
PLAND	Percent of landscape
PRD	Patch richness density
RMSE	Root mean squared error
SHDI	Shannon´s diversity index
SIDI	Simpson´s diversity index

1 INTRODUCTION

1.1 General background

The Fennoscandian countries have a long tradition in conducting forest inventories that facilitate assessment of timber volumes. In Finland, the first nation-wide forest inventories were done already at the beginning of the 20th century. Since then, the forest inventory methods have improved considerably, and currently they provide accurate information on forest resources. However, these methods are geared mainly to help timber production for industrial purposes, and the methods used in traditional forest inventories do not focus extensively on inventorying the old-growth forests, or to reveal patterns of forest biodiversity or other ecologically important patterns. The old-growth forests are defined as essentially unmanaged forests and in forestry terms over-aged, often including abundantly large living and dead trees (for further terminology see, Rouvinen and Kouki 2008). A great variety of different ecological characteristics should also be inventoried from the forests, and there is an urgent need to develop technologies for large-scale forest inventories which can also be used to detect and monitor environmentally important characteristics. Because of intensive forest management activities in Fennoscandia, the extent of old-growth forests has decreased during the last century and the remaining areas are relatively small and sparsely distributed (e.g. Hanski 2000, Angelstam and Anderson 2001, Kouki et al. 2001). Old growth boreal forests have characteristic forest structures that provide various habitats for many animal and plant species. The recent decline of old-growth forests has caused many species to become threatened. About 37% of the red-list species are primarily associated with forest habitats, particularly herb-rich woodland and old-growth (natural or semi-natural) habitats (Rassi et al. 2001). Numerically, there are 455 threatened, 646 near-threatened and 71 extinct species that live or lived primarily in wooded habitats in Finland (Rassi et al. 2001).

The protection of biodiversity has become one of the recognized objectives of forest management. Development of various methods to interpret especially old-growth forests as well as methods to follow possible changes in these habitats have become important. Airborne laser scanning (ALS) is a relatively new technique used in large-scale forest inventories with complete spatial coverage (wall-to-wall manner). ALS data with accurate vertical profiles on the vegetation covers of forests can be applied from small (square meters) to large scale (square kilometers) areas. Due to its accuracy, the ALS has a lot of potential to provide useful inventory information from forests and to locate the ecologically important old-growth and herb-rich forests. Remote sensing applications can provide useful and cost efficient information to develop interpretation and monitoring also for operational use. In addition, large-scale forest inventory methods with forest structure analysis are useful when estimating e.g. the amount of forest carbon (e.g. Gonzalez et al. 2010).

1.2 Forest inventories

1.2.1 *National forest inventory in Finland*

National Forest Inventory (NFI) in Finland began already in 1920s, shortly after Finland gained independence. The purpose of the NFI is to provide continuous information from the

whole country on the state of the forests and about the resources they offer. The NFI is a monitoring system based on statistical sampling and efficient field measurements, which nowadays produces information concerning national and regional forest resources, land use structure, forest health, biodiversity of forests and forest carbon stocks and their changes (Tomppo 2006). The information has been widely utilized in planning the management, timber production and harvest options. The 1st NFI in Finland was carried out in the 1920's (Ilvessalo 1927) and since then NFIs have been made regularly in 5-10 years cycles. The latest completed NFI, i.e. the 10th NFI, was started in 2004 and ended in 2008, and most of the results are already available. The ten NFIs of Finland form a unique long time series of information about the development of forests in Finland. The 10th NFI was special in terms of continuous country-coverage and it was executed under the concept of a 5-year programme. The ongoing 11th NFI started immediately after the 10th in year 2009.

The first four NFIs of Finland were carried out using a line survey method with about 50-100 parallel continuous south-west - north-east direction line transects, most of them crossing the whole country (Ilvessalo 1927). From the 5th NFI onwards a systematic cluster sampling method was applied, where sample plots are located systematically in the field as a regular network that cover the whole country (Kuusela and Salminen 1969). Basic units of the current cluster sampling are temporary and permanent sample plots, where trees belonging to the plot are selected with an angle gauge (relascope) (Kuusela and Salminen 1969). The basic NFI is designed for obtaining the statistical information at country and regional levels; the whole of Finland (30 million hectares), forest centers (from 1 to 3 million hectares), municipalities (median 36 000 hectares). The multi-source forest inventory (MSFI) method employs, for instance, satellite images and digital map data, in addition to field data. The MSFI can be utilized to achieve information also at lower levels; forest estates (about 100 hectares) and thematic maps (pixel size of 25 meters). The MSFI method was developed at the end of the 1980's and it based on field measurements, remote sensed data and other digital data sources such as land-use maps and elevation models (Tomppo 1996). In order to provide localized forest statistics and thematic maps for smaller areas the k-nearest neighbor (k-NN) classification method is applied in the image analysis (Tomppo 1996). The NFI provides information on a great variety of forest and land use characteristics from an ecologically important point of view. These estimates are totals and means for large-scale areas but they cannot be localized since the current information included in MSFI cannot provide accurate enough pixel or stand-level estimates. For example, the estimates of forest key biotopes, general information about the ecologically important tree species like European aspen, the amount of herb-rich forest site types and since the 8th NFI, even deadwood characteristics can be estimated for the large-scale areas.

1.2.2 Inventory by compartments

The stand-level forest inventory is used when spatially explicit forest information is needed for operational use, typically for single estates. In Finland, the stand-level forest inventory, namely inventory by compartments is traditionally applied (Poso 1983). The first inventories by compartments, were made by the strip survey method or by using either randomly or systematically located sample plots (Nyyssönen 1959). Nowadays, the forest compartments are delineated visually from aerial images and verified by field visits. The forest compartments are defined as spatially contiguous parcels of land that are more or less homogeneous in terms of site type and growing stock (Davis and Johnson 1987). The mapping of stand attributes, such as basal area, age, site, stand development class, mean

height and diameter, is based on subjectively located relascope sample plots (Bitterlich 1948). The calculation of forest characteristics is then based on diameter distribution, height and volume models. In the inventory by compartments one of the main challenges is the precise delineation of forest stands (Koivuniemi and Korhonen 2006). The delineation of forest stand borders is subjectively made by forest professionals from aerial photographs and field measurements and errors in the determination of the borderlines are common (Hyppänen et al. 1996). The subjectivity is also a problem for the assessment of stand attributes. In addition the forest characteristics are estimated using sample plots and then generalized to the stand level, thus including sample error. Despite its limitations, the method is widely accepted and commonly practised for forest management and conservation purposes. A great variety of different biodiversity characteristics are included in a stand-level forest inventory.

In Scandinavia, the ALS based methods in stand-level forest management inventory are already at the operational use. Since 2002, the ALS based inventory in practical forestry has been applied in Norway (Næsset et al. 2004). In Finland, the new forest inventory by compartments in private forests was launched in 2010. The method is based on ALS, aerial images and field sample plots (see Packalén 2009 for details) and it provides the basic forest characteristics for forest management planning purposes (Metsäkeskus 2010). The goal of this new inventory system is to cover 1.5 million hectares in a year and reduce inventory unit costs about 40 per cent (Metsäkeskus 2010). So far, it does not include any specific biodiversity characteristics.

1.3 Ecologically important biodiversity characteristics

1.3.1 Old-growth forests

In the Fennoscandian boreal forests human impact has caused changes in the natural ecosystem mainly due to the silvicultural regimes and timber production. Intensive slash-and burn cultivation was practised in eastern Fennoscandia until the late 19th century (e.g. Lehtonen 1997) and it had clear consequences on the age and tree species composition of forests today (Pitkänen 1999). In addition, more efficient and improved timber production has expanded during the last 60 years (e.g. Esseen et al. 1997, Kouki et al. 2001). The coverage of old-growth (i.e. natural or semi-natural) forests has clearly decreased during the last centuries and the remaining forests have mainly been under forest management activities. Therefore, large tracks of natural forests cannot be found in Fennoscandia any more (Achard et al. 2006, Potapov et al. 2008). However, small scale natural or at least semi-natural (Uotila et al. 2002), forests can still be found. These remaining old-growth forest areas are very important for sustaining the biodiversity of the boreal forest in Fennoscandia.

Old-growth forests are defined by long, often uninterrupted vegetation succession and have a diverse forest structure. In the boreal old-growth forests there are many physical (topography, soil and geology) and biological (succession stage, dominant tree species, etc.) factors affecting the vegetation characteristics. According to the habitat classification of Natura 2000, habitat type no. 9010 is western taiga (see European Commission 1999). Defining a natural stand representative of taiga forest is not easy, because several characteristics can be included. In the Natura 2000, the main characteristics of boreal old-growth forest are spatially random distribution of the trees, varying or continuous

vegetation layer, large amount of coarse woody debris (CWD), diverse size structure of the living trees, large individuals or groups of deciduous species (see also Esseen et al. 1997). In practice, only a subset of these characteristics are required to be met in order for a stand to fulfill the definition. Taiga forests are, however, characterized also by repeated disturbance that complicate the definition of natural forests. Disturbances such as fire and wind cause the amount of decaying wood and the number of small-sized gaps to increase and create local habitats that are vital for many red-listed species (Kuuluvainen 1994). According to Rouvinen et al. (2002), and Rouvinen and Kouki (2008) two simple and quite potential quantitative measures for identifying naturalness of the forests are the amount of CWD and the number of cut stumps, the latter indicating that in most cases selective thinning has been applied in the area.

1.3.2 Finnish forest site type system and the herb-rich forests

In Finland forest stands are classified by forest site types according to their understorey vegetation characteristics, especially indicator species. The site classification system is based on Cajander's (1926) forest site type theory and is a classic example of the indirect site quality estimators in the forestry context (Clutter et al. 1983). According to Cajander (1926) forest site type classification the five main vegetation types are: 1) very rich (e.g., *Oxalis-Maianthemum* type, OMaT), 2) rich (*Oxalis-Myrtillus*, OMT, herb-rich heath forest), 3) medium (*Myrtillus* type, MT, mesic heath forest), 4) rather poor (*Vaccinum* type, VT/EMT, subxeric heath forest) and 5) poor (*Calluna* type, CT/MCCIT, xeric heath forest). The vegetation of conifer dominated boreal forests is commonly considered to be relatively homogenous in the vegetation structure and low number of species richness. However, despite of the fact that the composition includes only a few tree species there also might coexist diverse plant species with different shapes and sizes (Kuusipalo 1984, 1985). In general, mature forests are often characterised by sparse understorey vegetation that may make it difficult, especially in boreal spruce forests, to determine their site types according to the classification of Cajander (1926). However, according to a study by Pitkänen (1997), there exists a connection between the different stand structures and variation in ground vegetation.

The Fennoscandian herb-rich forests (Natura 2000, habitat type no. 9050, see European Commission 1999) are important habitats with respect to forest biodiversity and for many red-listed species (Rassi et al. 2001, Hokkanen 2006). Herb-rich forests (i.e. grass-herb forests) are characterised by herbaceous flora, where grasses and shrubs are abundant (e.g. Cajander 1926) and are the most luxuriant and species-rich forests in Finland (Alanen 1992, Kuusipalo 1984). Boreal herb-rich forests are characterised by mixtures of deciduous trees (e.g. *Quercus robur* L., *Tilia cordata* Mill., *Alnus incana* (L.) Moench, *A. glutinosa* (L.) Gaertn., *Betula pendula* Roth., *B. pubescens* Ehrh. and *Populus tremula* L.) and Norway spruce (*Picea abies* (L.) Karst.), and by fertile brown soil with a thick mull layer which varies from slightly neutral to neutral in pH (Hokkanen 2006). Their understorey vegetation is therefore denser both vertically and horizontally than that of forests growing on podzolic soils.

Most of the herb-rich stands of Finland are rather small in size and occur as scattered small patches in the forest landscape (Alanen et al. 1996, Heikkinen 2002). Although herb-rich forests cover less than one percent of the total forest coverage in Finland (Alanen et al. 1996) they are the primary habitat for over 55% of the red-listed forest-dwelling species and for over 10% of all vascular plant species (see Rassi et al. 2001). Methods to locate and

map herb-rich stands are rather limited because it is mainly done in the conventional stand-based forest inventory (Poso 1983), which is based on stand delineation for forest management purposes. Therefore the small and spare herb-rich patches are quite often missed. However, small scale herb-rich stand inventories by using permanent sample plots (1 are) with detailed vegetation analysis squares (1m²) have been conducted in Koli National Park (Koli NP) to quantitatively assess their floristics composition and site type classification (Hokkanen 2006).

1.3.3 Aspen

The European Aspen (*Populus tremula* L.) is considered to be one of the key tree species that maintain biodiversity in boreal forests (Esseen 1992, Kouki et al. 2004). There are two main reasons for this: 1) large and often slightly decayed aspens host a diverse fauna and flora including many species that are currently classified as red-listed, and 2) very large-diameter dying and dead aspens have largely disappeared from managed forests. Large aspen trees have declined in numbers mainly because they are constantly being felled and replaced with economically more valuable species and partly because they are intermediate hosts of the pine rust fungus (*Melampsora pinitorqua* (Braun) Rostr.) that causes serious damage to young pine stands (Kurkela 1973, Heliövaara and Väisänen 1984). Notching with herbicides was commonly used in forest management in the 1970s to reduce the number of aspens (Kurkela 1999, Kouki et al. 2004). Currently the occurrence of the very large, old and partly decaying aspen trees is mostly restricted to protected areas.

Large aspens in Finland, both living and dead, host over 750 animal and plant species, including herbivorous and saproxylic beetles, polypore fungi, epiphytic lichens and vertebrates (Siitonen 1999, Kouki et al. 2004). Almost 150 of these species have specialized to live on or in large aspens, and about 50 species in Finland that are associated with aspen are currently on the red-list (Siitonen 1999, Rassi et al. 2001, Kouki et al. 2004). Aspen trees also modify their nearby surroundings in ecologically important ways. Their leaves create litter that is less acid than that of other tree species in boreal forests and provide a special habitat for ground-dwelling invertebrates (Koivula et al. 1999, Siitonen 1999), and other characteristics such as a canopy structure that lets some sunlight through (Almgren 1990), fast decomposition of the wood (Tikka 1954), and a thick, nutritious alkaline bark (Kuusinen 1994) also provide a very suitable substrate for various epiphytic species (Kuusinen 1996).

Old aspen trees are mostly found in old-growth mixed forests, where they grow in small groups or as scattered individuals (Tikka 1954, Syrjänen et al. 1994). The species favours fertile upland sites and herb-rich forests (Tikka 1955), and is traditionally regarded as a pioneer species that regenerates almost exclusively in disturbed areas, where seedlings grow mostly from roots via vegetative regeneration (Tikka 1954). Regeneration from seeds appears to succeed only occasionally (see e.g. Latva-Karjanmaa 2006). Some recent studies have indicated that aspen can maintain its populations in natural old-growth coniferous forests for up to several hundred years, even though they may slowly decline in abundance (Lilja et al. 2006). The exact patterns and mechanisms of aspen occurrence under these conditions have been little studied. Small-scale disturbances and gap dynamics probably promote aspen regeneration under old-growth conditions (Cumming et al. 2000).

Since the local, or at least regional continuity of ecologically important characteristics is regarded as important for conservation purposes (Stokland et al. 2002, Kouki et al. 2004), a knowledge of aspen dynamics is required for the management of conservation areas. This

issue is highly relevant ecologically, since it relates directly to the problem of whether it is also possible to maintain broadleaved trees that typically occur during the early succession in the older successional stages. It is also of interest whether the aspens will survive in protected areas in the future, or whether it will require active management to promote aspen occurrence. These aspects could be monitored with multi-source or remotely sensed data.

1.3.4 Canopy gaps

Canopy gap dynamics in boreal forests are of high importance to forest ecology (Liu and Hytteborn 1991, Kuuluvainen et al. 1998, Drobyshev 1999, McCarthy 2001). In old-growth boreal forests, extensive fire disturbance is the main cause of regeneration. However, interspersed between intensive disturbances small-scale, canopy gap dynamic changes are common (Kuuluvainen 1994). Small scale canopy gaps are caused by dying tree individuals or tree cohorts having different decomposition stages of varying diameter deadwood (CWD) (Kuuluvainen 1994). Canopy gaps in old-growth forests, with especially large diameter deadwood, provide ecologically important habitats for many endangered or threatened species (e.g. Siitonen et al. 2000, Kouki et al. 2004). In most cases, the death of individual trees is caused by wind or snow destruction, different diseases or insects (e.g. Liu and Hytteborn 1991, Kuuluvainen 1994, McCarthy 2001). Multilayer forests are formations of small-scale, continuous disturbances which promote regeneration in natural canopy openings by even forming the new tree generations (e.g. Zhu et al. 2003, Bollandsås et al. 2008). Furthermore, according to Spies and Franklin (1989) even shade-tolerant tree species require small canopy gaps to reach the canopy in old-growth forests, which indicates regeneration difficulties for shade-intolerant species. Small gap processes release little in the way of above-ground or below-ground resources, whereas large-scale disturbances such as fires release more resources to enable species to regenerate (Spies and Franklin 1989). In addition, according to Bartemucci et al. (2002), the smallest gap disturbances in northern old-growth forests are caused mainly by snapped stems and dying trees, which involve little floor disturbance and create few germination sites for seedlings. The stand-level persistence and regeneration properties of deciduous and shade-intolerant species in old-growth boreal forests have obvious and important consequences for forest biodiversity. If a tree species can survive and regenerate even under (mostly) shady old-growth conditions, this may have consequences for the conservation of the plant and animal species that are closely associated with these host trees.

Canopy gaps also exist in managed forests but then most openings originate from thinning and other logging activities implemented for the establishment of logging tracks, for instance. Large or even medium diameter CWD is practically missing from these manmade openings. However, some regeneration can be found in the canopy gaps in managed forest stands (e.g. Zhu et al. 2003), which is mainly due to the disturbances in soil surface caused by thinning operations and therefore creates more favourable site conditions for seedling than in natural canopy openings (Angelstam and Petterson 1997). Since there is no universal definition for the metrics of the canopy gaps, the delineation of the borders and sizes of the canopy gaps varies from one application to another. Accurate information on canopy gaps and CWD existence can improve conservation activities in the most environmentally important locations and reorient forest management activities towards a more environmentally friendly direction.

1.4 Remote sensing in forest inventory

1.4.1 Optical imagery-based methods

Aerial images have been used for forest inventory purposes since early 1900's. In Finland aerial images were initially used to estimate growing stock and to map forests (Nyyssönen 1959). Since then aerial images have been used in practical forest inventory for stand delineation. Satellite images have been used since the 1970's for mapping forests in large-scale (e.g. Kilkki and Päivinen 1987, Reese et al. 2003), especially by producing full coverage estimates of forest characteristics to be used as auxiliary information in smaller areas (Tomppo 2006). However, so far satellite images have not been successfully used in stand level inventories, but during recent years the resolution of satellite image data has improved remarkably.

Aerial photographs, coupled with both visual and computer-aided interpretation, have been tested to determine stand-level information. Visual interpretation is still used, for instance, in stand delineation but the results are subjective, because they depend on the outcome of the forest professional. Recently, three-dimensional (3D) photogrammetry has been applied to produce, for instance, tree heights (e.g. Korpela 2000, 2004). With computers the spectral and texture information can be utilized in the estimation of various characteristics of the growing stock including even the content of carbon (e.g. Brown et al. 2005). In addition, aerial images have been used to identify key biotopes and forest habitats (see Uuttera and Hyppänen 1998, Holopainen 1998). Haara and Nevalainen (2002) studied the detection of dead or defoliated spruces using digital aerial color infrared data. They showed that in general the defoliated tree segments and stands were classified satisfactorily and the accuracy of the pattern-recognition method was proved to be adequate for detecting dead or heavily defoliated trees and heavily defoliated stands. However, the images obtained for growing stocks or methods developed are not detailed or accurate enough to use for the purposes of large-scale forest inventories. In general, interest in using and developing methods based solely on aerial images has decreased at least to some extent, because of the forest inventory results achieved by ALS.

1.4.2 Airborne laser scanning-based methods

Airborne laser scanning provides spatially accurate horizontal and vertical information (3D) on targets (Ackermann 1999) and is already being applied in many studies in estimating forest characteristics (e.g. Magnussen and Boudewyn 1998, Næsset 2004, Næsset et al. 2004). ALS data are derived from the measured travel times of pulses between a sensor and a target. Since the location and orientation of the sensor is known, ALS echoes form a 3D point cloud that describes the target (Lim et al. 2003). The 3D nature of ALS data has proven to provide excellent information on landscapes and forests (see Ritchie et al. 1992, Næsset 1997b, Magnussen and Boudewyn 1998, Maltamo et al. 2006). The introduction and overview of the detailed theory of ALS has been introduced by Wehr and Lohr (1999), where they show, for instance, the main principles of pulse laser, range, resolution and precision. In addition, their article covers scanning mechanisms and their integrations with GPS and inertial navigation system (INS) for positioning and orientating including the data processing chain applied (Wehr and Lohr 1999).

ALS data can be used as forest inventory data from the level of landscapes down to the level of single trees. It can provide full coverage of study units, because the data collection

is not usually based on sampling. ALS data are well suited for large scale applications. The method is operationally applicable and since 2002, it has been extensively applied to operational forest inventory purposes in Norway. Additionally, ALS data based methods provide a modern method to improve the information on different ecological environments. Multiple ALS echoes with precise x, y and z coordinates can be identified by processing the backscatter energy of a simple pulse. The data yielded by this technology include various echo types (e.g., first, last, intermediate and only echoes), z-values and intensity values, where the z-value is the height of the echo and the intensity value describes the amount of backscattering from it. Quite often the first step is to construct a digital terrain model (DTM) and to subtract it from the original point cloud in order to scale heights to above ground level. Especially in forestry applications the height of the above-ground vegetation is of greatest interest (see Hyypä et al. 2001, Lim et al. 2003, Maltamo et al. 2006, Hopkinson et al. 2006). The height characteristics of ALS data have been used in various studies: when analysing the modelled canopy fuel parameters of vertical forest structures for the purposes of fire behaviour assessment (Riaño et al. 2003, Andersen et al. 2005), distinguishing dominant and understorey layers of vegetation (Maltamo et al. 2005, Goodwin et al. 2007, Hill and Broughton 2009), predicting ecological canopy variables, such as canopy cover and LAI (Smith et al. 2009, Solberg et al. 2009), analysing natural regeneration (Bollandsås et al. 2008), considering forest health issues (Solberg et al. 2006b) and assessing biodiversity, for example, forest beetle assemblages (Müller and Brandl 2009), habitat characterization (Vierling et al. 2008) and bird habitat quality and heterogeneity (Hinsley et al. 2002, Hill et al. 2004, Goetz et al. 2007). Intensity values have been studied by Brennan and Webster (2006) who found them to be suitable for distinguishing between different surfaces, but it is only very recently that their applicability to the determination of forest characteristics has been investigated (e.g. Hopkinson and Chasmer 2007, Ørka et al. 2009). This is mainly due to difficulties in scaling and normalizing intensity values or lack of training in their interpretation (Ahokas et al. 2006).

ALS based inventory by forest compartments has two main approaches; the individual tree delineation method (Hyypä and Inkinen 1999, Persson et al. 2002, Maltamo et al. 2004, Solberg et al. 2006a, Vauhkonen et al. 2010) and the area based (laser canopy height distribution) approach (Næsset 1997a, 2002, Maltamo et al. 2006, Packalén 2009). The first approach uses high-resolution laser data (4-10 pulses per square meter) and latter low-resolution laser data (about 1 pulse per square meter). The individual tree delineation method is based on extraction of the local tree crown maxima, which is a direct determination of tree height. The stand characteristics are then estimated based on these sample trees to cover the whole forest compartments. The canopy height distribution method is based on the 100 per cent coverage of the forest stand and characteristic are estimated from the height distribution. For example, the accuracy of the total volume of species-specific estimates has been even better by using ALS than using traditional field inventory method (Packalén 2009). The most of the forestry applications done with ALS based on the canopy height distribution method which is more cost efficient because of low-resolution laser data and good accuracy of the predicted total characteristics.

Due to the fact that different height attributes of trees are estimated accurately from laser data, the ALS technique has also been applied to the determination of standwise site quality indicators based on the height distribution characteristics (e.g. Rombouts 2006, Gatzliolis 2007). These remote-sensing based approaches, in fact, correspond to the traditional growth and yield studies, in which the site classification is based on the dominant height-age dependency (cf. Eerikäinen 2002). This phenomenon can be further

studied by applying ALS data -based techniques. In their recent study, Korpela et al. (2009) found that ALS data can be used as one source of information when assessing different boreal mire surface patterns, vegetation and habitats. Analysis was done by modeling mire surface patterns, examining intensity responses in different mire vegetations and testing area-based classification of mire habitats based on geometric and radiometric features (Korpela et al. 2009).

Species-specific estimation in ALS based forest inventory has become more important due to need of more detailed inventory information. The species-specific growing stock estimation, based on canopy height distribution, has been studied by Packalén (2009). Packalén (2009) showed that with the combination of ALS and aerial images the accuracy of estimation of species-specific tree characteristics were as good as estimates obtained by current field inventory practice. There are also studies on the species-specific estimation which are based on the individual tree delineation method (e.g. Persson et al. 2003, Holmgren and Persson 2004, Brandtberg 2007, Ørka et al. 2009). The ALS data with multiple returns have been used to identify single large aspens by using mean intensity and standard deviation of intensity (Ørka et al. 2009). The single large aspens were not accurately identified by using only intensity information, because the classification accuracy for the aspen was only 23.8 %, whereas the overall accuracy of all tree species varied from 68 to 74 % (Ørka et al. 2009). According to Ørka et al. (2009), surprisingly, intensity metrics from first and only echoes of aspen were more similar to spruce than birch which may be explained by reflectivity of the bark, crown characteristics such as density and structure or the foliage reflectivity. Säynäjoki et al. (2008) used high resolution aerial images and ALS data to detect aspen trees from among other deciduous trees. In their study the aerial images were used in the segmentation of individual trees and to separate deciduous trees from coniferous trees (Säynäjoki et al. 2008).

The ALS have also been used to study canopy gap disturbance regimes (e.g. St-Onge and Vepakomma 2004, Koukoulas and Blackburn 2004, Vepakomma et al. 2008a, 2008b). In addition, changes in the canopy gap dynamics have been described by using multi-temporal ALS data with various subtracting methods to find changes in the canopy gaps, i.e. appearance, enlargement, reduction and disappearance of the canopy gaps (St-Onge and Vepakomma 2004, Yu et al. 2004, Hirata et al. 2008, Vepakomma et al. 2008a, 2008b). In the studies by Koukoulas and Blackburn (2004, 2005) and Zhang (2008) they calculated spatial canopy gap characteristics by using non-temporal, i.e. cross-sectional, data and therefore the canopy gap dynamics was not taken into consideration. A fixed height threshold needed in the gap delineation has varied from four meters (e.g. Koukoulas and Blackburn 2004) to 15 meters (e.g. Hirata et al. 2008). However, a five meters threshold height has been commonly used in various studies (e.g. St-Onge and Vepakomma 2004, Hirata et al. 2008, Vepakomma et al. 2008a, 2008b). Zhang (2008) used a mathematical morphology based method in gap delineation of the mangrove forests and found it to be more flexible and adaptable for use in vertically variable forests when compared to a fixed height threshold-based delineation. In managed forests an overall accuracy of 88% was achieved for a canopy gap delineation method with local maxima identification, filtering and clustering of the high density laser point cloud data (Gaulton and Malthus 2008). Commonly applied minimum gap size is 5m^2 (e.g. St-Onge and Vepakomma 2004, Gaulton and Malthus 2008, Vepakomma et al. 2008a, 2008b). In the study by Hirata et al. (2008), over half of the canopy gaps were less than 5m^2 in size when using minimum size of 1m^2 . As a result of these earlier studies it can be stated that ALS data can be applied to accurately detect canopy gaps.

Finally, ALS data have been applied to assess CWD characteristics (Pesonen et al. 2008, Bater et al. 2009). When determining fuel parameters in fire behaviour models Seielstad and Queen (2003) stated that it might be possible to map CWD from ALS data. Pesonen et al. (2008) predicted existence of CWD in old-growth forest in Finland having the root mean squared error (RMSE) of 14.1m^3 (51.6%) to the downed deadwood (DDW) volume and the RMSE of 14.7m^3 (78.8%) to the standing deadwood volume. The DDW volume estimate with ALS data was found to be substantially more accurate than the estimates based on field-measured characteristics of living trees (Pesonen et al. 2008). In the study by Pesonen et al. (2009) they showed that ALS data can also be used as auxiliary information for the preliminary mapping of forests with high amounts of downed deadwood. Deadwood percentage predictions in unmanaged forests were studied by Bater et al. (2009) in Canada. They found that the lowest ALS height percentiles were the most significant predictors of dead trees, which is likely based on the direct linkage between the number of dead trees in a stand and its canopy architecture (Bater et al. 2009).

1.5 Objectives

The overall aim of this thesis is to develop identification and interpretation techniques for natural and old-growth over-mature forests characteristics. To reach this aim, several long-term or spatially representative data sets were used with particular emphasis on the potential that ALS data can provide. The focus is mostly on a limited number of forest characteristics that are generally approved to be important indicators of naturalness, high biodiversity or conservation value. These include the occurrence and dynamics of single tree species (European aspen), herb-rich forests hosting a wide range of red-listed plants as well as canopy gaps and their contents. The specific objectives are:

1. To clarify long-term spatio-temporal European aspen dynamics in old-growth forests (**I**)
2. To classify forest site types, especially herb-rich forest by using ALS data (**II-III**)
3. To identify and classify canopy gaps by using ALS data (**IV**)

Unit of observation in articles **I-III** was a forest stand. In article **IV** canopy gaps were analysed on stand level.

In addition, example calculations by occurrence classes for large aspens (**I**) (continuous large aspen area, large aspen disappeared and large aspen appeared) were made. The goal was to test ALS-based methods (**II-IV**) in three separate areas and analyse how they can be applied when estimating the naturalness of the ecologically important large aspen stands and to support hypothesis are reported in articles **II-IV**.

2 MATERIALS

2.1 Study area: the Koli National Park

The study area is located in the Koli NP in eastern Finland (E29°50', N63°5'). The area is characterized by a highly variable boreal landscape where the altitude varies from 94 to 347 metres above sea level (Lyytikäinen 1991, Kärkkäinen 1994). The area lies in the transitional area of the border between the southern and middle boreal vegetation zones (Kalliola 1973). The area belongs to the continental climate zone, with a mean annual temperature of 2.1°C (January -10.7°C and July 16.1°C) and mean annual precipitation of 601 mm (Drebs et al., 2002). The length of the thermal growing period is 150–155 days (Heino and Hellsten 1983).

There is a long tradition of forestry practice-related stand-based forest inventories in the Koli NP (Antikainen 1993). The first human settlement in the area of Koli has been dated to the middle of the 18th century, and towards the end of that century slash-and-burn cultivation was intensively practised in the area and the forests were widely used for woodland pastures (Oinonen-Edén 1991), leading to an increase in the presence of broadleaved species, while the commercial management of forests in the 20th century favoured coniferous species (Grönlund and Hakalisto 1998). The first inventory of fields, slash-and-burn areas, meadows and forest lands was made during the general land partition of 1835–1845. There were no signs of industrial forest use, in the form of commercial felling, for instance, until 1864 (Oinonen-Edén 1991). The central hill sites of Koli became state-owned in 1907, and the first forest inventory was carried out in 1910. From 1924 to 2007 the area was administered by the Finnish Forest Research Institute. In 1991, the Koli NP (1135 ha) was founded in the core area (Laki Kolin... 1991). The park has since been enlarged and now has a total area of about 3000 hectares, where the northern part is about one third of the whole area. Extensive areas in the highest hill sites and rocky areas in Koli NP northern part have been left unmanaged for decades; whereas forest management operations like thinning, clear cutting and planting were carried out in the southern part until the early 1990's (Antikainen 1993). During the years from 2003 to 2006 restoration of the forests and meadows programme, Life to Koli, was carried out by the Finnish Forest Research Institute (Eerikäinen et al. 2007). From the beginning of 2008 the administrative responsibility of the Koli NP was given to the Finnish Forest and Park Service (Metsähallitus).

This relatively narrow area displays a wide range of site type classes from infertile to very nutrient-rich (herb-rich) soils with values of pH indicating near neutrality (Hokkanen 2006). In addition, the number of vascular plants and moss species are much higher than in other parts of the region (Hokkanen et al. 2003). The soils are more fertile at lower altitudes, because the nutrients flow downhill with the rainwater and snow melt. The Koli NP contains 42.5 hectares (1.6 per cent from the whole forest area) herb-rich forests in 61 stands (Lovén 2005) and most of them are growing on diabase-rich bedrock (see Piirainen et al. 1974). Following the classification of Cajander (1926), the forest site types identified in Koli NP were in five classes: 1) very rich (e.g., *Oxalis-Maianthemum* type, OMaT), 2) rich (*Oxalis-Myrtillus*, OMT, herb-rich heath forest), 3) medium (*Myrtillus* type, MT, mesic heath forest), 4) rather poor (*Vaccinium* type, VT/EMT, subxeric heath forest) and 5) poor (*Calluna* type, CT/MCCIT, xeric heath forest).

Most forests in the area are dominated by Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) with a highly variable admixture of silver birch (*Betula pendula* Roth.), downy birch (*B. pubescens* Ehrh.), European aspen (*Populus tremula* L.) and grey alder (*Alnus incana* (L.) Moench) (Lyytikäinen 1991, Grönlund and Hakalisto 1998). The mean stand volume of the ecologically important European aspen is 5 m³/ha and the amount of stand volume of aspen varies from 0 to 228 m³/ha (Hyvönen 2004). Most of the forests within the area are of mixed species, mostly spruce-dominated stands. Some rare and red-listed species (Rassi et al. 2001), such as mosses (e.g., *Neckera pennata* Hedw.), molluscs (e.g., *Bulgarica cana* Held), the true fly (*Xylomya czekanowskii* Pleske), beetles (e.g., *Cis fissicornis* Mellié) and mammals that are dependent on or associated with aspen (e.g., *Pteromys volans* L.) have been detected in the area (Lovén 2005).

2.2 Inventory data

2.2.1 Forest inventories

The separate inventories by compartments provide comparable sets of characteristics for the forest stands for the purposes of economic and ecological analysis (Table 1). In the latest compartment-wise inventory (Hyvönen 2007), carried out in 2004, the mean total stand volume was 220 m³/ha, whereas in earlier inventories of 1910 and 1936 the mean stand volumes were 45 m³/ha and 123 m³/ha, respectively.

To assess the historical patterns of aspen occurrence for the long-term spatio-temporal aspen dynamics study (I), only those inventory data that included information on the occurrence of this species were used in the analysis. As a result, the legend books from the inventories of 1910, 1936 and 2004 with aspen data were used in the current analyses, whereas the data from 1835–1845, 1961–1962, 1971 and 1989 included only general information on broadleaved trees and were therefore used only for validation of the results and characterization of the management history of the area. In all the inventories the

Table 1. Sources of data used in the historical analyses (I).

Years of coverage	Map type	Map scale	Information type
1835 -1845	General land partition map	1:7000	Legend book
1910 -1911	Inventory map	1:8000	Legend book
1936	Inventory map	1:4000	Legend book
1961 -1962	Inventory map	1:5000	Legend book
1971	Inventory map	1:5000	Legend book
1989	Inventory map	1:10000	Legend book
2004	Inventory map	Digital	Updated legend tables with MELA ^a

^a MELA is a forest planning software package developed by the Finnish Forest Research Institute for calculating forest characteristics for management purposes (Redsven et al. 2004), more detailed in article I.

compartments were delineated according to the rules documented by Davis and Johnson (1987). The study area was about 840 hectares of forests in the northern part of the Koli NP. Stands containing aspen trees were extracted from these sources. To find out where the large aspen occurrence compartments existed, the compartments where the age of the aspen was over 70 years, those with a diameter at breast height (dbh equals 1.3 meters) over 25 cm or those that had written information suggesting large aspens (e.g. in 1910) were selected. The characteristics required by the compartments for different inventories were as follows: land area (hectares), patch area (may include many compartments with similar characteristics, ha), soil type, forest layers, stoniness, total volume ($\text{m}^3\text{ha}^{-\text{ha}}$), age (years), height (m), and the existence of information on occurrence of aspen. More detailed selection criteria of the selected stands are presented in the article **I**. The data for article **I** were processed with ArcGis software in seven steps, as follows: 1) digitization of the maps (1910) and fitting of the stand layers to make the total land area congruent between the years, given that the maps from 1936 (Pirilä 1999) and 2004 (Redsven et al. 2004) were already digitized, 2) identification of the compartments where aspen of any age or size existed in any of the three inventories (minimum of 0.1 ha), 3) creation of comparative tables for the aspen characteristics (age, height, volume), 4) creation of map layers for stands with large aspens (age > 70 yrs or dbh > 25 cm) or with small aspens in the inventories of 1910, 1936 and 2004, 5) collection of information on the occurrence of large aspens from different inventories and the merging of stands into the three predefined aspen occurrence classes (continuous, disappeared and appeared) using the ArcGis Analysis Tools, 6) checking of the historical information from all the inventories and the findings of the 2006 field survey of the presence of aspens and their cut stumps, and 7) classification of the compartments into the predefined aspen occurrence classes: areas where large aspens have existed throughout the time between the inventories, areas where large aspens have occurred and then disappeared between the inventories and areas where large aspens have appeared between the inventories. In addition, areas were also analysed in terms of forest management history and classified in two classes: natural forests and managed forests.

When identifying herb-rich forest stands (**II**) and classifying forest stands by Cajander's (1926) site type classes (**III**), the aforementioned forest inventory data from the year 2004 was used as well as a specific key-biotope studies of Koli herb-rich forests (Hokkanen et al. 2003, Puustinen et al. 2007). Most of the currently known herb-rich forests of Finland have been located and mapped in conventional inventories by compartments (see section 1.2.2). The total number of stands within the study area (**II** and **III**) of 930 ha was 680, and these were randomly assigned into modelling and test datasets, both of which included stands from the northern and southern parts of the National Park. In terms of development classes, the stands used in the analyses were advanced, thinning or mature stands. There were no sapling stands because the site is a designated conservation area. The whole data used in the article **III** included 274 selected forest stands covering an area of 337 ha, which included stands from the northern and southern parts of the National Park. These data were also randomly assigned into the modeling data and test data. The final modelling data consisted of 184 forest stands and comprised an area of 241 ha, while the test data consisted of 90 forest stands and covered a total area of 96 ha (**II** and **III**). The descriptive area statistics (see article **II**, Table 1.) for the whole data were similar to the model and test data. According to earlier forest inventories and mapping of the herb-rich forests (Hokkanen et al. 2003, Puustinen et al. 2007) there exists altogether 61 herb-rich stands in the Koli NP that represented the development classes 'Advanced thinning stands' and 'Mature stands' which were used in the present analyses. Since the stand delineations varied somewhat

from one inventory to another, the stand delineation data obtained from the inventory of herb-rich forests (Hokkanen et al. 2003) was used in cases of multiple delineations.

Article **IV** describes three stands which represented different forest areas within the northern part of the Koli NP. Two of them were located in managed forests, and the selection was based on the compartment-wise inventory data for the year 2004 and historical information on the forest stands (old inventory material). The selection of a natural forest stand was based on the historical inventory data analysed in article **I**. All the three stands represented mature forests.

2.2.2 Additional field inventories

In the summer 2006 each aspen stand included in article **I** was visually inspected for the occurrence of cut stumps. The absence of stumps or other signs of silvicultural treatments were taken as an indicator of naturalness. An additional validation survey for articles **II** and **III** was implemented in the field in summer 2007, in which all the misclassified stands and some of the borderline cases as classified by logistic regression and the k-NN method in article **II** were visited, in order to identify the reasons for the erroneous results. The field inventory of canopy gap study (**IV**) was implemented in the summer 2008. The total number of canopy gaps in the three stands was 589. The natural stage forest stand comprised altogether 220 and the two managed forest stands 369. All canopy gaps within the three stands were field visited and assessed or measured by the characteristics which were: 1) Manmade canopy gap (thinning applied); 2) Seedlings from 0.3m to 1.3m tall; 3) Seedlings over 1.3m tall; 4) Thickness of downed deadwood (DDW) under 0.3m (only small diameter DDW and level of DDW under 0.3 meters); 5) Thickness of downed deadwood over 0.3m (large DDW individuals or DDW height exceeded over 0.3 meters); and 6) Dense lesser-vegetation (species of non-timber value covering large parts of the canopy gaps). The time difference between the scanning of ALS data and field inventory, which was two growing seasons, was taken into account when assessing, for instance, the heights of seedlings.

2.3 Laser data (II-IV)

The same ALS data were used in articles **II**, **III** and **IV**. The ALS survey was performed on the 13th of July, 2005, using an Optech ALTM 3100 laser scanning system. Two Global Positioning System (GPS) ground stations were used and a total of nine transects (Figure 1) were flown at an altitude of 900 metres and a flight speed of 75 m/s. The area covered was approximately 2200 hectares. The laser pulse repetition rate was 100 KHz and the scanning frequency of a swath was 70 Hz, at an angle of ± 11 degrees. The pulse density of the data was 3.9/m², but because of nominal side overlap (35%) and variation in the terrain the actual ground hits varied from approximately 3.2/m² to 7.8/m². The data echoes collected included EUREF-FIN coordinates (x, y and z), flight line numbers, intensity values and echo types in four classes, which were 1) 'first of many', 2) 'intermediate', 3) 'last of many' and 4) 'only'. The digital terrain model (DTM) was produced by the Finnish Geodetic Institute from the last and only echo data using a pixel size of one metre, employing the TerraScan software, which uses the method proposed by Axelsson (2000). In order to analyse the ALS data, the orthometric heights were converted to an above-ground scale by subtracting the DTM from the corresponding ALS heights (Hyypä et al. 2005).

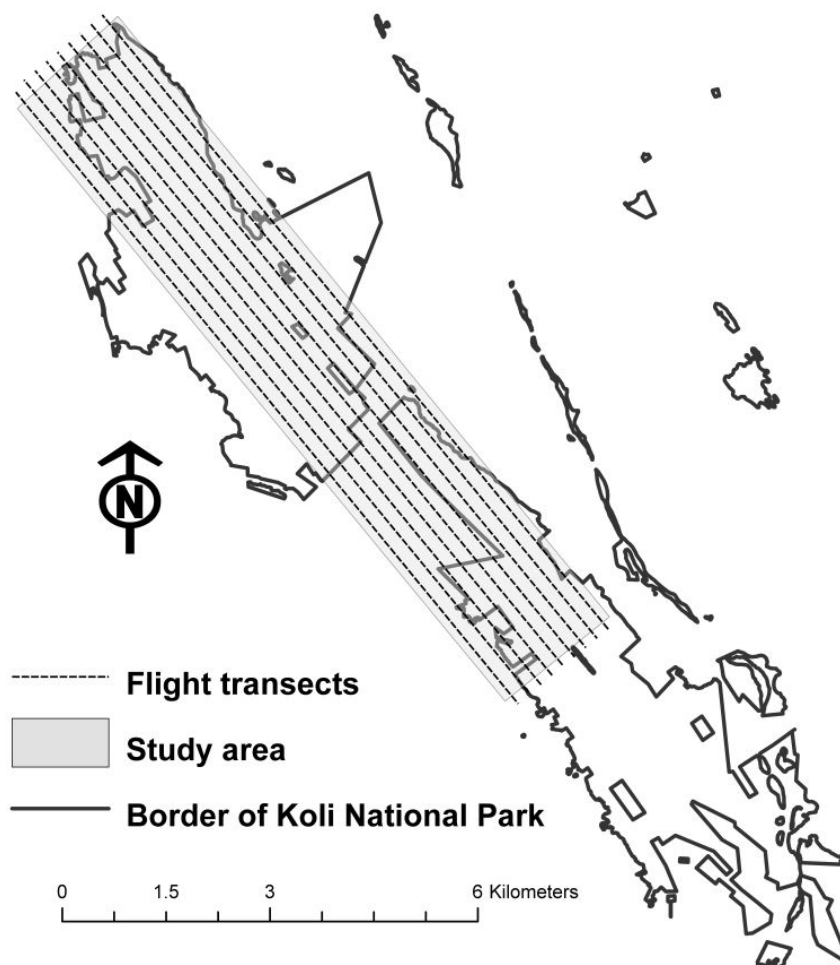


Figure 1. Map of the Koli National Park.

3 METHODS

3.1 Laser data metrics (II-IV)

The echo types used in these studies were: first of many (f), intermediate (i), last of many (l), only (o) and all echoes combined (all). In addition the combination of first of many and only echoes forms canopy echoes (fo), and last of many and only echoes forms ground echoes (lo). Articles **II** and **III** used all echo variants in analysis, where f, l, o and all echoes were used in article **IV**.

Descriptive statistics (mean, variance, standard deviation and maximum) and accumulation percent values (5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 95%) were calculated from the echo clouds of the laser point data for all the stands in articles **II** and **III** as well as in all canopy gaps in article **IV**. The height information was analysed through the z-values of laser echoes, whereas the laser reflectance was detected through the intensity

values. The proportion of vegetation, i.e. ratios between vegetation hits over 30 cm and ground hits, were calculated using the first and last echoes and the total numbers of echoes (**II** and **III**).

To identify canopy gaps from the ALS data in article **IV**, a Canopy Height Model (CHM) was created using height of hits that echoed from above ground level by inverse distance weighted interpolation method with a pixel size of 0.5 meters. All laser hits above 0 meters were applied in **IV**. Gaps were segmented from the CHM by using a height threshold limit of five meters and assigning a minimum size to the gaps of 5m² (see e.g. Vepakomma et al. 2008a). Segmented canopy gap polygons were used to select laser echoes with positive z-values. Canopy gaps were analysed by searching for differences in laser echo distributions in three predefined height classes: 1) less than 0.3 meters, 2) from 0.3 to 5 meters, and 3) more than 5 meters. The lowest limit was chosen because in general the accuracy of ALS data is very high but has errors under 0.3 meters in DTM (e.g. Hodgson and Bresnahan 2004). Because of the interpolation method adopted, there existed laser echoes at over 5 meters above ground level which were, however, mainly found nearby the edges of the canopy gaps and were reflected from the branches of bordering trees.

3.2 Logistic regression (**II**)

A logistic regression modelling technique was employed for predicting the probability of each stand belonging to the class of herb-rich forests, in which case the binary response y of the model was assigned the value 1, being otherwise 0, with the respective probabilities p and $1-p$ (e.g. McCullagh and Nelder 1989). Several combinations and transformations of height percentiles and relative intensity, the latter calculated as a ratio relative to the 50th percentile, from the modelling dataset were tested for the purpose of selecting independent variables for the logistic regression model.

3.3 K-NN (**II-III**)

Forest site types were classified by using the nonparametric k-NN classifier. The nearest neighbour method has been widely used for estimating continuous forest variables (e.g. by Moeur and Stage 1995, Holmström et al. 2001, Maltamo et al. 2006) and to some extent for determining discrete forest variables (e.g. Thessler et al. 2008). Peuhkurinen et al. (2008) studied species-specific diameter distributions and saw log recoveries with the k-NN method by using the first pulses of the data and noted that the method they introduced can also be applied in different classification procedures.

At least three issues need to be considered when using the k-NN method: 1) a suitable distance metric to find the nearest neighbour(s), 2) the number of neighbours to be used, and 3) the weighting of the neighbours (LeMay and Temesgen 2005). The k-NN estimation procedure applied in this study based on the method introduced by Peuhkurinen et al. (2008). The substudies **II** and **III** used a Minkowski distance metric of order one between the distributions. The Minkowski distance is applicable for measuring similarity between objects and takes into consideration the whole variability and the heterogeneous structure of laser distributions. A Minkowski distance can be defined as the sum of the absolute distances between discrete distributions:

$$D_{pq} = \sum_{i=1}^n |p_i - q_i| , \quad (1)$$

where D_{pq} is the distance between either the laser height distribution or laser intensity distribution to be compared, p_i is the proportion of observations of target units in class i , q_i is the proportion of observations of reference units in class i , and n is the number of classes in the distributions. The value of D_{pq} ranges between 0 (the distributions compared are the same) and 2 (the distributions compared have no observations in the same classes). The chosen distance metric is based on the absolute differences between the laser echo distributions of the target and reference stands and is suitable in situations in which the predictor variables are distributions with unknown characteristics (in this case laser echo height and intensity distributions) and it is assumed that the form of the distribution contains most of the information on the variables of interest (in this case forest site type classes). The distance value can be used in weighting the neighbours by subtracting it from the maximum value, which is 2. When using more than one predictor (i.e. distributions of laser echoes of different types), the distances are calculated separately from each distribution. The final distances are then the sum of distances. The distances are then weighted using subsequently determined optimal weights for the predictors:

$$D_{pq} = w_j \sum_{j=1}^m \sum_{i=1}^n |p_{ji} - q_{ji}| \quad (2)$$

where m is the predictor (laser height- or intensity distribution of certain laser echo type) and w_j is the weight of the predictor j .

The classification rule needed for applying the k-NN based classifier was adjusted for the case of several neighbours (n) as follows:

1. $n = 1$: the value of the predicted variable is the value of the nearest neighbour
2. $n > 1$: the weights of the neighbours are summed up by class and the estimated class for the target unit is the one with the highest sum of weights.

Two different methods of using the data were applied. 1) The whole data was divided into reference (modelling) and target (test) data (**II** and **III**) 2) the whole data and leave-one-out cross-validation (**III**); method described below is the same in both approaches, i.e. whole data approach and model/test data approach.

For the k-NN classification procedure the laser echo heights were classified into 10 cm classes, with the negative echo heights assigned to a class 0. This classification provided enough observations for all the approximately 300 classes. The laser echo intensities were thereafter classified with a class width of 10 intensity units that resulted in a corresponding number of classes which depend on maximum intensity value which can vary, for example, because of the echo type of different ground surfaces. The optimal weights for the different types of echoes were identified by optimizing the overall classification accuracy. The optimization algorithm weighted the combinations systematically so that every echo type was given a weight from 0 to 1 at intervals of 0.1. In addition, all the combinations of weights, which summed up to 1, were examined. The optimization was performed on the whole data and modelling data only and used a leave-one-out cross-validation technique in which the target unit was left out of the reference data. The test stands were classified using the optimal weights found from modelling data and the nearest neighbours were identified

only from the modelling (reference) data. In the case of several neighbours ($n > 1$), the procedure provides not only class estimates but also an idea of the closeness of the target unit to the other classes. However, it should be remembered that the forest site type classes may express the fertility levels on an ordinal scale, but the tree cover of those types should be handled as they are in a nominal scale.

3.4 Spatial canopy gap characteristics (IV)

The density, shape, isolation and diversity indexes for canopy gaps in article **IV** were calculated using the FRAGSTATS program (McGarigal et al. 2002). The pixel size of raster type data was 0.5 meters. Three forest stands were treated as landscape units. Canopy gaps with different contents were class units and single canopy gaps were seen as patches. The indexes obtained by stand types were: 1) the Patch Density (PD) index, 2) the Landscape Shape Index (LSI), 3) the Shannon's Diversity Index (SHDI) (Shannon and Weaver, 1949), and 4) Simpson's Diversity Index (SIDI) (Simpson, 1949). Note that the significance statistics were uncountable for the five indexes since the data comprised only three stands. In addition three mean canopy gap metrics with the level of significance were calculated by different stand types: 1) AREA in hectares, 2) SHAPE Index, and 3) Euclidean Nearest-Neighbour distance (ENN).

The PD index defines the number of canopy gaps per hectare, whereas the LSI is a simple measure for the aggregation by category:

$$LSI = \frac{e}{\min e} \quad , \quad (3)$$

where e is the total length of an edge in terms of the number of cell surfaces including all boundary and background edge segments, and $\min e$ is the minimum total length of a perimeter in terms of the number of cell surfaces. LSI is one when the landscape consists of a single square and LSI increases without limit as the patch type becomes more disaggregated.

Both the SHDI and SIDI are commonly used measures of diversity in community ecology (e.g. Magurran 1988, Stiling 1996) and are determined as follows:

$$SHDI = -\sum_{i=1}^m (P_i \ln P_i) \quad , \quad \text{and} \quad (4)$$

$$SIDI = 1 - \sum_{i=1}^m P_i^2 \quad , \quad (5)$$

where P_i is the proportion of the landscape occupied by the patch type i , i.e. the canopy gap class (CG- class) (see article **IV** for more detailed description of CG-classes). Simpson's index is less sensitive to the presence of rare types and has a more intuitive interpretation than that describing Shannon index. Specifically, the value of Simpson's index represents the probability that any two randomly selected pixels represent different patch types. Moreover, Magurran (1988) compared different diversity indices to determine their effectiveness, and stated that the discriminating ability and sensitivity to sample size of the widely applied Shannon's index are moderate. In addition, Stiling (1996) noted that the value of species diversity (SHDI) is often between 1.0 and 6.0, and the maximum diversity of a sample exists when all species area equally abundant.

The mean value of the SHAPE index equals one when a patch is maximally compact (circle) and in the case of raster format the most compact form is a square with a value of (1.13). The value of the index increases without limit as patch shape becomes more irregular. SHAPE index for one patch is defined as follows:

$$SHAPE = \frac{P}{\min p} \quad , \quad (6)$$

where p is perimeter in terms of the number of cell surfaces and $\min p$ is minimum perimeter in terms of the number of cell surfaces. The ENN distance (m), which approaches zero as the distance to the nearest neighbour decreases, is:

$$ENN = h \quad , \quad (7)$$

where h is planar (x/y-direction) distance from patch to nearest neighbouring patch of the same type (class), based on patch edge-to-edge distance, computed from cell centre to cell centre.

The same indexes were obtained also by the CG-classes, i.e. PD, LSI, AREA, SHAPE and ENN. In addition to the CG-classes, we calculated the Percent of Landscape values (PLAND), i.e. proportions of the landscape occupied by five CG-classes, and mean values of Gap Shape Complexity Index (GSCI) which bases on Patton's diversity or edge index (Patton, 1975):

$$GSCI = \frac{P}{2 \cdot \sqrt{a \cdot \pi}} \quad , \quad (8)$$

where p is the perimeter and a is the area of patch. The mean values of the GSCI index obtained for the circle shape and the square shape are 1.0 and 1.13 (indicates a relative complexity of 13%), respectively.

3.5 Example calculations

The methods applied in articles **II-IV** were tested to evaluate their applicability in separate test areas. Large aspen occurrence stands of the article **I** were used as a research area. First, a logistic regression model (**II**) was used to predict the existence of herb-rich stands in those areas. Second, a k-NN classifier (**III**) was applied for the site type estimate prediction in those areas. Third, differences of laser echo heights and intensity values (**IV**) in three predefined height classes were used to analyse canopy gaps to examine differences between three large aspen occurrence classes. An overview of the methods and materials respective to the individual articles **I-IV** is given in Figure 2.

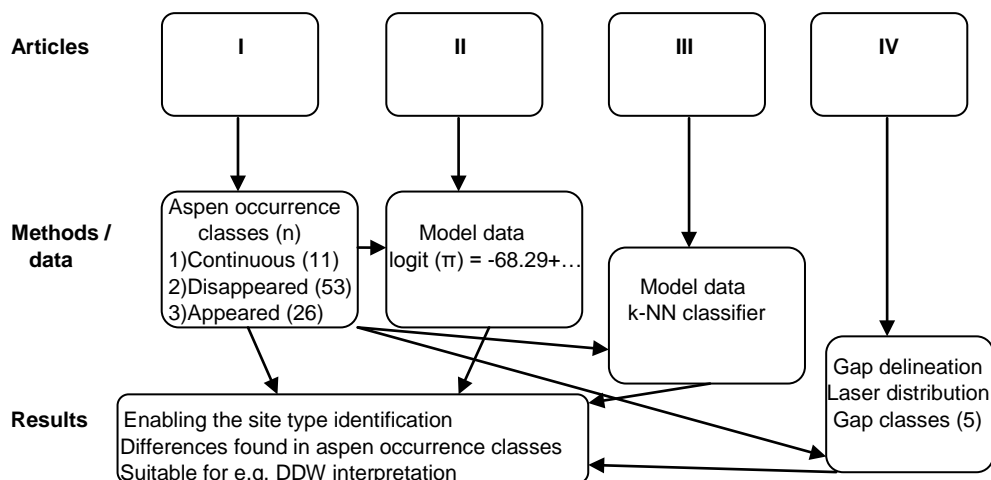


Figure 2. The example calculation procedure

3.6 Evaluation of the results and statistical tests

The performance of the logistic regression and the k-NN estimation method used in articles **II** and **III** were verified by calculating the success rates for the classification of herb-rich forests and overall classifications for five different forest site types as well as by deriving classification matrices, i.e. two-dimensional contingency tables. In addition, stands with different size classes were compared. The size classes in hectares (ha) were 0.05—0.25, 0.26—0.50, 0.51—0.75, 0.76—1.0, 1.1—2.0 and 2.1—12.1 (maximum stand size). The number of stands (n) from the whole data was in each size class 45, 48, 40, 39, 54, and 48, respectively. A kappa statistic (**II** and **III**) was used to measure agreement between the observed classification and predicted classifications in the case of herb-rich forests (**II**). In addition to the kappa statistic, the classifications with different numbers of neighbours and respective to different datasets were used (**III**). Kappa was also used to measure the similarities between the predicted classifications based on logistic regression and k-NN. Kappa is based on the differences between overall agreement and expected change agreement:

$$\kappa = \frac{p_o - p_c}{1 - p_c} \quad , \quad (9)$$

where p_o is overall agreement and p_c is expected change agreement. The maximum value for kappa occurs when the observed level of agreement is 1. A value of 1 implies perfect agreement and values less than 1 imply less than perfect agreement. One generally accepted interpretation of Kappa is as follows: poor agreement = less than 0.20, fair agreement = 0.20 to 0.40, moderate agreement = 0.40 to 0.60, good agreement = 0.60 to 0.80 and very good agreement = 0.80 to 1.00.

In the canopy gap study (**IV**), the t-test and the analysis of variance were applied to mean values of canopy gap metrics. The t-test was used to determine whether the difference between the stand-type-wise obtained means of a given canopy metric or a given laser echo

type was statistically significant or not. The analysis of variance was applied when the significances of differences between indexes determined by the CG-classes were examined. However, the other density and diversity indexes were only obtainable by stand types or by CG-classes and, therefore, no statistical tests were applicable to them. In addition, visual interpretation of the figures and data in all articles (I-IV) were used.

4 SUMMARY OF THE RESULTS

In **the first article (I)**, it was shown that forest areas containing aspen trees have doubled up to 364 hectares between years 1910 and 2004. However, the area with large aspens has remained fairly constant. The aspens have occurred at least temporarily over 34 per cent of the total forest area (840 ha) and 13 per cent of the forest area contained large aspen trees. In natural forest areas large aspen trees have persisted throughout the period in 2 % of the total area. The results indicate that aspen can maintain long-term occurrence in old-growth forests and that the species is not only transient or confined to young successional stages. Other notable results were that during the time period the aspen stand sizes have decreased from 5.0 to 2.1 hectares, aspen mean volume had increased from 2 to 5 m³ ha⁻¹ and areas where large aspens had persisted were over 90 per cent on nutrient-rich sites.

In **the second article (II)**, the best overall classification result of the herb-rich forest was 85.6 per cent, being 55.0 % for the herb-rich forests and 94.3 % for the other forest site types when I used parametric logistic regression. With the k-NN method the best overall classification accuracy was 88.9 %, where the herb-rich forests being classified correctly in 65.0 % of cases and the other forest site types in 95.7 %. The results show that ALS-based data analysis techniques are applicable to the detection of mature boreal herb-rich forests and that both methods used are potentially useful for separating herb-rich forests from other forest site types. All three main groups of herb-rich forests, i.e. dry, mesic and moist, were represented in the data. These types appeared to have an effect on the classification results, given that the proportions of first and intermediate laser echoes were higher in stands growing on highly fertile soils, and that a higher proportion of only echoes were observed in stands belonging to the dry forest site types.

In **the third article (III)**, the best overall classification accuracy achieved for all five forest site types was 58.0 per cent and for a single type it was 73.0 per cent. When the next nearest class was accepted as a correct neighbour the classification accuracy increased to 92.2 %. Stand size had no effect on the classification results. It is concluded that this ALS-based data analysis technique with wall-to-wall coverage can be applied to the detection of mature boreal forests site types in large-scale forest inventories. The accuracy was satisfactory (87%) also for operational use when classification was done between the most important site types MT (favourable for Norway spruce) and VT (Scots pine).

The fourth article (IV), reported that there is a clear difference between the canopy gaps of natural forests and managed forests in laser echo distributions, especially between echo heights of 0.3m – 5m. In addition, both the density of vegetation and existence of CWD can be used as characteristics of the ALS data-based identification of canopy gaps. The technique used in this study can be applied to the development of automatic identification of canopy gap types and to the detection of indirect indicator characteristics for assessing the naturalness of boreal forests.

Table 2. Herb-rich forest classification accuracy per cents in example calculations in three aspen occurrence classes.

Data	N	Accuracy
1)	11	63.6 %
2)	53	81.1 %
3)	26	88.5 %
All	90	81.1 %
Article II	90	85.6 %

N is the number of stands; 1) is continuous large aspen stands; 2) is large aspen disappeared stands; 3) is large aspen appeared stands; 'All' is all aspen occurrence classes; 'Article II' is the results of the test data used in article II.

The example calculations applied the same parametric logistic regression model, which was constructed in article II. The logistic regression formula gave rather similar herb-rich classification results to the large aspen stands than in article II (Table 2). In article II herb-rich forest were classified correctly in 85.6 % where as overall classification in large aspen stands was 81.1 %. In addition, 15 of the misclassified large aspen stands were from the next nearest site type class, which indicates that method is applicable also in this example calculation.

The same k-NN classifier was used to classify aspen occurrence stands by different vegetation site types that were used in article III. Classification accuracy of the five site types in a continuous aspen class was 54.5 % whereas the overall classification accuracy was only 40.0 %. However, in the case when the next nearest class was accepted as a correct neighbour the classification accuracy increased to 87.8 %. In general, classification accuracies were lower in example calculations than in the results achieved in article III. One reason for this might be that the aspen favors the nutrient soils (OMat, OMT and MT). Especially these site type classes (excluding herb-rich) are the most difficult to identify, because they have relatively similar vertical structure (see Figure 2 in Article III). Especially, when the stand sizes are less than one hectare there might be great variety between the stands in these two classes.

Differences were found between aspen occurrence classes based on the laser pulse height and intensity value distributions inside the canopy gaps. The reasons cannot be verified, because of the lack of accurate canopy gap field data on aspen stands. Congruence, were not found, between the aspen occurrence stands, nor differences between managed and semi-natural forests introduced in article IV. However, similarities were found between canopy gaps in aspen occurrence stands and canopy gap types identified in article IV. There were similarities found especially in canopy gaps with respect to the vegetation characteristics and the amount of downed dead wood.

5 CONCLUSIONS

This thesis focused on developing and evaluating methods to identify ecologically important old-growth forest habitats by using ALS data. Old-growth forests have high biodiversity and conservation value and therefore to sustain these vital habitats, monitoring setups in large- as well as in small-scale should be developed. In this thesis I studied important indicators of natural forests in Koli NP. The main indicators chosen to this study were the occurrence and dynamics of large European aspen sub-populations, existence of herb-rich forests and characteristics of the canopy gaps and their contents. In these studies I used long-term forest inventory data set and spatially representative ALS data. In addition, some ALS-based example calculations in the different large aspen occurrence classes (article I; continuous large aspen area, large aspen disappeared and large aspen appeared) were made to support the results achieved in the articles II-IV. Furthermore, I tried to find possibilities to estimate the naturalness of those ecologically important large aspen stands.

In the first article, I clarified long-term spatio-temporal European aspen dynamics. The results of article I show that aspen stands can maintain long-term continuity and most likely also regenerate naturally at least in the circumstances that prevail in fertile old-growth boreal forests. In the earlier studies the aspen population in natural old-growth forests can survive over several hundreds of years (Lilja et al. 2006) but the regeneration has succeeded only occasionally (Latva-Karjanmaa 2006), which is also confirmed in this study. Additionally, the vitality of the aspen population in the Koli area was good, which indicates that in this protected area large aspen population can live and even regenerate due the canopy gap dynamics. According to the acts of the restoration programme Life to Koli (small clearings, felling trees, peeling live trees, removing some spruces), for instance, survival possibility of the aspen population, are better (Eerikäinen et al. 2009). The present results of my thesis indicate that maintenance of aspen and the biota associated with it should be possible also in other conservation areas and nature preserves that share the same basic characteristics. However, local factors such as the browsing pressure by moose should be taken into consideration when evaluating the long-term potential of a preserve to maintain its aspen population. In their study, Härkönen et al. (2008) found that in the Koli NP moose browsing on aspen has been very intense. At the landscape level, moose damaged (twig-browsing, stem breakage, or bark stripping) 96% of aspens in the southern area and 62% in the northern area of the Koli NP (Härkönen et al. 2008). They concluded that the current browsing pressure retards the height development of young aspens, but even so a high proportion of aspens may reach maturity, and guarantee the spatio-temporal continuum of aspen occurrence at a level where biodiversity is maintained in the conservation area (Härkönen et al. 2008). It has been shown (Coops et al. 2010) that ALS data can also be used to estimate large browsing mammal habitats. The results (Coops et al. 2010), based on the data from the British Columbia, indicate that lidar-derived models describe up to 75% of the variance in overall stand structure of conventionally derived descriptors of mule deer winter habitat.

In the integration of **example calculations**, I noticed that areas suitable for aspen are more nutritious ones, which was stated already by Tikka in 1955. Therefore potential areas for occurrence of large aspen can be found indirectly through the ALS data based methods developed in articles II and III, i.e. through identifying fertility classes for the forests stands subject to analysis. By using the same study area and ALS data Säynäjoki et al. (2008) detected aspen trees by applying individual tree delineation method. The accuracy in

detecting aspen trees was 78.6 % by using vegetation hits, and heights and intensity values of the different height percentiles of the ALS data (Säynäjoki et al. 2008). These results support my studies to use ALS data to identify and interpret large aspen occurrence areas, because especially the large aspens can be identified accurately (87 %) by using remote sensing materials (Säynäjoki et al. 2008).

In the articles **II** and **III** I classified forest site types, especially herb-rich forest, by using ALS data. My results verify the fact that the nutrient rich site quality classes with the higher growth and yield potential can be separated from less fertile ones on the grounds of differences in the vertical and horizontal laser pulse distributions. This was the first study to classify boreal mature forest site types by analysing vertical distribution of ALS data in different forest site types. Korpela et al. (2009) classified different boreal mire habitats with approximately same overall classification accuracies than in my studies. The previous ALS based studies have mainly concentrated on determining the existence of differences in site quality indicators based on dominant tree heights (e.g. Gatzolis 2007). I used logistic regression and k-NN methods to classify forest stands and found both to be applicable in the case of mature forests, although their applicability to young stands still needs further studies. Employing the methods suggested here together with extensive reference data it is possible to obtain information on forest site types by using ALS data. This conclusion is supported by the rather similar site type classification results to the large aspen occurrence stands based on the performed **example calculations**, where I applied the parametric logistic regression model constructed in article **II** and the k-NN classifier from the article **III**. The technique is also applicable to the detection of potential herb-rich-forest sites in large-scale forest inventories. I nevertheless anticipate that the classification results could be further improved with a more accurate delineation of the area and by combining aerial images, laser scanner data and digital terrain maps.

In the article **IV**, I utilized ALS data to detect differences between canopy gaps of semi-natural and managed forests, based on the variation in point distributions of the different laser echo types. Canopy gap delineation was done with fixed threshold which is used successfully in many previous studies (e.g. St-Onge and Vepakomma 2004, Koukoulas and Blackburn 2004, 2005, Hirata et al. 2008, Vepakomma et al. 2008). Based on the analysis of the vertical differences in laser echo distributions canopy gap characteristics, such as dense undergrowth and downed deadwood (**IV**), the canopy gaps in the semi-natural forest can be separated from canopy gaps in the managed forest. Previous studies concentrated on height distribution changes in canopy gaps and were based on multi-temporal datasets (e.g. St-Onge and Vepakomma 2004, Hirata et al. 2008, Vepakomma et al. 2008), whereas I used a cross-sectional (non-temporal) set of data to find differences inside the canopy gaps. In **the example calculations** I found differences between aspen occurrence classes, based on similarities between the canopy gaps in aspen occurrence stands and canopy gap types with vegetation or downed dead wood that corresponds to the findings of article **IV**.

The ALS based methods to interpret and map old-growth forests have been developed over the course of this thesis project and the individual articles **I-IV**. The results obtained are promising and show the capability of ALS to separate forest characteristics based on the vertical and spatial differences in the laser echoes. I clarified the large aspen population occurrence in Koli NP based on compartment wise inventory information and further found some differences between different aspen continuity classes by using ALS data. Based on the articles **II**, **III** and **the example calculations** of this thesis the ALS data was also used successfully in forest site type classification to separate especially herb-rich site types, favored also by large aspen individuals. Differences in the most nutrient rich site types can

be very small in the forest and, therefore, estimating the classification accuracy of the pre defined compartments is challenging. Better stand delineation (e.g., grid or micro stand) should be used to achieve more reliable results. In further studies more stand units should be included to develop methods further and to ensure their applicability under different local conditions and with data representing earlier stages of stand development. In addition, more research is needed to improve identification of naturalness and the stage of forest succession by using laser-derived attributes.

In the past the forest inventory by compartments has been used also in protected old-growth forests by adding more characteristics to the field inventories. This thesis gives valuable information for forthcoming ALS based forest inventories by compartments by showing that different fertility classes (**II** and **III**) can be separated based on height distributions at least in mature forest conditions. In addition, through the method used in the canopy gap analysis (**IV**), the naturalness of the forest can be evaluated in some extent. The old practice, in the forest inventory by compartments, is not very cost-efficient and therefore, for instance, the use of remote sensing data has become one valuable option for assessing rare forest characteristics (e.g., Pesonen et al. 2009). Additionally, this thesis provides tools to identify herb-rich forests (**II**) and, for instance, identify and analyse the canopy gaps with large amount of downed deadwood (**IV** and **example calculations**) indicating naturalness of the forest.

In the large-scale multi-source NFI, field measurements, satellite images and digital maps are used to get better inventory statistics and thematic maps on local conditions (Tomppo 1996). The ALS studies show that the ALS data would be excellent additional inventory material to the multi-source NFI. For example, by using the forthcoming laser scanning data covering the whole Finland and collected by the National Land Survey of Finland (see e.g. Ahokas et al. 2008), it would be a good opportunity to provide more detailed information in various scales to NFI results. However, at this point the NFI does not provide detailed information from small areas such as the Koli NP. The improvement of using remote sensing data, especially the ALS data, has proven to give valuable auxiliary information about the forests and based on this thesis also the naturalness of the forest can be estimated to some extent. However, more studies are needed to achieve better accuracy of different old-growth forest characteristics studied already in this thesis. Furthermore based on this thesis and previous studies, there is a possibility to develop methods to interpret and monitor, for instance, all NATURA 2000 of western taiga (9010) indicators which are: random spatial distribution of trees, multi-layer and continuous canopy cover, large amount of coarse woody debris, existence of different tree generations and large deciduous (especially aspen) individuals occurring in groups (European Commission 1999, Airaksinen and Karttunen 2001). In the future, the development of an operational system for interpreting and monitoring old-growth forests or for the purposes of environmental protection and planning would however require additional investments of resources. The research in the field of the other laser platform applications such as terrestrial laser scanning (e.g. Watt and Donoghue 2005) (e.g. small-scale biotype description) should be also taken into account when planning new and more efficient forest inventory systems. Additionally, the full waveform laser (e.g. Buddenbaum and Seeling 2008) could be one solution to the many environmentally important inventory problems, which now seem to be impossible to solve with existing remote sensing tools and materials.

This thesis was done in a boreal vegetation zone, but the methods, especially in the case of study IV, used are likely to be applicable to most of the forest and vegetation zones, because of the universal characteristic of ALS to describe accurate vertical profiles of

objects with spatial metrics. ALS is one new technology that provides accurate and cost effective information about different kinds of forest resources and environmental inventories. The promising results and methods of this thesis and potential of the ALS technology should be exploited in small-scale inventories by compartments as well as in developing inventory and monitoring setups for environmental conservation acts like NATURA2000 (European Commission 1999) and METSO (Ministry of the Environment 2008) in both large- and small-scale use.

REFERENCES

- Achard, F., Mollicone, D., Stibig, H.J., Aksenov, D., Laestadius, L., Li, Z.Y., Popatov, P. & Yaroshenko, A. 2006. Areas of rapid forest-cover change in boreal Eurasia. *Forest Ecology and Management* 237: 322-334.
- Ackermann, F. 1999. Airborne laser scanning – Present status and future expectations. *ISPRS Journal of Photogrammetry and Remote Sensing* 54: 64-67.
- Ahokas, E., Kaasalainen, S., Hyypä, J. & Suomalainen, J. 2006. Calibration of the Optech ALTM 3100 laser scanner intensity data using brightness targets. In *The International Archives of the Photogrammetry and Remote Sensing, Paris, France, Vol. XXXVI, Part A1: T03-11*.
- , Kaartinen, H. & J. Hyypä, 2008. On the quality checking of the airborne laser scanning-based nation wide elevation model in Finland. 21st ISPRS Congress Beijing 2008. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 37(B1/I)*. p. 267–270.
- Airaksinen, O. & Karttunen, K. 2001. Natura 2000 -habitats manual. Environment Guide 46, 2nd revised edition. Edita Ltd., Helsinki. 194 p. (In Finnish with English summary)
- Alanen, A. 1992. Conservation and management of herb-rich forests. *Memoranda Soc. Fauna Flora Fennica* 68: 73-76. (In Finnish with English summary)
- , Leivo, A., Lindgren, L. and Piri, E. 1996. Lehtojen hoito-opas. *Metsähallituksen luonnonsuojelujulkaisuja B* 26: 1-128. (In Finnish)
- Almgren, G. (ed.) 1990. Lövskog. Björk, asp och al i skogbruk och naturvård. Skogstyrelsen, Jönköping. 261 p. (In Swedish)
- Andersen, H-E., McGaughey, R.J. & Reutebuch, S.E. 2005. Estimating forest canopy fuel parameters using LIDAR data. *Remote Sensing of Environment*. 94: 441-449.
- Angelstam, P. & Petterson, B. 1997. Principles of present Swedish forest biodiversity management. *Ecological Bulletins* 46: 191-203.
- & Andersson, L. 2001. Estimates of the needs for forest reserves in Sweden. *Scandinavian Journal for Forest Research, Supplement* 3: 38-51.
- Antikainen, M. 1993. Metsämaiseman suunnittelu Kolin kansallispuistossa. *Metsäntutkimuslaitoksen tiedonantoja* 456. (In Finnish)
- Axelsson, P. 2000. DEM generation from laser scanner data using TIN models. In: *The International Archives of the Photogrammetry and Remote Sensing, Amsterdam, The Netherlands, Vol. XXXIII, Part B4/1*. p. 110-117.
- Bartemucci, P., Coates, K.D., Harper, K.A. & Wright, E.F. 2002. Gap disturbance in northern old-growth forests of British Columbia, Canada. *Journal of Vegetation Science* 13: 685-696.
- Bater, C.W., Coops, N.C., Gergel, S.E., LeMay, V. & Collins, D. 2009. Estimation of standing dead tree class distributions in northwest coastal forests using lidar remote sensing. *Canadian Journal of Forest Research* 39: 1080-1091.
- Bitterlich, W. 1948. Die Winkelzählprobe. *Allgemeine Forst- und Holzwirtschaftliche Zeitung* 59: 4-5.
- Bollandsås, O.M., Hanssen, K.H., Marthiniussen, S. & Næsset, E. 2008. Measures of spatial forest structure derived from airborne laser data are associated with natural regeneration patterns in an uneven-aged spruce forest. *Forest Ecology and Management* 255: 953-961.

- Brandtberg, T. 2007. Classifying individual tree species under leaf-off and leaf_on conditions using airborne lidar. *ISPRS Journal of Photogrammetry & Remote Sensing* 61: 325-340.
- Brennan, R. & Webster, T.L. 2006. Object-oriented land cover classification of lidar-derived surfaces. *Canadian Journal of Remote Sensing* 32: 162-172.
- Brown, S., Pearson, T., Slaymaker, D., Ambagis, S., Moore, N., Novelo, D. & Sabido, W. 2005. Creating a virtual tropical forest from three-dimensional aerial imagery to estimate carbon stocks. *Ecological Applications* 15: 1083-1095.
- Buddenbaum, H. & Seeling, S. 2008 Characterization of forest stands using full waveform laser scanner and airborne hyperspectral data. *SilviLaser 2008*, Sept. 17-19, Edinburgh, UK. p. 377-383.
- Cajander, A.K. 1926. The Theory of Forests Types. *Acta Forestalia Fennica* 29: 1-108
- Clutter, J.L., Fortson, J.C., Pienaar, L.V., Brister, G.H. & Bailey, R.L. 1983. Timber management: A quantitative approach. John Wiley & Sons, New York. 333 p.
- Coops, N.C., Duffe, J. & Koot, C. 2010. Assessing the utility of lidar remote sensing technology to identify mule deer winter habitat. *Canadian Journal of Remote Sensing* 36: 81-88
- Cumming, S.G., Schmiegelow, F.K.A. & Burton, P.J. 2000. Gap dynamics in boreal aspen stands: Is the forest older than we think? *Ecological Applications* 10: 744-759.
- Davis, L.S. & Johnson, K.N. 1987. Forest management. 3rd edition. McGraw-Hill Book Company, New York. 790 p.
- Drebs, A., Nordlund, A., Karlsson, P., Helminen, J. & Rissanen, P. 2002. Climatological statistics of Finland 1971-2000. *Ilmastotilastoja Suomesta* 2002:1. (in Finnish, with English abstract)
- Drobyshev, I.V. 1999. Regeneration of Norway spruce in canopy gaps in Sphagnum-Myrtillus old-growth forests. *Forest Ecology and Management* 115: 71-83.
- Eerikäinen, K. 2002. A site dependent simultaneous growth projection model for Pinus kesiya plantations in Zambia and Zimbabwe. *Forest Science* 48: 518-529.
- , Hotanen, J.-P., Ihme, H., Lovén, L., Miina, J., Nieminen, E., Salo, K., Viiri, H. & Äänismaa, P. 2007. Kolin kansallispuisto Natura 2000 –suojelun alueen istutus- ja kylvömetseen ja ojitusalueiden ennallistamissuunnitelma. 86 p. (In Finnish)
- , Hotanen, J.-P., Miina, J., Neuvonen, S., Nevalainen, S., Salo, K. & Viiri, H. 2009. Taluusmetsien ennallistamisvaikutusten seuranta ja siihen liittyvä tutkimus Kolin kansallispuistossa. Working papers of the Finnish Forest Research Institute 130. 83 p. (In Finnish)
- Esseen, P.A., Ehnström, B., Ericson, L. & Sjöberg, K. 1992. Boreal forests - the focal habitats. In: Hansson, L. (ed.), *Ecological Principles of Nature Conservation*. Elsevier Applied Science, London. p. 252-325.
- , Ehnström, B., Ericson, L. & Sjöberg, K. 1997. Boreal forests. *Ecological Bulletins* 46: 16-47.
- European Commission, 1999. Natura 2000. Interpretation Manual of European Union Habitats (EUR 15/2). Nature prediction, coastal zones and tourism. European Commission, Brussels.
- Gaulton, R. & Malthus, T.J. 2008. LiDAR mapping of canopy gaps in continuous cover forests; a comparison of canopy height model and point cloud based techniques. *SilviLaser 2008*, Sept. 17-19, Edinburgh, UK. p. 407-416.

- Gatzliolis, D. 2007. Lidar-derived site index in the U.S. Pacific Northwest – challenges and opportunities. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Espoo, Finland. Vol. XXXVI, Part 3/W52. p. 136-143.
- Goetz, S., Steinberg, D., Dubayah, R. & Blair, B. 2007. Laser remote sensing of canopy habitat heterogeneity as a predictor of bird species richness in an eastern temperate forest, USA. *Remote Sensing of Environment* 108: 254-263.
- Gonzalez, P., Asner, G., Battles, J., Lefsky, M., Waring, K. & Palace, M. 2010. Forest carbon densities and uncertainties from Lidar, QuickBird, and field measurements in California. *Remote Sensing of Environment* 114: 1561-1575.
- Goodwin, N.R., Coops, N.C., Bate, C. & Gergel, S.E. 2007. Assessment of sub-canopy structure in a complex coniferous forest. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Espoo, Finland. Vol. XXXVI, Part 3/W52. p. 169-172.
- Grönlund, A. & Hakalisto, S. 1998. Management of traditional rural landscapes in Koli National Park. Separate plan of Koli National Park. North Karelia Regional Environment Centre, Joensuu. Regional environmental publications 104: 1-81. (in Finnish, with English summary)
- Haara, A. & Nevalainen, S. 2002. Recognition of dead or defoliated trees using digital aerial data. *Forest Ecology and Management* 160: 97-107
- Hanski, I. 2000. Extinction debt and species credit in boreal forests: modeling the consequences of different approaches to biodiversity conservation. *Annales Zoologici Fennici* 37: 271-280.
- Heikkinen, R. K. 2002. Complementary and other key criteria in the conservation of herb-rich forests in Finland. *Biodiversity and Conservation* 11: 201-224.
- Heino, R. & Hellsten, E. 1983. Climatological statistics in Finland 1961-1980. Supplement to the Meteorological Yearbook of Finland 80.
- Heliövaara, K. & Väisänen, R. 1984. Effects of modern forestry on northwestern European forest invertebrates: a synthesis. *Acta Forestalia Fennica* 189: 1-32.
- Hill, R. A., Hinsley, S. A., Gaveau, D. L. A. & Bellamy, P. E. 2004. Predicting habitat quality for great tits (*Parus major*) with airborne laser scanning data. *International Journal of Remote Sensing* 25: 4851-4855.
- Hill, R. A. & Broughton R. K. 2009. Mapping the understorey of deciduous woodland from leaf-on and leaf-off airborne LiDAR data: A case study in lowland Britain. *ISPRS Journal of Photogrammetry and Remote Sensing* 64: 223-233.
- Hinsley, S. A., Hill, R. A., Gaveau, D. L. A. & Bellamy, P.E. 2002. Quantifying woodland structure and habitat quality for birds using airborne laser scanning. *Functional Ecology*. 16: 851-857.
- Hirata, Y., Tanaka, H. & Furuya, N. 2008. Canopy and gap dynamics analysed using multi-temporal airborne laser scanner data in a temperate deciduous forest. *SilviLaser 2008*, Sept. 17-19, Edinburgh, UK. p. 144-150.
- Hodgson, M.E. & Bresnahan, P. 2004. Accuracy of airborne Lidar-derived elevation: Empirical assessment and error budget. *Photogrammetric Engineering & Remote Sensing* 70: 331-339.
- Hokkanen, P. 2006. Vegetation patterns of boreal herb-rich forests in the Koli region, eastern Finland: classification, environmental factors and conservation aspects. *Dissertationes Forestales* 27. University of Joensuu.
- , Salo, K. & Paatelainen, H. 2003. Flora of the key biotopes in the Koli National Park. The Finnish Forest Research Institute, Research Papers 893. (in Finnish, with English summary)

- Holmgren, J. & Persson, Å. 2004. Identifying species of individual trees using airborne laser scanner. *Remote Sensing of Environment* 90: 415-423.
- Holmström, H., Nilsson, M. & Ståhl, G. 2001. Simultaneous estimations of forest parameters using aerial photograph interpreted data and the k nearest neighbour method. *Scandinavian Journal of Forest Research* 16: 67-78.
- Holopainen, M. 1998. Forest habitat mapping by means of digitized aerial photographs and multispectral airborne measurements. University of Helsinki. Department of forest resource management publications 18.
- Hopkinson, C., Chasmer, L., Lim, K., Treitz, P. & Creed, I. 2006. Towards a universal lidar canopy height indicator. *Canadian Journal of Remote Sensing* 32: 139-152.
- & Chasmer, L. 2007. Modelling canopy gap fraction from lidar intensity. In *The International Archives of the Photogrammetry and Remote Sensing*, Espoo, Finland. Vol. XXXVI, Part 3/W52. p. 190-194.
- Hyppänen, H., Pasanen, K. & Saramäki, J. 1996. Päätehakkuiden kuviorajojen päivitystarkkuus. *Metsätieteen aikakauskirja* 4: 321-335. (in Finnish)
- Hyvönen, H. 2004. Aspen stands and their structure in Koli National Park. Master's thesis, University of Joensuu, Faculty of Forestry. 89 p. (In Finnish with summary in English)
- Hyvönen, P. 2007. The updating of forest resource data for management planning for privately owned forests in Finland. University of Joensuu, Faculty of Forestry. *Dissertationes Forestales* 38. 40 p.
- Hyypä, J. & Inkinen, M. 1999. Detecting and estimating attributes for single trees using laser scanner. *The Photogrammetric Journal of Finland* 16: 27-42.
- , Kelle, O., Lehtikoinen, M. & Inkinen, M. 2001. A segmentation-based method to retrieve stem volume estimates from 3-dimensional tree height models produced by laser scanner. *IEEE Transactions on Geoscience and Remote Sensing* 39: 969-975.
- Hyypä, H., Yu, X., Hyypä, J., Kaartinen, H., Kaasalainen, S., Honkavaara, E. & Rönnholm, P. 2005. Factors affecting the quality of DTM generation in forested areas. *The International Archives of the Photogrammetry, Laser scanning 2005*, Enschede, Netherlands. Vol. XXXVI, Part 3/W19. p. 85-90.
- Härkönen, S., Eerikäinen, K., Lähteenmäki, R. & Heikkilä, R. 2008. Does moose browsing threaten European aspen regeneration in Koli National Park, Finland? *Alces* 44: 31-40.
- Ilvessalo, Y. 1927. The forests of Suomi (Finland). Results of the general survey of the forests of the country carried out during the years 1921-1924. *Communicationes ex Instituto Quaestionum Forestalium Finlandiae* 11. (In Finnish with English summary).
- Kalliola, R. 1973. Suomen kasvimaantiede. Werner Söderström Osakeyhtiö, Porvoo. 308 p. (in Finnish)
- Kärkkäinen, S. 1994. Herb-rich forest vegetation of the Koli area. Publication of the Water and Environment Administration – series A, 172. p. 1-51. (in Finnish, with English summary)
- Kilkkä, P. & Päivinen, R. 1987. Reference sample plots to combine field measurements and satellite data in forest inventory. In: *Remote Sensing-Aided Forest Inventory. Proceedings of Seminars organized by SNS, 10-12 Dec. 1986, Hyytiälä, Finland. Research Notes No 19. Department of Forest Mensuration and Management, University of Helsinki, Helsinki.* p.209-215.
- Koivula, M., Punttila, P., Haila, Y. & Niemelä, J. 1999. Leaf litter and the small-scale distribution of carabid beetles (Coleoptera, Carabidae) in the boreal forests. *Ecography* 22: 424-435.

- Koivuniemi, J. & Korhonen, K. 2006 Inventory by Compartments. In: Kangas, A., Maltamo, M. (Eds.) *Forest Inventory, Managing Forest Ecosystems* 10, Springer, Netherlands. p. 271-278.
- Kouki, J., Löfman, S., Martikainen, P., Rouvinen, S. & Uotila, A. 2001. Forest fragmentation in Fennoscandia: linking habitat requirements of wood-associated threatened species to landscape and habitat changes. *Scandinavian Journal of Forest Research Supplement* 3: 27-37.
- , Arnold, K. & Martikainen, P. 2004. Long-term persistence of aspen - a key host for many threatened species – is endangered in old-growth conservation areas in Finland. *Journal for Nature Conservation* 12: 41-52.
- Koukoulas, S. & Blackburn, G.A. 2004. Quantifying the spatial properties of forest canopy gaps using Lidar imagery and GIS. *International Journal of Remote Sensing* 25: 3049-3071.
- & Blackburn, G.A., 2005. Spatial relationships between tree species and gap characteristics in broad-leaved deciduous woodland. *Journal of Vegetation Science* 16: 587-596.
- Korpela, I. 2000 3-D matching of tree tops using digitized panchromatic aerial photos. Licentiate thesis. University of Helsinki, Faculty of Agriculture and Forestry, Department of Forest Resource Management. 109 p.
- 2004. Individual tree measurements by means of digital aerial photogrammetry. Doctoral thesis, *Silva Fennica Monographs* 3. 93p.
- , Koskinen, M., Holopainen, M., Vasander, H. & Minkkinen K. 2009. Airborne small-footprint discrete-return LiDAR data in the assessment of boreal mire surface patterns, vegetation and habitats. *Forest Ecology and Management* 258: 1549-1566.
- Kurkela, T. 1973. Epiphytology of *Melampsora* rusts of Scots pine (*Pinus Sylvestris* L.) and aspen *Populus tremula* L. *The Finnish Forest Research Institute Research Papers* 79: 1-68.
- 1999. Haapa uhkana ja uhattuna. In: Hynynen, J., Viherä-Aarnio, A. (eds.), *Haapa – Monimuotoisuutta metsään ja metsätalouteen – The Finnish Forest Research Institute Research Papers* 725. p. 41-48. (In Finnish)
- Kuuluvainen, T. 1994. Gap disturbance, ground microtopography, and the regeneration dynamics of boreal coniferous forests in Finland: a review. *Annales Zoologici Fennici* 31: 35-51.
- , Syrjänen, K. & Kalliola, R. 1998. Structure of a pristine *Picea abies* forest in northeastern Europe. *Journal of Vegetation Science* 9: 563-574.
- Kuusela, K. & Salminen, S. 1969. The 5th national forest inventory of Finland. General design, instructions for field work and data processing. *Communicationes Instituti Forestalis Fenniae* 69.
- Kuusinen, M. 1994. Epiphytic lichen flora and diversity on *Populus tremula* in old-growth and managed forests of southern and middle boreal Finland. *Annales Botanici Fennici* 31: 245-260.
- 1996. Haavan epifyytiset jäkälät. *Sorbifolia*. 27, 159-163. (In Finnish)
- Kuusipalo, J. 1984. Diversity pattern of the forest understorey vegetation in relation to some site characteristics. *Silva Fennica* 18: 121-131.
- 1985. An ecological study of upland forest site classification in Southern Finland. *Acta Forestalia Fennica* 192: 1-77.
- Laki Kolin kansallispuistosta N:o 581/1991. 1991. [Internet site]. Available at: <http://www.finlex.fi/fi/laki/alkup/1991/19910581>. [Cited 31 Aug 2010]. (In Finnish).

- Latva-Karjanmaa, T. 2006. Reproduction and population structure in the European aspen. Academic dissertation, University of Helsinki, Department of Biological and Environmental Sciences. 25 p.
- Lehtonen, H. 1997. Forest fire history in North Karelia: a dendroecological approach. University of Joensuu, Faculty of Forestry, Doctoral dissertation.
- LeMay, V. & Temesgen, H. 2005. Comparison of Nearest Neighbor Methods for Estimating Basal Area and Stems per Hectare Using Aerial Auxiliary Variables. *Forest Science* 51: 109-119.
- Lilja, S., Wallenius, T. & Kuuluvainen, T. 2006. Structural characteristics and dynamics of old *Picea abies* forests in northern boreal Fennoscandia. *EcoScience* 13: 181-192.
- Lim, K., Treitz P., Wulder, M., St-Onge, B. & Flood, M. 2003. ALS remote sensing of forest structure. *Progress in Physical Geography* 27: 88-106.
- Liu, Q. & Hytteborn, H. 1991. Gap structure, disturbance and regeneration in a primeval *Picea abies* forest. *Journal of Vegetation Science* 2: 391-402.
- Lovén, L. 2005. Kolin kansallispuisto 2010 – Hoito ja käyttösuunnitelma vv. 2003-2010. Finnish Forest Research Institute, Joensuu Research Unit. 108 p. (In Finnish)
- Lyytikäinen, A. 1991. Kolin luonto, maisema ja kulttuurihistoria. Kolin luonnonsuojelututkimukset. Vesi- ja ympäristöhallituksen monistesarja 308. (in Finnish)
- Magnussen, S. & Boudewyn, P. 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Canadian Journal of Forest Research* 28: 1016-1031.
- Magurran, A. E. 1988. *Ecological Diversity and Its Management*. Princeton University Press, Princeton. 179 p.
- Maltamo, M., Mustonen, K., Hyypä, J., Pitkänen, J., & Yu, X. 2004. The accuracy of estimating individual tree variables with airborne laser scanning in a boreal nature reserve. *Canadian Journal of Forest Research* 34: 426-436.
- , Packalén, P., Yu, X., Erikäinen, K., Hyypä, J. & Pitkänen, J. 2005. Identifying and quantifying structural characteristics of heterogenous boreal forests using laser scanner data. *Forest Ecology and Management* 216: 41-50.
- , Malinen, J., Packalén, P., Suvanto, A. & Kangas, J. 2006. Nonparametric estimation of stem volume using airborne laser scanning, aerial photography and stand-register data. *Canadian Journal of Forest Research* 36: 426-436.
- McGarigal, K., Cushman, S. A., Neel, M. C. & Ene, E. 2002. [Internet site]. FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available at: www.umass.edu/landeco/research/fragstats/fragstats.html. [Cited 30 Jan 2009].
- McCarthy, J. 2001. Gap dynamics of forest trees: A review with particular attention to boreal forests. *Environmental Reviews* 9: 1-59.
- McCullagh, P. & Nelder, J.A. 1989. *Generalized Linear Models*, 2nd ed. Chapman & Hall, University Press, Cambridge. 532 p.
- Metsäkeskus. 2010. Metsäsuunnittelu ja tietopalvelut uudistuvat. 13 Dec 2010. Available at http://www.metsakeskus.fi/web/fin/palvelut/Tulossa/Metsasuunnittelu_ja_tietopalvelut/etusivu.htm [Cited 25 October 2010].
- Ministry of the Environment. 2008. [Internet site]. The Forest Biodiversity Programme for Southern Finland (METSO) 2008-2016. Available at: <http://www.ymparisto.fi/default.asp?contentid=274911&lan=fi&clan=en> [Cited 15 March 2010].

- Moeur, M. & Stage, A.R. 1995. Most Similar Neighbor: An improved sampling inference procedure for natural resource planning. *Forest Science* 41: 337-359.
- Müller, J. & Brandl, R. 2009. Assessing biodiversity by remote sensing and ground survey in mountainous terrain: the potential of LiDAR to predict forest beetle assemblages. *Journal for Applied Ecology* 46: 897-905.
- Næsset, E. 1997a. Estimating timber volume of forest stands using airborne laser scanning data. *Remote Sensing of Environment* 51: 246-253.
- 1997b. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry & Remote Sensing* 52: 49-56.
- 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. *Remote Sensing of Environment* 80: 88-99.
- 2004. Practical large-scale forest stand inventory using small-footprint airborne scanning laser. *Scandinavian Journal of Forest Research* 19: 164-179.
- , Gobakken, T., Holmgren, J., Hyypä, H., Hyypä, J., Maltamo, M., Nilsson, M., Olsson, H., Persson, Å. & Söderman, U. 2004. Laser scanning of forest Resources: The Nordic experience. *Scandinavian Journal of Forest Research* 19: 482-499.
- Nyysönen, A. 1959. Metsänarvioimistieteellinen tutkimus Suomessa vuosina 1909-1959. *Acta Forestalia Fennica* 70: 1-23. (In Finnish)
- Oinonen-Edén, E. 1991. Pielisjärven ja Juuan historia 1811-1864, Pielisjärven historia III. Pieksamäki. 399 p. (In Finnish)
- Ørka, H.O., Næsset, E. & Bollandsås, O.M. 2009. Classifying species of individual trees by intensity and structure features derived from airborne laser scanning data. *Remote Sensing of Environment* 113: 1163-1174.
- Packalén, P. 2009. Using airborne laser scanning data and digital aerial photographs to estimate growing stock by tree species. *Dissertationes Forestales* 77, University of Joensuu.
- Persson, Å., Holmgren, J. & Söderman, U. 2002. Detecting and measuring individual trees using an airborne laser scanner. *Photogrammetric Engineering & Remote Sensing* 68: 925-932.
- , Holmgren, J. & Söderman, U. 2003. Detection, measurements, and species classification of individual trees for forest inventory and visualization. *Proceedings of the Scandlaser scientific workshop on airborne laser scanning of forests, Umeå, Sweden, 2-4 September 2003.* p. 223-234.
- Pesonen, A., Maltamo, M., Eerikäinen, K. & Packalén, P. 2008. Airborne laser scanning-based prediction of coarse woody debris volumes in a conservation area. *Forest Ecology and Management* 255: 3288-3296.
- , Leino, O., Maltamo, M. & Kangas, A. 2009. Comparison of field sampling methods for assessing coarse woody debris and use of airborne laser scanning as auxiliary information. *Forest Ecology and Management* 257: 1532-1541.
- Puuhkurinen, J., Maltamo, M. & Malinen, J. 2008. Estimating species-specific distributions and saw log recoveries of boreal forests from airborne laser scanning data and aerial photographs: a distribution-based approach. *Silva Fennica* 42: 625-641.
- Piirainen, T., Honkamo, M. & Rossi, S. 1974. A preliminary report on the geology of the Koli area. *Bulletin of the Geological Society of Finland* 46: 161-166.
- Pirilä, M. 1999. Kolin vuoden 1936 metsämaiseman havainnollistaminen. (Visualizing forest landscapes of Koli of 1936) Diploma work, Degree programme in forestry, North Karelia Polytechnic. 49 p. (In Finnish with summary in English)

- Pitkänen, A. 1999. Paleocological study of the history of forest fires in eastern Finland. PhD thesis, University of Joensuu Publications in Sciences no. 58, Joensuu.
- Pitkänen, S. 1997. Correlation between stand structure and ground vegetation: an analytical approach. *Plant Ecology* 131: 109-126.
- Poso, S. 1983. Kuvioittaisen arviomismenetelmien perusteita. Basic features of forest inventory by compartments. *Silva Fennica* 17: 313-349. (in Finnish, with English summary)
- Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., Aksenov, D., Egorov, A., Yesipova, Y., Glushkov, I., Karpachevskiy, M., Kostikova, A., Manisha, A., Tsybikova, E. & Zhuravleva, I. 2008. Mapping the world's intact forest landscapes by remote sensing. *Ecology and Society* 13: 51. [Online journal]. Available at: <http://www.ecologyandsociety.org/vol13/iss2/art51/>.
- Puustinen, S., Hokkanen, P., Kouki, J. & Eerikäinen, K. 2007. Kolin kansallispuiston lehtojen hoitosuunnitelma. Metsäntutkimuslaitos, Joensuun toimintayksikkö, Kopijyvä Oy, Joensuu. (in Finnish)
- Rassi, P., Alanen, A., Kanerva, T. & Mannerkoski, I. (eds.) 2001. The Red List of Finnish Species. Ministry of the Environment and Finnish Environment Institute, Helsinki. 432 p. (In Finnish with summary in English)
- Redsven, V., Anola-Pukkila, A., Haara, A., Hirvelä, H., Härkönen, K., Kettunen, L., Kiiskinen, A., Kärkkäinen, L., Lempinen, R., Muinonen, E., Nuutinen, T., Salminen, O. & Siitonen, M. 2004. MELA2002 Reference Manual (2nd edition). Finnish Forest Research Institute. 606 p.
- Reese, H., Nilsson, M., Granqvist Pahlén, T., Hagner, O., Joyce, S., Tingelöf, U., Egberth, M., & Olsson, H. 2003. Countrywide Estimates of Forest Variables Using Satellite Data and Field Data from the National Forest Inventory. *Ambio* 32: 542-548.
- Riaño, D., Meier, E., Allgöwer, B., Chuvieco, E. & Ustin, S.L. 2003. Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behaviour modelling. *Remote Sensing of Environment* 86: 177-186.
- Ritchie, J.C., Jackson, T.J., Everitt, J.H., Escobar, D.E. & Murphey, J.B. 1992. Airborne Laser: A Tool to Study Landscape Surface Features. *Journal of Soil and Water Conservation JSWCA* 47: 104-107.
- Rombouts, J.H. 2006. Exploring the potential of airborne LiDAR for site quality assessment of radiata pine plantations in South Australia: initial results. Research Working Group 2, Forest Measurement and Information Systems, Biennial meeting, 21-24 November 2006, Woodend.
- Rouvinen, S., Kuuluvainen, T. & Karjalainen, L. 2002. Coarse woody debris in old *Pinus sylvestris* dominated forests along a geographic and human impact gradient in boreal Fennoscandia. *Canadian Journal of Forest Research* 32: 2184-2200.
- & Kouki, J. 2008. The natural Northern European boreal forests: unifying the concepts, terminologies, and their application. *Silva Fennica* 42: 135-146.
- Säynäjoki, R., Packalén, P., Maltamo, M., Vehmas, M. & Eerikäinen K. 2008. Detection of aspens using high resolution aerial laser scanning data and digital aerial images. *Sensors* 8: 5037-5054.
- Seielstad, C.A. & Queen, L.P. 2003. Using airborne laser altimetry to determine fuel models for estimating fire behavior. *Journal of Forestry* (101) 4: 10-15.
- Shannon, C. & Weaver, W. 1949. The mathematical theory of communication. Univ. Illinois Press, Urbana.

- Siitonen, J. 1999. Haavan merkitys metsäluonnon monimuotoisuudelle. In: Hynynen, J., Viherä-Aarnio, A. (eds.), Haapa – Monimuotoisuutta metsään ja metsätalouteen – The Finnish Forest Research Institute Research Papers 725. p. 71-82. (In Finnish)
- , Martikainen, P., Punttila, P. & Rauh, J. 2000. Coarse woody debris and stand characteristics in mature managed and old-growth boreal mesic forests in southern Finland. *Forest Ecology and Management* 128: 211-225.
- Simpson, E. H. 1949. Measurement of diversity. *Nature* 163. 688 p.
- Smith, A.M.S., Falkowski, M.J., Hudak, A.T., Evans, J.S., Robinson, A.P. & Steele, C.M. 2009. A cross-comparison of field, spectral, and lidar estimates of forest canopy cover. *Canadian Journal of Remote Sensing* 35: 447–459.
- Solberg, S., Næsset, E., & Bollandsås, O.M. 2006a. Single-tree segmentation using airborne laser scanner data in a structurally heterogeneous spruce forest. *Photogrammetric Engineering & Remote Sensing* 72: 1369-1378.
- , Næsset, E., Hanssen, K.H. & Christiansen, E. 2006b. Mapping defoliation during a severe insect attack on Scots pine using airborne laser scanning. *Remote Sensing of Environment* 102: 364-376.
- , Brunner, A., Hanssen, K.H., Lange, H., Næsset, E., Rautiainen, M. & Stenberg, P. 2009. Mapping LAI in a Norway spruce forest using airborne laser scanning. *Remote Sensing of Environment* 113: 2317-2327.
- Spies, T. A. & Franklin, J.F. 1989. Gap characteristics and vegetation response in coniferous forests on the Pacific Northwest. *Ecology* 70: 543-545.
- Stiling, P. B. 1996. *Ecology: Theories and Applications*, Prentice Hall International Editions, Second Edition, 539 p.
- Stokland, J. N., Holien, H. and Gaarder, G. 2002. Areal tall for boreal regnskog i Norge. NIJOS-rapport 2/2002: 1-20. (In Norwegian)
- St-Onge, B. & Vepakomma, U. 2004. Assessing forest gap dynamics and growth using multi-temporal laser-scanner data. In *Proceedings of Laser- Scanners for Forest and Landscape Assessments – Instruments, Processing Methods and Applications International Conference, Freiburg im Breisgau, 3-6 October 2004*. p. 173-178.
- Syrjänen, K., Kalliola, R., Puolasmaa, A. & Mattson, J. 1994. Landscape structure and forest dynamics in subcontinental Russian European taiga. *Annales Zoologici Fennici* 31: 19-34.
- Thessler, S., Sesnie, S., Ramos Bendaña, Z., Ruokolainen, K., Tomppo, E. & Finegan, B. 2008. Using k-nn and discriminant analyses to classify rain forest types in a Landsat TM image over northern Costa Rica. *Remote Sensing of Environment* 112: 2485-2494.
- Tikka, P. S. 1954. Structure and quality of aspen stands. I. Structure. *Communicationes Instituti Forestalis Fenniae*, 44: 1-33. (In Finnish with summary in English)
- , 1955. Structure and quality of aspen stands. II. Quality. *Communicationes Instituti Forestalis Fenniae*, 45: 1-54. (In Finnish with summary in English)
- Tomppo, E. 1996. Multi-source national forest inventory of Finland. In R. Päivinen, J. Vanclay and S. Miina (eds.), *New Thrusts in Forest Inventory. Proceedings of IUFRO XX World Congress, 6.12 Aug. 1995, Tampere, Finland*. p. 27-41.
- , 2006. The Finnish National Forest Inventory. In: Kangas, A & Maltamo, M. (eds.) *Forest Inventory. Methodology and applications. Managing Forest Ecosystems. Vol. 10*. Springer, Dordrecht. p. 179-194.
- Uotila, A., Kouki, J., Kontkanen, H. & Pulkkinen, P. 2002. Assessing the naturalness of boreal forests in eastern Fennoscandia. *Forest Ecology and Management* 161: 257-277.

- Uuttera, J. & Hyppänen, H. 1998. Determination of potential key-biotope areas in managed forests of Finland using existing inventory data and digital aerial photographs. *Forest & Landscape Research* 1: 415-429.
- Vauhkonen, J., Tokola, T., Maltamo, M & Packalén, P. 2010. Applied 3D texture features in ALS-based forest inventory. *European Journal of Forest Research* 129: 803-811.
- Vepakomma, U., St-Onge, B. & Kneeshaw, D. 2008a. Spatially explicit characterization of boreal forest gap dynamics using multi-temporal lidar data. *Remote Sensing of Environment* 112: 2326-2340.
- , St-Onge, B. & Kneeshaw, D. 2008b. Height growth of regeneration in boreal forest canopy gaps – does the type of gap matter? An assessment with lidar time series. *SilviLaser 2008*, September 17-19, Edinburgh, UK. p. 159-167.
- Vierling, K. T., Gould, W. A., Mertinuzzi, S. & Clawges R. M. 2008. Lidar: shedding new light on habitat characterization and modeling. *Frontiers in Ecology and the Environment*. 6. Doi 10.1890/070001
- Watt, P. J. & Donoghue, D. N. M. 2005. Measuring forest structure with terrestrial laser scanning. *International Journal of Remote Sensing*, 26: 1437-1446
- Wehr, A. & Lohr, U. 1999. Airborne laser scanning – an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing* 54: 68-82.
- Yu, X., Hyypä, H., Kaartinen, H. & Maltamo, M. 2004. Automatic detection of harvested trees and determination of forest growth using airborne lidar scanning. *Remote Sensing of Environment* 90: 451-462.
- Zhang, K. 2008. Identification of gaps in mangrove forests with airborne LIDAR. *Remote Sensing of Environment* 112: 2309-2325.
- Zhu, J., Matsuzaki, T., Lee, F. & Gonda, Y. 2003. Effect of gap size created by thinning on seedling emergency, survival and establishment in a coastal pine forest. *Forest Ecology and Management* 182: 339-354.