Forest Inventory and Planning in Nordic Countries.

Proceedings of SNS Meeting at Sjusjøen, Norway

September 6-8,2004

Kåre Hobbelstad

Norsk institutt for jord- og skogkartlegging

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Kåre Hobbelstad (editor)

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Utdrag:
SNS møte 2004 innen nordisk skogtaksering ble arrangert på Sjusjøen 6.-8. september 2004. Denne publikasjonen er en sammenstilling av hva som ble diskutert under de ulike temaene på møtet. Artiklene er skrevet av foredragsholderne på møtet. Temaene er delt i rapporter fra de ulike nordiske land om hva som har skjedd innen forskning og utvikling siden forrige møte, anvendelse av laser data i skogtakseringen, utvikling innen de nasjonale skogtakseringer, bruk av fjernmåling ved skogregistrering, skogplanlegging og skogmodellering.

Abstract:
SNS-meeting 2004 in Nordic Forest Inventory was held at Sjusjøen, Norway, September 6-8, 2004. This publication is a collection of all the subjects dealt with at the meeting. The articles are written by the speakers on the meeting. The subjects were country and team reports, lidar measurements in forest inventory, national forest inventory, remote sensing studies, forest planning and current topics in forest modelling.

Emneord:	Keywords:	Sideantall: 268
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Utgiver: Norsk institutt for jord- og skogkartlegging, Postboks 115, 1431 Ås, Tlf.: + 47 64 94 97 00 Faks: + 47 64 94 97 86, E-post: nijos@nijos.no		Forsidefoto: John Y. Larsson Blefjell. Buskerud

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Preface

The Nordic countries were the first ones in the world to establish national forest inventories more than 80 years ago. The similarity in forest conditions and forest thinking lead to close cooperation between the Nordic countries from the very beginning of the national forest inventories. A more formalised cooperation started, however, in 1979 with a meeting on August 27-30 in Torpshammar, near Sundsvall. From that date, regular meetings every 2 or 3 years have been held, and several cooperation projects with common funding have been accomplished.

The topics of the meetings are research work that has taken place in the Nordic countries between the meetings and the experience with new inventory methods. Funding from the Nordic Forest Research Co-operation Committee (SNS) has made it possible to get good participation from all countries. This is of great importance, because getting to know each other and exchange of experiences and knowledge have lead to good cooperation between institutions and to common projects.

The globalisation of forestry and the need for common definitions and similar practises for international reporting have lead to close cooperation between the national forest inventories also outside the meetings.

The eleventh meeting was held at Sjusjøen in Norway September 6-8, 2004. The following countries were represented at the meeting: Denmark, Estonia, Finland, Iceland, Sweden, USA and Norway. Most of the presentations given at the meeting at Sjusjøen are collected in this report. The content of the report has been organised into topical chapters: country and team reports, lidar measurement in forest inventory, national forest inventory, remote sensing studies, forest planning and current topics in forest modelling.

The type of presentations ranged from practical experiences, case studies to wide reviews. As a result, the articles are quite heterogeneous in length and style, and attempts to harmonize them were considered impossible and unnecessary. However, this collection serves as a comprehensive documentation of the state of the art in Nordic forest inventories and management planning.

The success of the meeting was a result of the efforts of many individuals, not least the participants of the meeting from many different countries. On the behalf of the local organisers, I will thank all individuals and groups contributing to the meeting, as well as the Nordic Forest Research Co-operation Committee (SNS) and the Norwegian Ministry of Agriculture and Food for financial and institutional support.

Ås, June 2005.

Kåre Hobbelstad

Team and Country Reports

Photo: John Y. Larsson

Picture from excursion. Åstadalen, Hedmark.

Team Report from University of Joensuu, Faculty of Forestry, Forest Mensuration and Planning 2001-2004

Maltamo, M., Anttila, P., Eerikäinen, K. Malinen, J., Packalén, P. and Pitkänen, J.

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1. General

The Faculty of Forestry at the University of Joensuu forms the core of diverse forestry know-how based in Joensuu, eastern Finland. The goals of the Faculty of Forestry are to carry out research on the boreal forest ecosystem, Finland's principal natural resource, and to train graduate foresters in the study, management, protection, and utilisation of this natural resource.

The Faculty has special expertise for example on the impacts of climate change, remote sensing, forest modelling and environmental sciences. Increasingly, post-graduate students work for their doctorate within a graduate school programme. The Faculty participates in the Graduate School programmes of Forest science, Remote sensing and Wood Science and Engineering. The research group working on The Effects of Climatic Change on the Forest, led by Professor Seppo Kellomäki, has been awarded the distinction of being a "Centre of excellence in research" by the Ministry of Education. The Faculty is or have been involved in more than ten research projects funded by the European Union, with the co-ordination of several being the responsibility of the Faculty. The Faculty is also actively operating with local and national business life in research and development.

The staff of the faculty includes 12 professors, 9 senior assistants, 70 researchers and 20 other staff including office and laboratory staff. The Faculty have 60 graduate students and 480 undergraduate students with admittance of 50 new students every year. The Faculty awards about 45 Master's degrees and 12 Doctoral degrees every year.

2. Personnel

Docent Matti Maltamo
Professor of forest mensuration science
Research interests
- diameter distribution models
- non-parametric methods
- modelling of laser scanning based forest attributes
- growth and yield modelling
- inventory of non-wood forest products

Professor Timo Pukkala
Professor of forest planning
Research interests:
- multi-criteria forest decision analysis
- participatory planning
- integration of landscape ecology into forest planning
- visualisation of forest for decision analysis
- management of plantation forests.

Dr. Sc..Jukka Malinen
Senior assistant of forest mensuration science 2002-2004
Research interests:
- prediction of characteristics of marked stand and metrics for similarity of log distribution for wood-procurement management
- value formation of marked stands when targeting for alternative end-products in timber harvesting

M.Sc. Susanna Sironen
Assistant of forest mensuration science 2001
Researcher 2002-
Ph.D. student
Topic: The use of non-parametric methods in constructing tree level growth models

Dr. Sc. Ari Talkkari
Senior assistant of forest planning 2003-
Research interests
- forest planning and GIS

Dr. Sc. Jouni Pykäläinen
Senior assistant of forest planning 2001

Dr. Sc..Mikko Kurttila
Senior assistant of forest planning 2001-2002

M.Sc. Heikki Parikka
Senior assistant of forest planning 2002-2003
Senior assistant of forest information systems 2003-2004

M.Sc. Satu Löfman
Senior assistant of forest information systems 2001-
Ph.D. student
Topic: The regional structure of forest landscape and the landscape changes caused by forestry

M.Sc. Juho Pitkänen
Senior assistant of forest information systems 2001-2002
Researcher 2002-
Ph.D. student
Topic: High-resolution image interpretation in forest inventory

M.Sc. Petteri Packalén
Senior assistant of forest information systems 2002
Researcher 2002-
Ph.D. student
Topic: Characterizing forest structure and tree species composition using small-footprint airborne lidar and digital aerial photos

M.Sc Mikko Vehmas
Aassistant of forest mensuration science 2004
Ph.D. student
Topic: Monitoring system based on modern remote sensing imagery for natural forests and restored forests of conservational areas

M.Sc.Perttu Anttila
Researcher
Ph.D. student
Topic: Aerial photographs in updating stand-level information on growing stock

Dr. Sc. (For) Kalle Eerikäinen
Researcher 2001-2003

M.Sc. Arto Haara
Researcher 2002, 2004
Ph.D. student
Topic: Reliability of forest inventory data

Msc. Tero Heinonen
Researcher 2004
Ph.D. student
Topic: Forest planning

Dr. Sc. (For) Antoni Trasobares
Researcher
Research interests:
- Modelling and management of uneven-aged pine forests in North-East Spain

Lic.Sc.Lauri Vesa
Researcher 2001-2002

3. Major research projects

3.1 Earth Observation for Natura 2000+ (EON2000+)

Petteri Packalén. Lauri Vesa, Timo Pukkala

'Earth Observation for Natura 2000+ (EON2000+)' is an RTD project co-funded by the European Commission as part of the 5th Framework Programme. The project is a partnership of 14 members from seven European countries working for a duration of three years (2001-2004) and follows on from a Fourth Framework project. The Finnish partners are the Faculty of Forestry in the University of Joensuu and the Finnish Environment Institute as an end-user.

The aim of the EON2000+ project is to develop and demonstrate integrated indicators of environmental state and socio-economic pressures for environmental protection purposes in support of the conventions on Biodiversity and European Biodiversity Strategy. The suitability of the Very High Resolution satellite data for the environmental monitoring was tested in Finland. Classification based on segmented Ikonos image was tested in the recognition of mire water throughflow areas and the comparison of Landsat and Ikonos data was carried out in order to predict species richness over large areas.

3.2 Forest Information Assessment and Updating and Aerial photographs in updating stand-level information on growing stock

Perttu Anttila

In Finland, initial data for forest planning is collected in stand-level field inventories. Because field work is costly, there is an urgent need for more cost-efficient methods to replace or supplement traditional field inventories. Aerial photographs provide an attractive alternative to survey forest stands, since they are familiar for end-users, affordable, and their spatial and temporal resolution is high. 'Forest Information Assessment and Updating' was a project where methods based on remote sensing were sought for stand-level inventories in private forests. The project was funded by Finnish Ministry of Agriculture and Forestry and the participants were University of Joensuu, Finnish Forest Research Institute, Forestry Centre Pohjois-Savo and Forestry Development Centre Tapio. The work has then continued as a project 'Aerial photographs in updating stand-level information on growing stock'.

At the University of Joensuu, three approaches to use aerial photos in forest inventories were examined. Visual interpretation coupled to updating of old inventory data proved to be a simple but working method and will be in operational use year 2004. In a more automatic method, *k*-nearest-neighbor (*k*nn) estimation was utilized. Stand-level spectral and textural features calculated from aerial photographs and old inventory data were used as indicator variables. Though *k*nn is routinely used in national forest inventory with Landsat TM and SPOT images, bidirectional reflectance and radial displacement present in aerial photographs caused problems that could not be totally solved. Finally, semi-automatic tree-level interpretation of aerial photographs was tested. Tree crowns were segmented with an application by Oy Arboreal Ltd. The results indicated underestimation of stand attributes, because only dominant and co-dominant trees were detected. The same result was achieved later, when another method to estimate number of stems was studied. In 2003, tests that aim to estimating canopy height applying image matching of aerial photographs were started. The first results have shown that estimated stand heights are likely biased but precise.

3.3 The Usability of Single Tree Laser Scanning in Forest Planning

Juho Pitkänen, Matti Maltamo

In the project 'The Usability of Single Tree Laser Scanning in Forest Planning', funded by the Academy of Finland, laser scanning data is used to produce height estimates of individual trees, which can then be used as a basis for the prediction of forest stand estimates. The other participant of the project is Finnish Geodetic institute, Department of Remote sensing and Photogrammetry.

The research has so far concentrated on the accuracy of laser scanning based forest resource estimates and development of more advanced tree crown detection and segmentation algorithms. To reduce data volume and enable use of image processing methods, a crown height image is first calculated from the original xyz-point data, produced by the laser scanner. Local maxima finding and variations of watershed segmentation algorithm are then used for tree detection and crown segmentation. However, knowing the height of each pixel gives possibilities to make standard processing chains better. To improve tree detection, height based filtering as pre-processing and crown width based elimination of candidate tree locations have been tested. For the elimination method, crown width estimates are obtained from the relation between height and crown width. The same relation can also be used after segmentation in splitting and merging of candidate tree crown segments.

The accuracy of laser scanning has been found satisfactory for dominating tree layer but suppressed trees cannot not be found using current tree identification methods. Therefore, estimates of height distribution of trees, which are based on combination of scanning laser altimetry and expected tree size distribution functions, were also produced. The accuracy of this approach was found to be as good as the conventional stand-level field inventory which is used in Finland. Finally, temporal change detection between two laser acquisitions has also been examined.

3.4 ITM - Implementing Tree Growth models as Forest Management Tools

The ITM project "Implementing Tree Growth models as Forest Management Tools", which was financed by the European union, began on 1st February, 2001, and ended on 31st January 2004. The aims of this project were: i) to develop a preliminary framework definition for modelling terminology and to identify and categorize individual tree growth models within a European focus, ii) to develop models and model based simulation systems for the establishment and development of regeneration, economics and decision support, and extending or localising individual-tree models to new applications, areas and regions, and iii) to design every new model explicitly according to the interest of the model developer and his scientific background. The project had eight partners from seven scientific organisations in Austria, Denmark, Finland, Germany, Greece, Portugal and Slovakia. In addition, there were altogether eleven representatives from forest companies (private enterprises) which participated in the project.

The project brought together experts to develop missing or weak aspects of the existing individual-tree models and to help those partners of the consortium who had a need for individual-tree models based on simulation systems but little experience on modelling these prediction tools. The research implemented within the project was focused on four main topics on growth modelling which were: i) regeneration, ii) economics, iii) decision support, and iv) extension and adaptation of individual-tree models to new applications, areas and regions. The purpose was also to simplify, clarify and harmonise the theory, technical aspects and terminology dealing with individual-tree growth modelling. This process was based on an open exchange of information between model developers, model users and the forest industry. The knowledge gained in the research component was also used to demonstrate for representatives of the private enterprises that individual-tree growth models are a sophisticated alternative to existing yield tables. Another important task of the research component was to search for documented and programmed algorithms which can be immediately implemented into existing tree growth models.

Specific topics studied within the project were as follows: i) regeneration establishment and development in uneven-aged mixed-species stands, ii) economically sustainable timber harvesting scenarios for uneven-aged mixed species stands, iii) tree growth models in the optimization of stand treatments, iv) individual-tree growth model as an alternative tool to existing yield tables, v) development of individual-tree growth models based decision support system for the management of biodiversity and scenic beauty, selection of harvesting options for stands, and analyses of risks and recreational aspects, vi) optimisation of cork production in southern Europe, vii) conversion of even-aged pure secondary coniferous stands into uneven-aged mixed species stands, and viii) development of growth models for coppice forests in Greece.

3.5 Modelling stand development on Pinus kesiya plantations in southeastern Africa

Kalle Eerikäinen

The aim of the thesis was to develop a set of prediction models that can be used: i) to characterise relationships between measurable tree and stand variables, ii) to analyse the temporal development of stand structure of *Pinus kesiya* Royle ex Gordon, and iii) to develop a stand yield prediction model for the management of *P. kesiya* plantations in southeastern Africa. The thesis consists of five sub-studies in which different aspects of tree and stand level modelling were analysed in accordance with current theories on forest growth and yield. In the first sub-study a calibrateable site index model with random coefficients for the prediction of dominant height-age curves was developed. The second sub-study yielded a model set for the prediction of over and under bark stem volumes and tree taper curves, whereas in the third sub-study a stand level simultaneous yield model based on the growth projection modelling approach was achieved. The fourth and fifth sub-study analysed the development of the height-diameter patterns and the basal area diameter distributions, respectively. Data used in the five sub-studies of the thesis were collected from Tanzanian, Zimbabwean and Zambian forest plantations.

Because of the spatially hierarchical (plantations, stands and trees) and temporal (measurement occasions) correlation structures of the data, the basic assumption about noncorrelated residuals did not hold. Therefore, random parameter models were applied, i.e. random effects were taken into consideration in the model formulations and estimations of fixed and random model parameters. The random parameter models which are linear can be calibrated in accordance with standard linear prediction theory, i.e. parameters for random effects are obtained using the Best Linear Unbiased Predictor (BLUP). The third and the fifth sub-study developed simultaneous equations, i.e. systems of equations, which parameters were estimated using the Nonlinear Three-Stage Least Squares (N3SLS) estimator.

The tree or stand level models of the thesis are either relation models or development models. All the independent variables of the models are assessable in the inventories of forest plantations, which simplifies and thus increases their practical applications. The stand characteristics selected are also frequently employed in both traditional stand yield tables and modern growth simulators. The results of the study showed that the set of models can be used to predict not only the relationships between tree and stand characteristics but also the development of stand structure. The model set achieved comprises a simulator for stand growth and yield, which can be used, for example, to predict stand characteristics for forest inventories. Furthermore, the methods are also applicable to other tree species and in other locations where managed even-aged forest stands are established with one species and where the development of the tree and stand characteristics of the given species corresponds to those of *P. kesiya*.

3.6 Evaluation of the suitability of the ICP data set for forest biodiversity monitoring

Petteri Packalén, Matti Maltamo

The interest towards forest biodiversity has lately increased in the European Union. However, there is no large scale monitoring system of forest biodiversity in Europe. Recently, the possibilities to extend the Level I ICP network for monitoring forest biodiversity have been discussed. The principal advantages of such an approach would be the application of the already existing network, avoidance of the establishment of new permanent plots or multiple monitoring schemes and possibilities to apply the already accumulated information for detecting changes in forest biodiversity over time. Prior to any concrete steps an assessment of the suitability of the network for forest biodiversity monitoring is needed. The current study serves this purpose. Geographically, the study comprises 28 European countries.

Currently, there is no agreement on a single definition, determinants or indicators of forest biodiversity. Commonly, structural, compositional and functional aspects of biodiversity have been distinguished and found suitable for biodiversity monitoring purposes. In a forest, the tree species composition determines to a large degree the more detailed structure and species composition. It is also easy to determine and belongs to the most commonly assessed parameters in forest inventories. On each ICP Level I plot, tree species – and concurrently – tree species composition has been determined. Thus, the tree species composition offers a natural starting point when the possibilities to extend the Level I ICP network for biodiversity monitoring are studied. The specific aim of the study was to examine how well tree species detected in the Level I ICP plots represent the statistical and spatial distribution of all the tree species found in Europe and in a particular country.

Although the Level I ICP plots were found to be representative for the 'Dominant' and 'Abundant' tree species when compared with the TBRFA-2000 database the description of 'Rare' or 'Occasional' tree species was considerably worse. Especially many of these

'Rare' and 'Occasional' tree species may be of special interest with respect to biodiversity. On a large scale, the data is also lacking on information e.g. about forest types, forest ownership, protection and afforestation/deforestation.

When considering the ICP sample plots on a stand level it can be said that the data contain information only about the dominant tree layer. If the stand is multi-layered it cannot be recognised from the data. Furthermore, single suppressed trees (and tree species) under a dominant tree layer are also ignored. The size of the plot is not fixed and registered and, therefore, the results can not be generalized to larger areas. The measurements of the plots do not include any tree size characteristics, and also the age structure of the tree stock is unknown. Finally, the amount coarse woody debris is not known. All these characteristics are mentioned as important structural key factors of biodiversity (Puumalainen 2001).

Therefore, it can be concluded that although the Level I ICP sample plot network is representative on a large scale, the current measurements are mostly inadequate to describe different aspects of biodiversity. However, it has been proposed that some additional measurements could be included to the ICP Forests monitoring programme for the purposes of biodiversity assessments. As a basis of the results of this study, the proposals for the additional future measurements of the Level I ICP sample plot network in relation to biodiversity are:

1. The size of the plot should be representative on the stand level and the plot area should be registered
2. Information about both vertical and horizontal stand structure should be gathered. Especially diameter distribution of the plot should be measured
3. The amount of coarse woody debris should be measured
4. Landscape and habitat level information could be obtained using remote sensing materials.

The project was funded by European commission, DG JRC, Insitute for Environment and Sustainability, Management Support unit, under contract no. 18674-2001-11 F1EI ISP FI.

3.7 Forest inventory in Novgorod region, Russia

Matti Maltamo, Jari Kinnunen

The project is a sub-study of a European Fores tInstitiute project "Modelling and assessment of forest resources, their future use and economic accessibility in Northwest Russia. In general, compartmentwise forest inventories are carried out in many countries. Such inventories produce comprehensive information of forest resources in certain area. The basic problems of this kind of inventory approach is that the measurements per stands are few in number and that the reliability of the inventory can not be calculated since the method is not based on statistical sampling. Therefore, the checking of compartmentwise forest inventory was done in order to investigate the accuracy of Russian inventory data in the Novgorod region. The basic idea of checking inventory is to choose a sample of original compartments, which are re-measured more accurately.

The field work of checking inventory was carried out in summer 2002 considering 179 compartments in four forest management units (leshozes). The selection of compartments to be checked was done objectively from the stands belonging to the development stages of middle-aged or older in randomly chosen kvartals. However, the compartments dominated by coniferous tree species were emphasised in the selection process. The basic principle of the checking inventory is to locate a systematic net of about 10-15 relascope sample plots in each selected compartment. On these relascope sample plots tree species as well as diameters of all trees are registered. Stand volumes were calculated using constructed tree height model and existing volume models. To enable the comparison between the obtained results and older Russian field inventory data, the volumes were updated 4-6 years.

The results showed that the original stand total volumes that were based on Russian forest inventory were on average underestimates, the bias being 13.4 %. The correspondent root mean-square error (RMSE) was 32.4 % for the whole material. When considering geographical sub-areas it was discovered that the bias varied between 8-20 % in different leshozes. When comparing the inventory data in relation to different dominating tree species, the bias was in pine dominated compartments 12 %, in birch dominated compartments 14 %, in aspen dominated compartments 21 % and in the case of spruce dominated compartments there was slight negative bias of 4 %. Finally, the results were calculated separately according to stand volume. The bias indicated clear trend the volumes being overestimates (12 %) in sparse and younger stands with less volume and underestimates (22-28 %) in dense, heavily stocked stands.

3.8 Stem database based prediction of stand characteristics by non-parametric methods and neural computing

Jukka Malinen

Dr. Jukka Malinen has been working in his doctoral thesis “Prediction of characteristics of marked stand and metrics for similarity of log distribution for wood-procurement management” (2003) with the production of pre-information for wood procurement planning. The study has been concentrating on developing a non-parametric application suitable for use in Finnish forest enterprises with stem databases generated by harvester and forest inventory. In the study, the nearest neighbour methods were further developed by local adaptation and the method was applied also for prediction of internal quality and value of Norway spruce trees. In addition, the similarity comparisons between different log length-diameter distributions have been studied.

Since doctoral thesis, Dr. Malinen has continued working with prediction of marked stand characteristics in the project “Stem database based prediction of stand characteristics by non-parametric methods and neural computing”. The objective of the study is to further develop non-parametric methods by automated variable selection via optimization process. In addition, soft computing methods are to be tested and compared to non-parametric methods.

Recently Dr. Malinen has been working with Finnish Forest Research Institutes research project “value formation of marked stands when targeting for alternative end-products in timber harvesting”. The goal of the project is to provide decision support information for timber purchase and sales on the issues how different characteristics of the stand, dimensions and quality factors of wood assortments, and principles and objectives of bucking affect the value formation of an individual stand.

4. Academic degrees

4.1 Doctoral thesis

2001:

Kalle Eerikäinen: Modelling stand developement on *Pinus kesiya* plantations in Southastern Africa

Miika Kajanus: Strategy and innovation model for the entrepreneurial forest owner

Mikko Kurttila: Methods for integrating ecological objectives into landscape-level planning of non-industrial private forestry

Mbae Muchiri : Yield and management of maize -Grevillea robusta agroforestry in Kenya

Gert Jan Nabuurs: European forests in the 21st century: Impacts of nature-oriented forest management assessed with large-scale scenario model

Jouni Pykäläinen: Interactive use of multi-criteria decision analysis in forest planning

Jouni Vettenranta: Growth dynamics and economic return of mixed forests of Norway spruce and Scots pine

2002:

Marc Palahí: Modelling the stand development and optimising the management of even-aged Scots pine forests in North-East Spain

2003:

Jukka Malinen: Prediction of characteristics of marked stand and metrics for similarity of log distribution for wood procurement management

2004:

Antoni Trasobares: Modelling and management of uneven-aged pine forests in Catalonia, North-East Spain

Lauri Mehtätalo: Predicting Stand Characteristics Using limited Measurements

4.2 Licenciate thesis

2001:

Lauri Vesa: The structure and yield of logged-over tropical stand of the Kintap Trial Area, South Kalimantan, Indonesia

2002:

Helena Mäkelä: Estimation of forest stand parameters by Landsat TM imagery and stand-level inventory data

2004

Ron Store: Paikkatietomenetelmät metsäsuunnittelun apuvälineenä. (In Finnish)

4.3 M.Sc. Thesis

2001:

Susanna Holopainen: Metsähallituksen Itä-Suomen alueen metsätiestrategian laatiminen osallistavan suunnittelun avulla. (In Finnish)

Sanna Härkönen: Asiantuntijajärjestelmä viljelymetsien puulajivalintaan itäisessä ja eteläisessä Afrikassa (In Finnish)

Katja Kenttämaa: Metsänomistajien mielipiteet säästöpuiden määrästä ja tilajärjestyksestä (In Finnish)

Jukka Koivumäki: UPM-Kymmene Metsän metsäsuunnittelujärjestelmien soveltuvuus metsäpalveluasiakkaille (In Finnish)

Satu Laamanen: Maisematekijöiden sisällyttäminen suuralueen metsäsuunnitteluun – tapaustutkimus Vienan Karjalassa (In Finnish)

Mikko Mutka: Harvennushakkuiden korjuujälki Karjalan tasavallassa Sortavalan ja Pitkärannan metsäpiireissä vuosina 1989-1994 (In Finnish)

Petteri Packalén: Superresoluution käyttö NOAA/AVHRR-satelliittikuvissa (In Finnish)

Eeva Sundström: Metsikkökuvion sisäisen vaihtelun huomioonottaminen metsäsuunnittelussa (In Finnish).

2002:

Petri Hallikainen: Kuvioittaisen arvioinnin arviointivirheet ja niiden vaikutus läpimittajakauman avulla suoritettavassa tilavuuden laskennassa (In Finnish)

Elina Heikkinen: Puustotunnusten maastoarvioinnin luotettavuus ja ajanmenekki (In Finnish)

Kari Mustonen: Tilajärjestyksen ja puuston pituuden määrittäminen laserkeilainkuvilta (In Finnish)

Janne Nissinen: Improving compatibility between prediction of basal area diameter distributions and assessments of young stands

Karri Pasanen: Internet-metsäsuunnitelma ja elektroniset metsäpalvelut – kyselytutkimus pohjoiskarjalaisille metsänomistajille (In Finnish)

2003:

Heikki Björn: Aluesuunnitelmatietojen käyttö raakapuun tarjonnan ennustamisessa Stora Enso Metsän Karjalan hankinta-alueella (In Finnish)

Henna Etula: Metsien virkistysarvon määrittäminen metsien rakenteen perusteella Metsähallituksen luonnonvarasuunnittelussa (In Finnish)

Tero Heinonen: 2-naapuriston käyttö spatiaalisessa heuristisessa optimoinnissa (In Finnish)

Mikko Vehmas: Yksinpuittain tulkitun kaukokartoitusaineiston täydentäminen jakaumamalleilla. (In Finnish) (Completing single trees remote sensing data with distribution models)

Päivi Ylikoski: Spatiaalisten tekijöiden vaikutus metsiköiden uudistushakkuuseen (In Finnish)

2004

Geraldo Barcos: Utilisation of GIS tools to analyse the accessibility, fragmentation and human pressure of Urban forest around big cities in Europe

Jarkko Heikkinen: Internet-menetelmä yleisömielipiteen keräämiseen Metsähallituksen Hyrynsalmen Kokkoharjun osallistavassa suunnittelussa (In Finnish)

Kirsi Ikonen: Yksittäisten puiden tunnistaminen ja niiden latvusten segmentointi digitaalisilta ilmakuvilta (In Finnish) (Detection and segmentation of individual trees from aerial images)

Juha Laiho: Ilmakuvalta automaattisesti muodostettujen segmenttien soveltuvuus metsäsuunnittelun lähtöaineistoksi (In Finnish) (Applicability of automatically segmented aerial photographs in forest planning)

Teemu Mäkelä: Verkkometsäsuunnitelman käyttäjätyytyväisyys (In Finnish)

Marko Nenonen: Spatiaaliset hakkuutavoitteet metsäsuunnittelussa – ratkaisumenetelminä Hero-optimointi, tabu-haku, simuloitu mellotus ja geneettiset algoritmit (In Finnish) (Using HERO, simulated annealing, tabu search and genetic algorithms to solve spatial forest planning problems)

5. Publications

5.1 Refereed scientific publications

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5.3 Textbooks

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Country Report for Sweden

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Introduction

This country report provides an overview of activities within the fields of forest inventory, remote sensing, and forest management planning conducted, mainly, at the Swedish University of Agricultural Sciences during the last few years. A summary is included for each of the above- mentioned fields, and a list of publications is amended for those who might wish to study more in depth what the developments in different areas have been. The summary texts are given without any literature references.

Forest inventory

Under this subject heading, field based research achievements as well as developments of national level monitoring programmes, e.g. the National Forest Inventory, are summarised. Forest inventory activities within the field of remote sensing are covered in a separate section (see below).

Research related to the area of field based forest inventory has covered four main fields: (i) objective sampling methods for surveying sparse populations, (ii) methods for vegetation monitoring (iii) relascope methods for the inventory of coarse woody debris, and (iv) development of biomass functions for living and dead trees.

Within the first area the main part of the work has involved further development and evaluation of the Guided Transect Sampling method, e.g. to use the method in connection with probability proportional to prediction sub-sampling and to obtain an application that mimics the way a field ecologist subjectively would search for individuals of some sparse population, yet keeping the inventory under the framework of random sampling theory. Within the second area, the Presence/Absence Sampling approach to vegetation monitoring has been further developed and evaluated in connection with field studies. New inventory methods for the inventory of dead wood, using relascope principles, have been developed and evaluated in cooperation with biometricians from the USDA Forest Service. One promising method concerns a further development of the critical height inventory concept to cover also downed material, proposed as Critical Length Sampling. Biomass functions have been developed both for living trees (above and below ground) and dead wood. Compared to the previously available functions the new ones provide more accurate estimates especially for the below ground biomass of trees. In addition to the biomass functions, decay functions for different categories of dead wood also have been developed.

During 2003, a revised National Forest Inventory (NFI) programme started in Sweden. Compared to the previous programme, the same basic principles remain. However, some important changes involve:

- A shift towards a larger proportion of permanent sample plots. In the new programme, 2/3 of the sample plots are permanent. The background mainly is increased requirements for data on changes.
- Additional changes in the design involve an introduction of large plots for the survey of sparse populations, as well as small plots for the monitoring of field layer vegetation and regeneration.
- A large number of changes have been made regarding what variables are recorded in the inventory. For example, several new biodiversity oriented variables have been introduced, new methods for the recording of stand level damages (incl. moose browsing) have been incorporated, and some new variables have been added in order to facilitate the reporting of carbon pools according to the Climate Convention.

In addition to the design and scope of the NFI, the technical infrastructure of the inventory has been modified. This involves, e.g., a new system for the field data collection and new procedures for map preparation. From 2004 onwards, the NFI also uses satellite remote sensing together with the poststratification principle in order to improve the precision of small area estimates.

Moreover, the NFI ("Riksskogstaxeringen") from 2003 onwards is conducted in even closer cooperation with the Soil Survey ("Markkarteringen, previously called "Ståndorts-karteringen"). To mark the close cooperation, the two inventories together nowadays are often denoted by the common umbrella name: "Riksinventeringen av Skog (RIS)".

In 2003, a new national level monitoring programme, covering forests but also all other land cover types, was introduced: The National Inventory of Landscapes in Sweden (NILS). The main objective of NILS is to monitor biodiversity at a landscape level. The programme comprises two different phases: (i) an air photo interpretation phase which provides the landscape context within 1*1 km large squares, and (ii) a field inventory phase where 12 sample plots are visited within each landscape quadrate and registrations are made of a number of biodiversity oriented variables. Additionally, line intersect sampling is carried out between the plots in order to assess characteristics of important linear features in the landscape, such as water courses and forest margins. All landscape quadrates and field sample plots are permanent, and the plan is to revisit them with a 5 yrs interval. In total, about 630 landscape quadrates are included in the NILS sample.

Most of the work in all of the above mentioned areas has been conducted at the Dept of Forest Resource Management and Geomatics at SLU, Umeå.

Remote sensing

Satellite remote sensing

Since the previous SNS meeting, satellite remote sensing has become truly operational among Swedish Forest Authorities. The Swedish Forest Administration has, since some years ago, checked land owner cutting permits by comparing them with changes detected in multitemporal satellite imagery. Since January 2003, this routine includes yearly delineation of all clearfelled areas in Sweden. The mapping is carried out at about 100 local district offices, using yearly summer imagery of Landsat or SPOT – type, and tailor-made change detection software. The availability of this imagery at district level has also inspired further development of practical applications, like detection of areas where pre-commercial thinning is needed.

A seven year research program, called Remote Sensing for the Environment (RESE), was finalised in 2002. The program focused on environmental satellite remote sensing. It included forestry and is partly documented in a special issue of Ambio, December 2003. One of the outcomes of RESE was the development of methods and a production line called Munin, for combining satellite remote sensing data with National Forest Inventory data. The NFI plots were used, not only for estimation, but also for reduction of within-scene haze differences and slope effects. The Munin production line was used by SLU for production of the forest part of the Swedish Corine landcover data base, including a national product with better resolution and more classes. Munin has also been used for producing a nation wide kNN data base, similar to the one earlier produced in Finland. The kNN data base has been used by several authorities, including the Forest Administration and the National Environmental Protection Agency. It has also been used by several research groups e.g. for habitat modelling. A version of the national kNN data base, segmented into homogeneous stands, was finalised during December 2004. In an ongoing project, the Munin production line is also used for reflectance calibration of satellite scenes, using functions that predict reflectance from the forestry data at the NFI plots. In the same project are also tools that use the reflectance calibrated imagery for various analysis carried out at local level, developed.

The Swedish National Forest Inventory has developed routines for using the segmented kNN data base for poststratification of sample plot based NFI estimates. This has resulted in a considerable error reduction, especially for estimates of stem volume and woody biomass. For example, for an area of 1 milj ha in northern Sweden, the standard deviation for woody biomass was reduced from about 4 % using NFI plots only, to about 2,5 % when using poststratification.

Since year 2000, there has been one PhD thesis in satellite remote sensing: Jörgen Wallerman, who investigated the use of geostatistics for improving raster based estimates.

Airborne remote sensing

Several projects have been carried out together with the Swedish military VHF SAR system CARABAS, which operates with wavelengths between 3 m and 15 m. Most studies have been concentrated on assessment of stem volume on stand level. The slope effect is reduced by using radar data observed in two flight directions.

Also laser scanning has been a very active area of research. Both statistical methods for stand-wise estimates and single tree methods have been developed. Table 1 illustrates typical RMSEs obtained with CARABAS SAR and Laser scanning; as a comparison results for aerial photo interpretation and satellite image based estimates are also given. The results are from the estate Remningstorp in southern Sweden.

Table 1. Results regarding estimation of stem volume at stand level, from different tests at the estate Remningstorp in southern Sweden.

Sensor	**RMSE (%)**
Satellite remote sensing estimates using Landsat or SPOT	23 – 31
Visual interpretation of aerial photos in photogrammetric instruments	18 – 24
CARABAS VHF SAR	19
Laser scanning	12

In year 2003, the first semi-operational large area laser scanning inventory for forestry purposes was carried out in co-operation between SLU and the regional forestry board in Gävleborg-Dalarna.

Also, research on laser scanning at singletree level has been intensive. In this area, SLU in Umeå is cooperating with the Swedish Defence Research Agency, FOI. Results using 5 laser pulses / m^2 include detection of over 70 % of all stems in coniferous stands, representing over 90 % of the stem volume, measurement of tree height and canopy diameter with 0,6 m RMSE, and separating spruce from pine with 90 % accuracy.

A PhD thesis in laser scanning of forest resources by Johan Holmgren at SLU in Umeå was finalised in September 2003. At the same occasion, SLU, in co-operation with NLH in Norway and FGI in Finland, arranged ScandLaser, which was the first international Forestry laser scanning meeting in Europe. ScandLaser is documented in a proceedings volume and selected articles are printed in a special issue of Scandinavian Journal of Forest Research (no 6, 2004).

In the area of single tree detection using high resolution optical imagery, a thesis was finalised 2004 by Mats Eriksson at the Centre for image analysis at SLU in Uppsala. At SLU in Umeå, the template matching approach for single tree detection has been implemented and improved. About 2/3 of the stems can be detected using this method and we hope to use it in for example imputation.

The Swedish National Land Survey did during 2004 acquire a Z/I DMC digital mapping camera. In an early test with imagery from October 2003, spruce, pine and deciduous could be automatically separated with an accuracy of 90 %, using colour information on single tree level.

Finally, an interesting development using small, unmanned, airplanes for various kinds of local level aerial surveys has been on-going during the last years at SLU in Umeå. Potential applications involve surveys of pre-commercial thinning requirements and assessments of the impact of wind-throw events.

Forest management planning

In Sweden, research in forest management planning is mainly performed at SLU and at the Forestry Research Institute of Sweden (SkogForsk). An exception is, however, the research conducted concerning operational (short term) planning and transportation logistics at the University of Linköping.

In December 2004, a major research programme, Sustainable Forestry in Southern Sweden (SUFOR) was concluded. SUFOR was a joint programme between SLU and a number of universities in southern Sweden. The main goal was to show how a high biodiversity, a better forest health and a sustainable production can be combined with profitable forestry. Projects concerning e.g., soil factors, risk of wind damages (the WINDA model) and root rot were included. A management simulator, "the Time Machine" was developed applicable on stand and estate level but also used for projection of forest landscape developments.

The current major research programme dealing with forest management planning in Sweden is the Heureka programme, aiming at the development of a new generation of analysis and planning tools. The programme has been running since 2000 and ends its first phase in September 2005. Heureka develops four applications for different users and problem areas, namely:

1) National and regional (sub-national) analyses as a basis for policy making by authorities, forest organizations and environmental agencies.
2) Long term planning at forest companies.
3) Operational (short term) planning at forest companies, forest owners' associations, etc.
4) Management planning for non-industrial private forest owners.

The first application is intended to be a successor of Hugin and the second one is likely to replace Indelningspaketet. The operational planning application, for which SkogForsk is responsible, should be closely linked to the long term planning application. In all applications, except the operational planning application, the development of the tree cover makes up the core. Linked to the tree cover, different other models are attached in order to predict the conditions for other goods and services, such as biodiversity and recreation.

The projections can easily be linked to an optimisation software. The system design and programming started from scratch; the development environment is "dot-net" and the programming language C#. Within Heureka, a number of models necessary in multi-purpose forest management planning systems have been developed or are under progress. New functions for individual tree growth, functions for below ground tree biomass, habitat models, and recreation models have been developed. Decay functions for dead wood, root rot models, correction factors for growth due to climate change, and models describing actions taken by forest owners are under progress.

The SLU part of SUFOR was performed at the Southern Swedish Forest Research Centre in Alnarp. This department also participates in Heureka and experience and models from the "Time Machine" will be transferred to Heureka. The Department of

Forest Products and Markets in Uppsala deals with models for the behaviour of private forest owners, and the implications for forest management. A major department at SLU performing forest management planning research is the Department of Forest Resource Management Planning and Geomatics in Umeå. Here, a number of projects are ongoing. "Carbon management", i.e. the use of forests for timber production, bio-fuel production for substitution of fossil fuel, and sequestration of carbon in forests and products, is studied. Part of this research is done in co-ordination with INRA, France. Another research area is spatial problems related to nature conservations aspects and its related optimisation problems. Forest management planning has typically been structured in a hierarchical manner, subdivided into strategic, tactical and operational planning. One project is looking at the possibility to integrate the first two levels of this sequence. Optimization problems linked to the Heureka development are studied and, e.g., the applicability of the commercial optimization software AIMMS, is investigated.

Publications

Below, a list of publication for the period 2000-2004 from SLU, Dept of Forest Resource Management and Geomatics, is included. Note that this list does not involve all relevant literature in the field of forest inventory and forest management planning. Further, unfortunately the references are not always complete, and thus the interested reader in those cases is referred to the author in order to obtain the complete reference or a reprint.

Abebe, T.	2003	The Influence of Selective Logging on Residual Stand and Regeneration in a Tropical Rain Forest in Southwestern Ethiopia. ISBN 91-576-6345-9
Abebe T. & Holm S.	2003	The Effect of Commercial Selective Logging on a Residual Stand in Tropical Rain Forest of South-western Ethiopia Journal of Tropical Forest Science
Allard, A.	2003	Detection of Vegetation Degradation on Swedish Mountainous Heaths at an Early Stage by Image Interpretation Ambio
Allard. A, Nilsson, B., Pramborg, K., Ståhl, G. & Sundquist, S.	2003	Instruktion för bildtolkningsarbetet vid Nationell Inventering av Landskapet i Sverige, NILS
Anerud E.	2003	Kalibrering av ståndortsindex i beståndsregister - en studie åt Holmen Skog AB. SLU-SRG-AR--105—SE Arbetsrapport
Belyaev, Y.	2000	On the accuracy of discretly colored maps created by classifying remotly sensed data.
Belyaev, Y.K and Sjöstedt-de-Luna, S.	2000	Weakly approaching Sequences of Random Distributions. Journal of Applied Probability.
Belyaev, Y.K.	2000	Unbiased Estimation of Accuracy of Discretely Colored Digital Images. Theory of Stochastic Processes. To be published in a special issue of the journal devoted to 70th birthday of Skorokhod A.V.), pp. 12.

Belyaev, Yu. K.	2002	On Accuracy of Classifiers and Related Digital Discretely Colored Images. Theory Probability and Math. Statist., 66, pp.23 - 34.
Belyaev, Yu. K.	2002	Comment to the paper "Some Cracs in the Empire of Chance" by Singpurwalla N. D. International Statistical Review, 70, 1, pp.53-78.
Belyaev, Yu. K. and Seleznjev, O. V.	2000	Approaching in Distribution with applications to Resampling of Stochastic Processes Scand. Journ. of Statistics, 27, No 2.
Berg Lejon, S.	2003	Studie av mätmetoder vid Riksskogstaxeringens årsringsmätning. SLU-SRG--AR--110—SE
Boman, M., Mattsson, L., Fransson, J. och Gong, P.	2001	Naturturism i Norrlands inland och fjälltrakter - Deskriptiva resultat från en fallstudie. Arbetsrapport 302, Institutionen för skogsekonomi, Sveriges Lantbruksuniversitet, Umeå, 2001.
Bååth, H., Gällerspång, A., Hallsby, G., Lundström, A., Löfgren, P., Nilsson, M. & Ståhl, G.	2000	Metodik för skattning av lokala skogsbränsleresurser. ISRN SLU-SRG-AR--65—SE
Bååth, H., Gällerspång, A., Hallsby, G., Lundström, A., Löfgren, P., Nilsson, M., and Ståhl, G.	2002	Remote sensing, field survey, and long-term forecasting: an efficient combination for local assessments of forest fuels. Biomass & Bioenergy 22: 145-157.
Bååth H. ,Eriksson B. ,Lundström A, Lämås T. ,Sundquist S., Persson J-A, Johansson, T	2004	Internationellt utbyte och samarbete inom forskning och undervisning i skoglig mätteknik och inventering. 1401-1204 SLU-SRG--AR--129--SE Arbetsrapport
Chikumbo, O.	2001	Multi-catchment Forest Harvest Scheduling for the Eden Management Area in Australia. Volume 4 of the MODSIM 2001 Proceedings, International Congress on Modelling and Simulation, 10-13 December 2001, The Australian National University, Canberra, F. Ghassemi, D. White, S. Cuddy and T. Nakanishi (eds), Published by the Modelling and Simulat
Chikumbo, O. and Bradbury, R.	2001	A Comparison between Regional and Multi-catchment Forest Harvest Scheduling. Volume 4 of the MODSIM 2001 Proceedings, International Congress on Modelling and Simulation, 10-13 December 2001, The Australian National University, Canberra, F. Ghassemi, D. White, S. Cuddy and T. Nakanishi (eds), Published by the Modelling and Simulat
Chikumbo, O. and Davey, S.	2001	Use of Models in Ecologically Sustainable Forest Management and Decision-Making. Volume 4 of the MODSIM 2001 Proceedings, International Congress on Modelling and Simulation, 10-13 December 2001, The Australian National University, Canberra, F. Ghassemi, D. White, S. Cuddy and T. Nakanishi (eds), Published by the Modelling and Simulat

Chikumbo, O., Spencer, R.D., Turner, B.J. & Davey, S.M.	2001	Planning and monitoring of forest sustainability: an Australian perspective. Australian Forestry 64(1), pp. 1-7, 2001.
Dahlberg, U.	2001	Quantification and classification of Scandinavian mountain vegetation based on field data and optical satellite images. ISBN 91-576-5581-2 ISSN 1401-0070 ISRN SLU-SRG-R--12—SE
Dahlberg, U. and Vencatasawmy, C.P.	2001	Biomass of mountain vegetation in optical satellite data. Skograektarritio (Icelandic Forestry association) 1, 151-155.
Dettki, H. & Bodenhem, J.	2002	Utvärdering av fjärranalysmetoder för att förbättra effektivitet i urvalsförfarandet av ungskogsbestånd inom den enkla ÄlgBetningsINventeringen (ÄBIN). Rapport Nr 7 2002. Skogsstyrelsens förlag, Jönköping.
Dettki, H. & Edenius, L.	2001	Animal movement and habitat use estimates for moose Alces alces from GPS tracking and satellite images. In: Proceedings of the Conference 'Tracking Animals with GPS', eds. Angela M. Sibbald & Iain J. Gordon, The Macaulay Institute, Craigiebuckler, Aberdeen, UK. Pp. 21-22.
Dettki, H. & Wallerman, J.	2004	Skoglig GIS- och fjärranalysundervisning inom Jägmästar- och Skogsvetarprogrammet på SLU. - En behovsanalys. ISRN SLU-SRG-AR--122—SE
Dettki Holger,Esseen Per Anders	2003	Modelling long-term effects of forest management on epiphytic lichens in northern Sweden Forest Ecology and Management
Dettki H., Löfstrand R. & Edenius L.	2003	Modeling habitat suitability for moose in coastal northern Sweden: empirical vs. process-oriented approaches AMBIO
Egberth, M, Granqvist Pahlen T.,Hagner O, Joyce S, Nilsson M, Olsson H, Reese H, Tingelöf U	2003	Countrywide Estimates of Forest Variables Using Satellite Data and Field Data from the National Forest Inventory Ambio
Egberth M, Granqvist Pahlen T ,Olsson H, Sandström P, Hagner O, Edenius L, Tømmervik H, Hemberg Jougda L, Baer K , Stenlund T & Brandt L-G.	2003	Projekt Renbruksplan 2000-2002, Slutrapport - ett planeringsverktyg för samebyarna Rapport 2003:5 Skogsstyrelsen Rapport 2003:5
Ekström, M. & Belyaev, Y.	2001	On the Estimation of the Distribution of Sample Means Based on Non-Stationary Spatial Data. ISRN SLU-SRG-AR--89—SE
Ekström, M. & Sjöstedt-de Luna, S.	2001	Estimation of the Variance of Sample Means Based on Nonstationary Spatial Data with Varying Expected Values. ISRN SLU-SRG-AR--90—SE
Eriksson B & Walheim M	2003	Fältinstruktion 2003 - RIS Riksinventering av skog Fältinstruktion

Eriksson, L.O. and Lämås, T.	2001	Analysis and planning systems for multi-resource, sustainable forestry - The Heureka research programme at SLU. In: Proceedings from the IUFRO conference "Forest Modelling for Ecosystem Management, Forest Certification, and Sustainable Management Conference", Vancouver, BC, Canada, Aug. 12-17, 2001. pp 81-89.
Eriksson, L.O., Lämås, T, Sallnäs, O.	2000	Swedish efforts for a sustainable, multi-resource forestry. The role of research in management planning. In: Forests and Society: The Role of Research. Vol. 2, Abstracts of group discussions, p. 129. Proceedings from the XXI IUFRO World Congress 2000, 7-12 Aug. 2000, Kuala Lumpur, Malaysia.
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Eriksson L.O. & Lämås T	2003	Analysis and planning systems for multi-resource, sustainable forestry - The Heureka research programme at SLU Canadian Journal of Forest Research
Eriksson, O. et. al.	2002	Wood supply from Swedish forests managed according to the FSC-standard. ISRN SLU-SRG-AR--94—SE
Eriksson M & Olofsson K	2004	Comparison of Three Individual Tree Crown Detection Methods. 1401-6230 91-576-6704-7 Acta Universitatis Agriculturae Sueciae, Silvestria
Ericsson, S	2003	Arthandbok fältskiktsarter för nationell inventering av landskapet i Sverige, NILS
Fransson, J. et al.	2002	CARABAS kartlägger stormskador i skogen. Miljöforskning, Nr. 1.
Fransson, J., och Walter, F.	2000	Radar sprider nytt ljus över skogen. Fakta Skog. Nr 8.
Fransson, J.E.S., Frölind, P.-O., Gustavsson, A., Smith, G., Ulander, L.M.H., and Walter, F.	2002	A new remote sensing tool for forestry applications. In Proceedings of RadioVetenskap och Kommunikation 02, Stockholm, Sweden, 10-13 June, 2002, pp. 244-248.
Fransson, J.E.S., Frölind, P.-O., Gustavsson, A., Smith, G., Ulander, L.M.H., and Walter, F.	2002	Introducing VHF SAR data in forestry applications. In Proceedings of ISPRS 2002 Conference, 29th International Symposium on Remote Sensing of Environment, Buenos Aires, Argentina, 8-12 April, 2002.
Fransson, J.E.S., Gustavsson, A., Ulander, L.M.H., and Walter, F.	2000	Towards an operational use of VHF SAR data for forest mapping and forest management. In Proceedings of IGARSS'00 Symposium, Taking the Pulse of the Planet: The Role of Remote Sensing in Managing the Global Environment, Honolulu, Hawaii, 24-28 July, 2000, pp. 399-401.

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Team Report from Agricultural University of Norway, Department of Ecology and Natural Resource Management

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1. Introduction

The Department of Ecology and Natural Resource Management (INA) is dealing with:

- Biology and ecology
- Natural resource management
- Forest science

The Department was founded in September 2003 through a merger of the Department of Biology and Nature Conservation and Department of Forest Sciences. The present areas of activity of the department are:

- Graduate teaching
- Postgraduate teaching
- Research
- Continuing education
- Public relations

The department has Bachelor programmes in Ecology and Nature Management, in Environment and Natural Resources and in Forest, Environment and Industry, while Master programmes are provided in Environment and Natural Resources, in Nature Management, in Ecology, in Forest Business and in Forest, Environment and Industry. Totally there are about 300 students.

The staff of the department comprises about 35 permanently employed academic persons, about 40 temporally employed academic person and about 15 technical and secretarial persons. A total of approximately 90 man-labour years is performed. The budget is about 50 Mill. NOK per year. The output for 2003 comprise about 50 publications in international scientific series with referee, 65 MSc theses / graduates at MSc level and 10 *Dr.* Scient. degrees (PhD level).

At present there are 8-10 persons at the department working with subjects related to inventory, planning and biological modelling in forestry. The following subjects are dealt with;

1. Resource inventories
   Inventory, sampling
   Mapping sciences, GIS, photogrammetry

Remote sensing
2. Management planning
Valuation of forest and environmental goods
Large-scale forestry scenario modelling
Long-term harvest- and investment analyses
3. Biological modelling
Tree growth models
Recruitment and natural mortality
Growth simulators

2. Research findings

2.1 Resource inventories

A relatively large number of projects within the field of resource inventories have been completed over the last years. They have partly been related to the development of inventory methods where new technology, i.e. airborne laser scanners, digital photogrammetry/image matching and GPS, have been applied, and partly related to development and evaluation of more traditional field inventory methods.

In particular inventories by means of airborne laser scanning have been paid much attention. In addition to the development and testing of methodology for practical inventories of large areas, efforts have been made to 1) investigate the effect of flying altitude on the accuracy of such laser-based stand inventories, 2) to assess assessing the accuracy of growth predictions based on multitemporal laser datasets, and 3) to assess the accuracy of diameter distributions derived from airborne laser data.

2.1.1 Testing practical inventories for large areas based on laser-scanning

Airborne scanning lasers with the ability to collect height measurements of the terrain and the vegetation from strips with a width of up to several hundred meters on the ground, were for the first time tested in forest measurements in the mid 1990s. The first studies indicated that laser technology could be used for wall-to-wall mapping in forest inventories. Over the last five years, practical procedures for large-area, stand-based forest inventories based on laser-scanning that complies with the data requirement in forest management planning, have been developed and tested in Norway and Sweden. These tests have been performed in study areas with a size of up to 6500 ha. The procedure developed in Norway is now implemented in six operational commercial projects. The largest project covers a total area of 490 km^2. It is of high importance to assess whether the results obtained from scientific projects in smaller areas are valid even in areas 5-10 times larger than what has been considered so far.

The major results from an evaluation of the first operational stand-based Nordic forest inventory using airborne laser scanner data is now completed. Laser data from a forest area of 250 km^2 were used to predict six stand variables. The predictions were based on regression equations estimated from 250 m^2 field plots distributed systematically throughout the forest area. Test plots with an approximate size of 0.1-0.4 ha were used for validation. The testing revealed standard deviations between ground-truth values and predicted values of 0.36-1.37 m (1.9-7.6%) for mean height, 0.70-1.55 m (3.0-7.6%) for dominant height, 2.38-4.88 m^{2}ha^{-1} (7.8-14.2%) for basal area and 13.9-45.9 m^{3}ha^{-1} (6.5-

13.4%) for stand volume. No serious bias was detected. To conclude, this testing is a confirmation that the practical laser-based procedure used to inventory forest stands is able to provide precise estimates of stand-level variables used in forest planning. It is also the first demonstration in any Nordic country that the method can provide robust stand-level estimates also when it is applied in operational projects in a forest area covering hundreds of square kilometres.

2.1.2 Photo interpretation versus laser scanning by means of cost-plus-loss analyses

Evaluations of inventory methods often end when precision and bias are quantified. Additional information on the appropriateness of a method may be provided through cost-plus-loss analyses, where the total costs are calculated as the sum of NPV-losses, i.e. expected economic losses as a result of future incorrect decisions due to errors in measurements, and inventory costs. A study, where the aim was to compare inventories of basal area, dominant height and number of trees ha^{-1} based on photo interpretation and laser scanning from two sites by means of cost-plus-loss analyses, has been performed. In average for the two sites, the inventory costs, NPV-losses and total costs for photo interpretation were about 6 EUR ha^{-1}, 49 EUR ha^{-1} and 54 EUR ha^{-1}, respectively, while they were 11 EUR ha^{-1}, 13 EUR ha^{-1} and 25 EUR ha^{-1} for laser scanning. The data used for the comparison were limited to two sites and 77 stands, and certain simplifying assumptions were done in the cost-plus-loss analyses. Still, it is reason to believe that the results of the study are of general validity with respect to the main conclusion when comparing the two methods.

2.2 Management planning

Many of the activities within management planning are closely connected to large-scale forestry scenario modelling and analyses. A continuous work with the purpose of enhancing existing models (i.e. GAYA-JLP and AVVIRK-2000) is going on, along with large-scale scenario analyses at different geographical levels and for different purposes. A new field has also been opened over the past few years since an increased attention has been drawn to uneven-aged forests and selective cutting regimes. The department has initiated several projects related to the planning and accomplishment of such treatments.

2.2.1 Testing AVVIRK-2000 by means of successive inventories on a forest property

Modellers of large-scale forestry scenario models face numerous challenges. Information and sub-models from different disciplines within forestry, along with statistical and mathematical methodology, have to be considered. The individual biological sub-models (i.e. models for recruitment, growth and mortality) applied in large-scale forestry scenario models are in general well documented and extensively evaluated. However, evaluations by means of full-scale comparisons of observed and predicted values for continuous forest areas, where the totality of the large-scale forestry scenario model including interactions between sub-models and other parts of the model, are considered, have rarely been seen.

The aim of a recently completed study was to test the totality of AVVIRK-2000, and thereby evaluate the applicability of the model for use in management planning. The test was done by means of successive inventories and accurate recordings of treatments over a period of 30 years for a property comprising 78.5 ha forest-land. Seen in the perspective of management planning, the differences between observed and predicted values for potential harvest level, growing stock and growth were quite small, e.g. a difference between observed growing stock in year 2000 and growing stock in the same year predicted from 1970 of 2.6%. The model may therefore be applied for practical purposes without any fundamental changes of the biological model basis. However, the test should be seen as an example that failed to falsify the model, rather than a final validation. A similar evaluation, based on sample plots from National Forest Inventory and harvest statistics from Hedmark and Nord-Trøndelag counties, has also been initiated. Since the data used in this project is representative for two of the largest forest districts in Norway and comprise a period of 40 years, more certain conclusions with respect to the applicability of the model can possibly be drawn.

2.2.2 Effects of cooperation between properties

The Norwegian forest ownership structure, with many small properties and forest conditions with large heterogeneity in production potential and accessibility, points towards considerations beyond the property boundaries in order to satisfy traditional forest production objectives or more environmentally oriented treatment requirements. Such questions have been raised from different perspectives in two recently completed projects.

In the first project the aim was to analyse how cooperation between properties may provide efficiency gains when certain long-range target levels of old forest area coverage were applied. A case study with 48 properties, where long-range timber production was optimised under different levels of cooperation, was performed. The case study showed that cooperation, in addition to be a necessity to reach feasible solutions with respect to the applied long-range target levels of old forest area coverage, also produced gains in terms of increased net present value. The results also pointed out some additional results likely to be of general validity; the feasibility of certain environmentally oriented requirements normally increases and the potential loss in net present value related to the constraints decreases, when the size of the area under cooperative management increases. The gains of cooperation in terms of increased net present value were in general small, however.

In the second project, the effects of different management levels on long-term non-decreasing harvest paths were studied. The study was based on data from the Norderhov area with 40 000 ha of forest and 458 different forest owners. The property sizes varied from less than one ha to more than 2000 ha. The results indicated that the difference with respect to the overall harvesting level was small, when comparing the potential harvest calculated at the property level with the potential harvest calculated at the regional level. The net present value increased by 1.6% when the calculations were done at the regional level. This result indicates that “the costs of the Norwegian property structure” is low.

2.2.3 Assessing forest areas suitable for selective cuttings by means of stand indices

Even-aged forest management with clear cutting and artificial regeneration has been the dominating silvicultural regime in Norway for 50-60 years. Although such a

management regime is expected to dominate also in future, the past few years has seen an increased attention drawn to uneven-aged forests, selective cutting regimes and natural regeneration. This increased interest is partly due to expected enhancements for landscape aesthetics and biodiversity, and partly to expected benefits for regeneration costs, timber quality and profits.
This change of focus requires the department to face new challenges across the entire range of forestry-related disciplines. The department has over the past few years contributed with a significant portfolio of projects related to selective cuttings, e.g. in sampling, growth, simulations and planning. One of the basic challenges is related to the assessment, i.e. quantification, localization and prioritisation, of forest areas suitable for selective cuttings. In a recently finished project such an assessment has been approached by means of a stand-level index describing the suitability for selective cuttings.

Indices have frequently been used in forestry to describe landscape aesthetic values and biodiversity. Many of these indices have been formulated mainly on a theoretical basis, and often require more data than can be collected for practical managerial decision-making. A simplification was necessary, first of all to reduce inventory costs, but also to make the concept applicable to practical forest management. The developed index comprised different sub-indices describing diameter diversity, growth potential, stability and conditions for natural regeneration. High values for the final Selective Cutting Index (SCI) indicate forest conditions where selective cutting is likely to be successful. SCI can be used for managerial decision-making at the stand level, to quantify potential areas suitable for selective cutting, to study changes in suitability for selective cuttings over time and as an integrated part of growth simulators in order to control silvicultural treatments in projections. In a case study, based on data from the National Forest Inventory, 6.2% of the Norwegian forest area was classified as “suitable” and 9.5% as “probably suitable” for selective cutting.

2.3 Biological modelling

The department has traditionally been working with inventories, planning and economic analyses related forestry. Over the past five years quite a lot of efforts have also been done in modelling stand growth and dynamics. This work has mainly been induced as a result of detecting obvious "biological knowledge gaps" when dealing with management planning and economic analyses. The modelling includes all phases in forest development, i.e. recruitment, mortality and growth, and comprises Nordic boreal as well as tropical conditions.

2.3.1 Recruitment and natural mortality

The recruitment part of the stand dynamics is crucial for long-term and large-scale forestry scenario models and analyses. A study where the aim was to develop recruitment models for application in a large-scale forestry scenario model has recently been finished. Models were developed for Norway spruce, Scots pine, birch and other broadleaves based on the permanent sample plots of the National Forest Inventory. Recruitment can be a stochastic event with two outcomes, and a two-stage modelling approach was applied. The probability of recruitment was estimated in a first stage, and a conditional model for the number of recruits was developed in a second. Variables describing location, site conditions and stand characteristics all had significant influence on the models. Provided the generally high level of uncertainty connected to large-scale forestry scenario analyses and the stochastic nature of recruitment, the models seems to give satisfactory levels of accuracy. The models are applicable to even-aged and uneven aged forests as well as forests with mixed and pure species composition, and they include independent variables directly or indirectly available from forest inventories for practical forest management planning.

In addition, recruitment models for Norway spruce, Scots pine, birch and other broadleaves in young even-aged forests has been developed. Also these models were developed from permanent sample plots established by the National Forest Inventory, and a similar two-stage modelling approach as described above was applied.

Also models for predicting natural mortality in even-aged stands have been developed. These models relied on data from the Norwegian National Forest Inventory, and were designed for use in large-scale forestry scenario models. A two-step modelling strategy was applied: i) logistic regression models predicting the probability of complete survival to occur, and ii) multiplicative regression models for stem number reduction and diameter calibration. A joint model for all species predicting the probability of survival to occur on a plot was developed. Separate models for spruce, pine and broadleaved-dominated forests were developed for stem number reduction, while no appropriate models for diameter calibration were found. Mortality as phenomenon is a stochastic, rare and irregular. This was reflected in the models as low R^2 and high RMSE. However, the model performance appeared logical and the results of validations based on independent data were reasonably good. With new rotations of permanent sample plots, the models should be evaluated and, if necessary, revised. These models are now applied in GAYA and AVVIRK-2000. A similar work, developing models for individual trees adapted to selective cuttings, has been done previously.

2.2.2 Growth simulations based on models for individual trees

Ecological and economical consequences of different management regimes may be analysed with growth simulators. In Norway, several growth simulators have been developed from area based models, and they have frequently been used to analyse even-aged forest management regimes. Area based models are, however, not well suited for analyses of uneven-aged forest management. The main reason is that growth simulators that rely on area based models use the stand as decision unit, while uneven-aged forest management requires each individual tree or size class to be the decision unit. A prototype growth simulator based on models for individual trees have been developed in order analyse different consequences of uneven-aged forest management. The simulator predicts growth and mortality for each individual tree or size class for four different species groups (Norway spruce, Scots pine, birch and other broadleaves). Number of trees recruited to the smallest size class is predicted with a two-stage recruitment model. Expected revenues and net present value from timber production are calculated with gross value functions while harvesting and forwarding costs are calculated with cost functions.

All sub-models included in the simulator are based on variables directly or indirectly available from practical forest inventories. The growth simulator offers a great potential for risk analyses, since the mortality models as well as the recruitment model can be used stochastically. It is therefore reason to believe that this growth simulator will improve forest management analyses of uneven-aged forests in Norway, and hence be a valuable tool for development of practical management prescriptions for uneven-aged forests.

2.4 Biological modelling under tropical conditions

The basic models for describing forest conditions (e.g. volume- or biomass equations) or forest dynamics under tropical conditions are quite often inadequate or not available at all. The Department has over the past years been involved in several projects related to biological modelling under tropical conditions. Two of these projects are shortly described here.

A density-dependent matrix model has been constructed for the dry woodlands of Uganda based on material collected from 42 permanent sample plots with 7904 trees. The matrix model was based on sub-models for individual tree growth and mortality, and area-based recruitment, with explicatory variables representing tree size, stand density and stand structure. The trees were grouped into three species groups based on ecological and morphological criteria. For all groups, parameter estimates for tree size and stand density were found highly significant in predicting diameter growth and mortality, except stand density for the upper storey species group, while stand structure was found highly significant only for the intermediate storey species group. Recruitment was modelled by a two-stage approach. Parameter estimates for a logistic model predicting the probability of recruitment were statistically significant only for the intermediate storey species group. No appropriate conditional models for number of trees could be built for any species group. The evaluation of the models revealed a generally high level of uncertainty. It was still concluded that the matrix model is a reliable and fairly accurate tool for prediction of growth of dry woodland trees in Uganda. The model may become a useful tool for a sustainable management of these woodlands, which are an important source of bio-energy for consumers in several urban centres.

It is well known in the Nordic countries that a quantitative measure of the timber production potential of a given site may be provided by site index equations. Such equations predict site index at a reference age from height and age information of a forest stand. In a project performed at the department data from permanent sample plots laid down in even aged stands of <u>Tectona grandis</u> in six states of India were used to develop such site index equations. Site index curves with dominant heights in the 11 to 28 m range at a reference age of 25 years were developed.

3. Ongoing projects

At present there are 11 research projects related to inventories, management planning and biological modelling going on at the department. Among these 3 projects are within the field of resource inventories, 5 within planning and 3 are within biological modelling.

3.1 Resource inventories

Project title: Practical methods for assessing diameter distributions in forest stands by means of airborne laser scanning
Leader: Erik Næsset
Co-workers: Terje Gobakken
Time frame: 2004-2005

Project title: Forest inventories in mixed forest by means of airborne laser scanning
Leader: Erik Næsset
Time frame: 2004-2005

Project title: Using inventory data in timber trade -methods for assessing timber quality
Leader: Erik Trømborg
Co-workers: Tron Eid, Terje Gobakken, Erik Næsset
Cooperation: Prevista A.S.
Time frame: 2004-2005

3.2 Management planning

Project title: Forest planning and economics in open wood-lands in Uganda (Ph.D)
Leader: Ole Hofstad
Co-workers: Justine Namaalwa, Prem Sankhayan, Tron Eid
Time frame: 2002 – 2005

Project title: Developing a management model for un-even-aged forest (Ph.D)
Leader: Erik Næsset
Co-workers: Ole Martin Bollandsås
Time frame: 2003-2006

Project title: Assessing areas suitable for selective cuttings
Leader: Tron Eid
Co-workers: Nils Lexerød
Cooperation: Glommen and Mjøsen Associations of Forest Owners
Time frame: 2003-2005

Project title: Evaluating large-scale forestry scenario models by means of National Forest Inventory data and harvest statistics
Leader: Tron Eid
Co-workers: Kåre Hobbelstad
Cooperation: Hedmark and Nord-Trøndelag county

Time frame: 2003-2004

Project title: Valuation of forest land – www-application
Leader: Terje Gobakken
Co-workers: Asbjørn Svendsrud
Time frame: 2004

3.3 Biological modelling

Project title: Growth models for use in large-scale forestry scenario models (Ph.D)
Leader: Tron Eid & Hans Fredrik Hoen
Co-workers: Nils Lexerød
Time frame: 2001-2005

Project title: Bio-economic models for joint production of forest and moose
Leader: Ole Hofstad
Co-workers: Hilde Hvam, Prem Sankhayan
Time frame: 2001-2005

Project title: Modelling forest for ecological and economical management
Leader: Terje Gobakken
Time frame: 2002-2005

4. Publications 2002-2004

4.1 Resource inventories

2002

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Næsset, E. 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. Remote Sensing of Environm. 80:88-99.

Næsset, E. 2002. Determination of mean tree height of forest stands by means of digital photogrammetry. Scandinavian Journal of Forest Research 17: 446-459.

Næsset, E. & Jonmeister, T. 2002. Assessing point accuracy of DGPS under forest canopy before data aquisition, in the field and after postprocessing. Scandinavian Journal of Forest Research 17: 351-358.

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Næsset, E. 2002. Ressursregistrering med flybåren laser-scanner - snart virkelighet. Norges landbrukshøgskole, Institutt for skogfag, Aktuelt fra skogforskningen, 3/2002: 35-38.

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Eid, T. 2003. Registreringer i Aas skog - skogtilstand i år 2000 og utvikling fra 1960 til 2000. Oppdragsrapport fra Skogforsk 8/03: 1-24 s. (In Norwegian.)

Gobakken, T. & Næsset, E. 2003. Determination of tree size distribution models in mature forest from laser scanner data. In: Hyyppä, J., Næsset, E., Olsson, H., Pahlen, T. G. & Reese, H. (Eds). Proceedings of the Scandlaser Scientific Workshop on Airborne Laser Scanning of Forests, 3-4 September 2003, Umeå. Swedish University of Agricultural Sciences, Working Paper 112, pp. 71-77.

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4.2 Management planning

2002

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Country Report from the National Forest Inventory in Norway 2001-2004

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County reports

Inventory of individual counties will be carried out over a 15 year period, divided into three groups. Totally there will be published separate reports for 17 counties.
Data for the first 6 counties was collected during the period 1995-1999. These counties were Østfold, Akershus, Hedmark, Aust-Agder, Vest-Agder and Nord-Trøndelag, and the reports were published in 2001. The second group of counties will be assessed 2000-2004, the last one 2005-2009.

For Vest-Agder County a detailed report has been worked out in cooperation with regional forest authorities. This publication also includes results from long-term harvesting scenarioes.

New attributes in the NFI

Every 5 years, or at the beginning of each inventory cycle, a main revision of the instructions for field work will take place. Still there may also be made some changes to the instructions at other times. In 2001 and 2002 the following attributes were included or redefined:

-coverage of bilberry plants (redefined)
-humus type
-thickness of humus layer
-occurrence of charcoal in humus layer
-natural regeneration of introduced tree species
-distance from tree of origin to natural regeneration of introduced species

2004 was the last year of the 8th inventory cycle. A rather extensive revision of the contents of the NFI will take place before start-up of the 2005 season

Environmental assessments integrated in the NFI

A methodology for assessment and mapping of habitats (MIS) has been developed for use in forestry management planning. The same type of assessment has now been implemented on NFI sample plots. Representative data on occurrences of specific habitats will provide a tool for evaluating value and a further need of consideration for the habitats. Preliminary results from the study are expected in late 2004/early 2005.

A separate project has been defined on extended assessments of tree species with limited occurrence in Norway. This is expected to facilitate monitoring of rare species.

After developing a methodology a pilot project has been evaluated, and the method has been fully implemented in 5 counties.

Miscellaneous

An online database is now allowing user-defined queries, where tables can be downloaded in MS Excel format (***Skog.nijos.no***)

A study has been carried out to estimate forest resources in areas with no significant human impact. The study was based on sample plot data from the NFI and maps from the environmental management agencies, defining areas within a certain distance from roads, built-up areas etc. The effects of planned future road building have also been considered.
There has also been a study on the relation between size of the forest holding and the forest situation. Some conclusions from the study were the following: Higher level of harvesting, more intensive silvicultural activities, and a higher proportion of regenerations at the larger forest holdings.

A case study on roundwood supply to forest industry was based on sample plot data from the NFI. The aim was to assess current and future available quantity of roundwood in the area surrounding a major industrial plant.

Comparison between actual forest situation and results obtained from modelling is still ongoing. By using 40-50 years old NFI data as a starting point, estimates from growth models will be checked against the actual development that have taken place in the forests later on.

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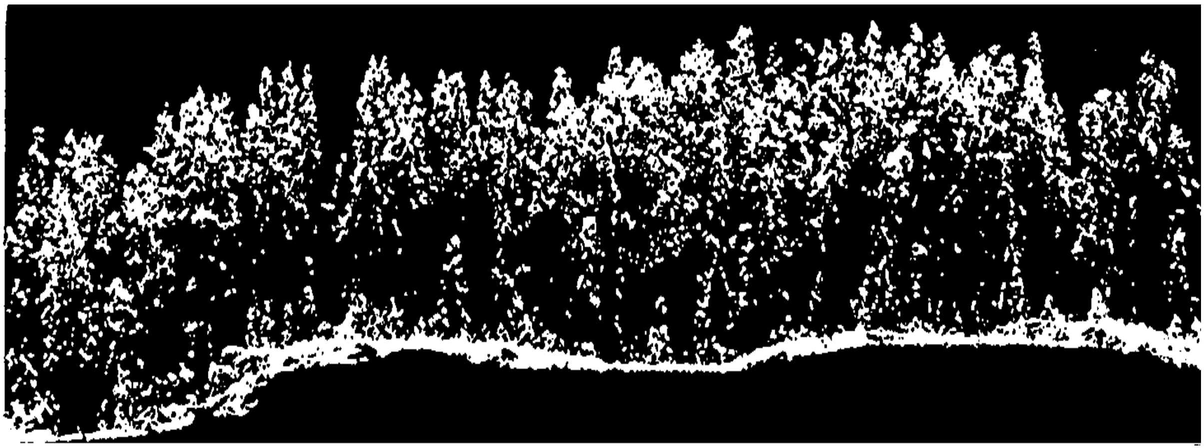
Lidar Measurements in Forest Inventory



Laser illustration of forest profile. Source: Hyyppä & al. Cortesy of Andre Samberg

Measuring Biomass and Carbon in Delaware using an Airborne Profiling Lidar

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Abstract

A portable, inexpensive profiling lidar was used to inventory forests in Delaware, a small state (5,205 km^2) on the mid-Atlantic seaboard of the US. Ground and airborne sampling procedures are described, and large-area inventory results are reported and compared to independent estimates. Systematic airborne lidar profiling measurements were used (1) to estimate forest merchantable volume, biomass, and above-ground carbon statewide; and (2) to estimate impervious surface and open water area. Over 1300 km of laser profiling data acquired along parallel flight lines 4 km apart were analysed. Four explicitly linear models were considered to predict merchantable volume and total above-ground dry biomass. Merchantable volume estimates were within 21% of US Forest Service estimates at the county level and within 1% statewide. Total above-ground dry biomass estimates were within 22% of USFS estimates at the county level and within 16% statewide. Lidar estimates of percent impervious area surface for the three counties - Newcastle, Kent, and Sussex - were 10.9, 3.4, and 2.8% respectively, and 4.7% statewide. Comparable estimates developed using 30m Enhanced Thematic Mapper digital data and mixture modelling were 8.8, 3.5, and 3.9% respectively, and 4.9% statewide. Laser estimates of open water at the county and state level were comparable to 1997 GIS estimates. Open water estimates based on laser transect data showed the 3 counties to have 3.0, 2.0, and 4.6% of their county area covered by water, and 3.5% of the state covered by open water. Comparable 1997 GIS estimates were 2.6, 2.1, 4.8% (county), and 3.5% (state), respectively. The results of the study indicate that Line Intercept Sampling techniques can be used in conjunction with a relatively inexpensive, portable airborne laser system to assess multiple resources regionally.
Keywords: airborne laser profiling, forest biomass, regional forest inventory.

Introduction

In an effort to reduce carbon emissions to mitigate global climate change, efficient sampling procedures need to be developed to periodically inventory standing carbon regionally on a timely basis. To this end, an investigation was undertaken to develop the statistical framework and the associated hardware and software to inventory above-ground forest biomass and carbon remotely. An inexpensive, portable airborne laser system was built from off-the-shelf components (Nelson et al. 2003a) and used to inventory the standing forest biomass and carbon of Delaware, located on the mid-Atlantic seaboard of the eastern United States. The State covers 5,205 km^2; it's dimensions are approximately 150 km N-S, 55 km E-W near the southern end, and 16 km E-W near its northern border. Line Intercept Sampling techniques were employed to convert the systematic, linear airborne laser profiling measurements of forest height, height variability (i.e., the variance of the individual pulse heights within a given segment of laser data), and canopy closure to estimates of merchantable volume, total above-ground dry biomass, and carbon. Transect crossing distances across roofs, asphalt, concrete, and water were delineated using the CCD camera video record and measured to estimate impervious surface area and open water area.

Materials and Methods

Study Area

Three counties comprise the state - Newcastle, Kent, and Sussex. Newcastle County, northernmost of the three and encompassing 1124 km^2, is largely urban and suburban, with rolling topography which ranges from sea level to 137 m above MSL at the Pennsylvania line at the northern tip of the state. Kent County (1542 km^2) and the southernmost county, Sussex (2539 km^2), have a larger agricultural base; the topography is essentially flat. Slightly less than one third of the State is forested, and forest area is distributed fairly evenly across the counties in small, dissected parcels. The state supports coniferous, deciduous, and mixedwood stands. Predominant conifer species include loblolly pine (Pinus taeda L.) and Virginia pine (Pinus viginiana Mill.). The major deciduous species in terms of frequency of occurrence include sweetgum (Liquidambar styraciflua L.), black gum (Nyssa sylvatica Marsh.), various oaks (Quercus spp.), hickories (Carya spp.), yellow poplar (tulip poplar or tulip tree, Liriodendron tulipifera L.), and red maple (Acer rubrum L.).

The University of Delaware (http://www.udel.edu/FREC/spatlab) provided a digital land cover which classifies the state into 44 land cover classes. These land cover classes were delineated on 1992 color-infrared airphotos with a spatial resolution of 1 m. A minimum mapping unit of 1.6 ha (4 acres) were used to build the initial GIS, which was updated in 1997 using B&W, 1m aerial photography. These 44 classes were condensed into eight general land cover types - hardwood (i.e., deciduous), mixedwood, conifer, wetlands, agriculture, residential, urban/barren, and water - and these 8 classes were used to stratify the state.

Airborne Laser Profiler

A small, portable, first-return airborne laser profiling system was built using off-the-shelf components. The system consists of a 2000 hz laser transmitter/receiver, a CCD video camera, a video titler, and video recorder, a differential Global Positioning System (dGPS) receiver, and a laptop computer. The entire system, called PALS (Portable Airborne Laser System) cost approximately $30,000 USD in 1999. The entire sytem fits in two suitcases, and is designed to be bolted onto/into local for-hire aircraft. Generic components, compact size, portability, and low cost drove system design. The system is described in full in Nelson et al. (2003a).

PALS was used to collect ranging data (Figure 1) on 1304 km of systematically located flight transects during the summer of 2000. The State's long axis is oriented N-S; 14 flight lines were oriented parallel to the western boundary of the state every 4 km. Individual data collection runs ranged from 3 to 153 km. At 50m/s (180 kph) in a Bell 206 Jet Ranger, the longest flight transects took approximately 1 hour to complete. With turns, a 5 km run-up at the start of each line, and transit time to/from airports, 2 flight lines could be measured within the safe operational fuel limits of the helicopter. The ~1300 km of flight transect data were acquired in less than two flying days at a cost of $6000 USD.

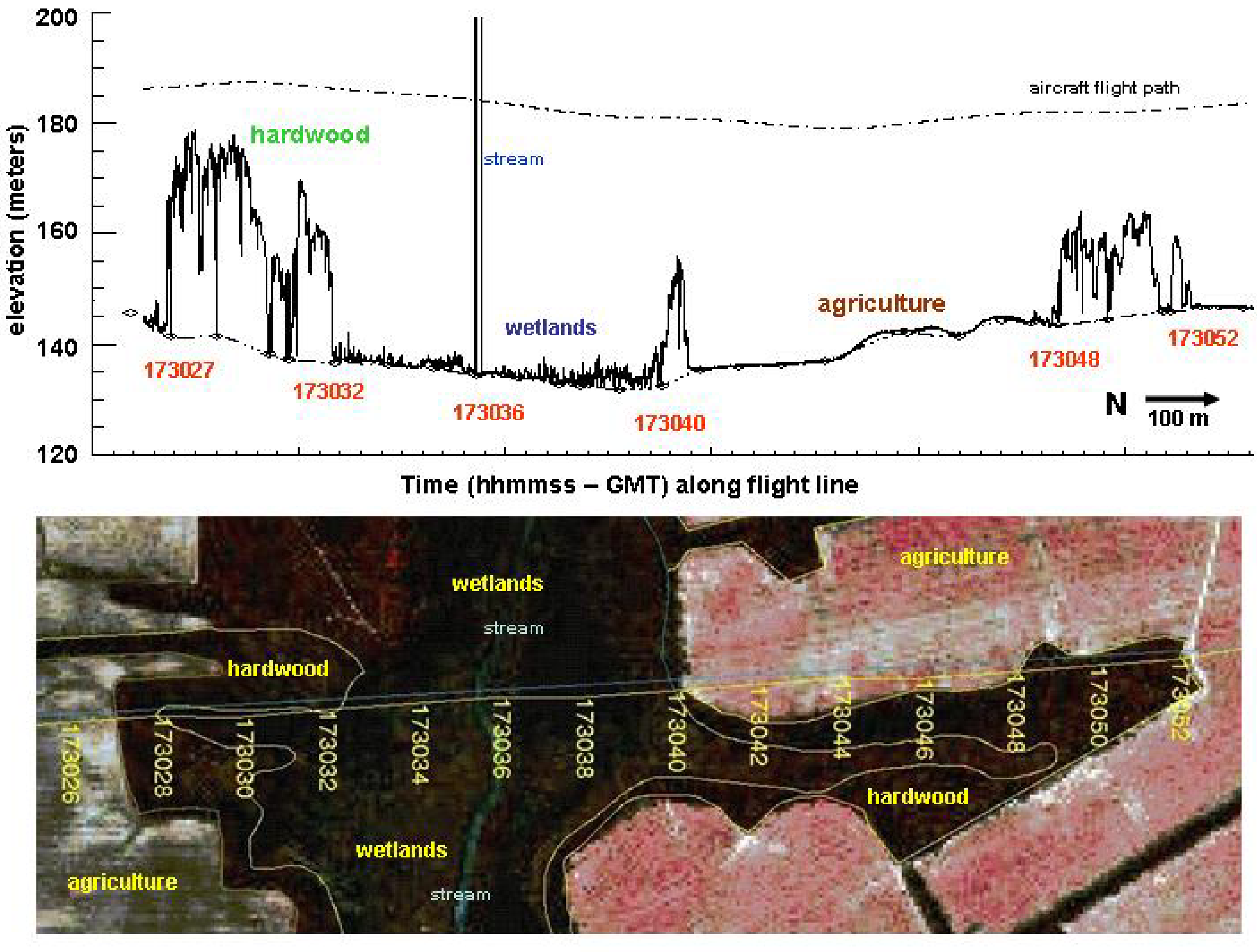

Figure 1. A 1.4 km section of a PALS flight line acquired over Delaware during June of 2000. The dotted line above the laser trace describes the aircraft flight path above mean sea level; that line is negatively offset to fit the flight profile onto the canopy trace. The

nominal flight altitude was 150m AGL (above ground level). A 1992 color infrared photo (archived by the Spatial Analysis Laboratory, University of Delaware) of the flight segment is shown below the laser trace. GMT times (hhmmss) are posted along the actual flight line; each two second interval represents approximately 100m on the ground. The faint blue line just above the actual flight line (yellow) marks the planned flight path.

A LabVIEW front end was written to collect the laser serial stream - range and amplitude - and the differential GPS serial stream. Only one of every 10 pulses was recorded, no pulse averaging was done. At a nominal flying height above ground of 150m, a laser transmitter beam divergence of 1.8 mr, and 10 cm optics, the laser spot size at target was 37 cm. At 50m/s, the system recorded a laser pulse every 25 cm along the flight transect. Post-processing was done to identify the ground line beneath the forest canopy by connecting occasional ground hits with a spline. Once a ground line is defined, heights can be calculated for each pulse, permitting the calculation of tree heights, height variability, and canopy density from the first-return laser ranges. In addition to the ranging meaurements, uncalibrated amplitude measurements, i.e., the brightness of the return pulse on a 0-127 scale, are recorded. The amplitude signal is extremely noisy, but the signal is used to help separate impervious surfaces from grass and forest.

The CCD video camera collects videography coincident with the laser range and amplitude measurements. The Pulnix **TMC**-7 color camera refreshes every other line in the 768 column x 494 line pixel array at 60 hz, effecting a complete refresh every thirtieth of a second. A 16 mm, manually focused and shuttered lens fronts the camera. The focus is set to infinity, and on all but the darkest flights, i.e., dusk or dawn acquisitions, the f-stop was set at f16. Bright afternoon sun with an f11 setting would saturate the camera over bright targets, e.g., concrete, dirt roads. At 150m AGL (Above Ground Level), the system has a field-of-view of 60m along-track x 40 m across-track. At a flight speed of 180 km/hr (50m/sec) the image remains sharp, and individual tree crowns are easily discerned. The color imagery is time-stamped with the dGPS location and time and stored on an 8mm tape recorder. The dGPS location and time recorded in the video stream are coincidently interleaved in the laser data stream so that the two data sources (laser and video) can be easily reconciled. The video imagery is used to delineate impervious surface and open water crossings, and to address any questions which might arise concerning anomalous or out-of-the-ordinary laser profiles.

Line Intercept Sampling on the Ground

A total of 142 - 40 m ground transects were located and measured in 7 of the 8 strata statewide (open water was not sampled). All trees whose crowns were intercepted by a plane vertically projected from the randomly oriented, 40 m transect were sampled. Sample tree location, i.e., distance along and across track, dbh, total height, merchantable height (10cm top), and maximum crown radius perpendicular to the sample transect were noted. The ground data were used to estimate merchantable volume and total above-ground dry biomass per hectare on each transect, as follows:

$$\hat{b} = \frac{10{,}000}{l}\left(\sum_{i=1}^{n}\frac{b_i}{c_i}\right) \qquad (1)$$

where $\hat{b}$ is estimated biomass per hectare on a given sample transect, n is the number of trees
sampled along the ground transect of length l, i.e., 40 m, b_i is the biomass of tree i, and c_i is the crown diameter, i.e., twice the crown radius, of tree i, $i = 1, n$, measured perpendicular to the sample transect (Kaiser 1983, DeVries 1986).

Relating Ground-measured Volume, Biomass to Airborne LiDAR Measurements

In order to calculate estimates of merchantable volume and dry biomass, regressions must be developed which predict these forest measures as a function of measurements acquired by the airborne laser system. Typically in a two-phase sampling scheme, such regressions would be developed by 1) locating a subsample of the airborne laser profiling measurements on the ground, and 2) locating ground sample transects along the flight transects. Ground-based estimates of volume and biomass, then, would be regressed against the laser measurements, and the resultant equations used to estimate the ground measurements of interest across the entire study area.

This study employs a non-standard, two-phase sampling procedure that employs canopy simulation software. The software, described in Nelson (1997), utilizes that data collected from the 142 - 40 m transects described in the section above and simulates the top-of-canopy height structure so that laser height measurements can be deduced from the same data used to estimate volume and biomass. The use of the simulation software precludes the need to accurately locate the airborne laser profiling transects on the ground, a non-trivial exercise given the fact that the PALS system employed (at the time) a relatively imprecise airborne differential GPS good to ±5-10m with no pointing (i.e., aircraft attitude - roll, pitch) information. Simulation has the added advantage of opening up the temporal and spatial sampling window, i.e., ground data can be collected anytime prior to, during, or well after the flight mission and in areas physically removed from the actual flight transects, as long as similar cover types are sampled. The use of such software would make sense in situations where significant sections of the study area are inaccessible, inhospitable (e.g., portions of the Amazon, the central or western Congo, northern Siberia or northern Canada), or dangerous (e.g., the Caucasus, Chechnya, the eastern Congo). Such concerns were not the case in Delaware, however the software was employed to test it within the the sampling framework of a regional inventory. The use of the simulation software has at least one distinct disadvantage, that being the verisimilitude of the canopy reconstruction. To the degree that the simulator does not accurately reconstruct the structural attributes of the top of the forest canopy along the 40 m ground transect, airborne laser-based estimates will be biased. Field verification of the simulator at specific sites in the eastern USA is ongoing.

The PALS dGPS system has recently been upgraded to enable WAAS, the Wide Area Augmentation System, and now aircraft positional information is known to within 1-2 m horizontal and 2-3m vertical within the continental US and parts of Alaska. The WAAS upgrade facilitates ground location of the flight line. This study, done prior to the GPS upgrade, was an initial attempt at a general verification whereby close agreement of laser-based and ground-based regional inventory estimates would suggest an adequate canopy simulation.

The LIS data collected along the 142 - 40 m ground transects (not coincident with any airborne laser measurements) were used to develop canopy height models (CHM) for each of the ground transects. The CHM simulated what the airborne laser profiler would have measured had it flown over the top of the forest canopy directly above the 40 m ground transect (Nelson 1997). Regression models were then developed which predicted ground-measured biomass (or volume) as a function of simulated laser measurements. Generic regressions were developed to predict merchantable volume, as follows:

Model 1: parametric linear regression, non-stratified

merchantable volume: $\hat{v}_{ijk} = (11.60)(\bar{h}_{qc}) - 17.0$, n = 142, $R^2 = 0.68$; (2)

where v_{ijk} is the merchantable volume (m^3/ha) in county i, stratum j, and segment k;

$\bar{h}_{qc}$ is the quadratic mean height (m) of only those pulses in the forest canopy (i.e., the square root of the mean squared height, canopy hits only) along segment k.; and

total above-ground dry biomass: $\hat{b}_{ijk} = (9.07)(\bar{h}_{qc}) - 1.90$, n = 142, $R^2 = 0.66$; (3)

where $\hat{b}_{ijk}$ is the biomass (t/ha) in county i, stratum j, and segment k.

Model 2: nonparametric linear regression, non-stratified

merchantable volume: $\hat{v}_{ijk} = (14.14)(\bar{h}_{qc}) - 75.36$, n = 101; $R^2 = 0.55$; (4)

total above-ground dry biomass: $\hat{b}_{ijk} = (10.09)(\bar{h}_{qc}) - 23.04$, n = 103, $R^2 = 0.45$. (5)

Parametric and nonparametric equations were also developed for five stratified cover types, i.e., hardwood, mixed wood, conifer, wetlands, and nonforest. The nonforest cover type grouped the agricultural, residential, and urban cover types together to facilitate construction of the predictive equations because only 19 of the 51 - 40 m ground transects located in these three nonforest strata contained any trees. R^2 values for the stratified, parametric equations ranged from 0.41 (hardwood) to 0.95 (wetlands). R^2 values for the stratified, nonparametric equations ranged from 0.28 (mixedwood) to 0.89 (wetlands). The variables included in these stratified equations as volume and biomass predictors included squared height values (e.g., quadratic mean height squared, three tallest heights squared) or the quadratic mean height by canopy closure cross-product. These equations, formulated using ground transect data and forest canopy simulation software, were applied to the individual airborne laser segments, stratified by cover type.

Airborne Profiling LiDAR Inventory of Delaware

The basic sampling unit in Line Intercept Sampling is a single sample transect. Measurements (of biomass, for instance) made on objects intercepted along a linear transect can be used to estimate that item of interest acros the entire study area (Kaiser 1983). In this study, the basic sampling unit for estimation of merchantable volume or biomass for a county or state is the flight line. Fourteen flight lines were flown over Delaware in y2000. Estimates of merchantable volume and total above-ground dry biomass are developed for each of the eight land cover strata on each flight line within a county. County estimates are then summed to arrive a the state estimates.

Equations are provided below to calculate total biomass in each stratum for each county and for the state. The Model 1 and Model 2 equations reported in the previous section predict biomass per hectare. These model-based per-hectare biomass estimates are used to estimate the total biomass in a particular stratum, by county, for a given flight line, as follows:

<u>Total biomass for the kth flight line, jth stratum, ith county:</u>

$$\hat{b}_{ijk} = a_i \left[\sum_{s=1}^{n_{ijk}} \left(w_{ijks} \right) \left(\hat{b}'_{ijks} \right) \right] \left[\frac{\sum_{s=1}^{n_{ijk}} l_{ijks}}{\sum_{j=1}^{8} \sum_{s=1}^{n_{ijk}} l_{ijks}} \right] \qquad (6)$$

where

$\hat{b}_{ijk}$ = total biomass (tons) in county i (i = 1,3), stratum j (j=1,8), on flight line k (k=1,n_i),

n_i = number of flight lines which transect county i,

$\hat{b}'_{ijks}$ = biomass per hectare (tons/ha) on the sth segment, kth flight line, for the jth stratum in county i; a regression estimate based on the airborne laser measurements acquired on this segment,

a_i = area (hectares) of county i,

w_{ijks} = weight of the sth segment on the kth flight line in the jth stratum in county i, $= \dfrac{l_{ijks}}{\sum_{s=1}^{n_{ijk}} l_{ijks}}$, and $\sum_{s=1}^{n_{ijk}} w_{ijks} = 1.0$,

n_{ijk} = the number of segments along flight line k in stratum j in county i, and

l_{ijks} = the length, in meters, of the sth segment on flight line k, stratum j, county i.

The quantity in the leftmost square bracket of equation 6 calculates an average biomass per hectare for the k[th] flight line for stratum j in county i. The quantity in the rightmost square bracket of equation 6 provides an estimate, for flight line k, of the proportion of stratum j in county i. Certainly the situation may arise where a particular cover type is not intercepted along a given flight line. Such was the case in this study where, for example, only one of eight flight lines in Newcastle County traversed conifer stands. In this situation, the length of interception for that cover type will be zero, and consequently $\hat{b}_{ijk}$ will be zero. This biomass estimate is a legitimate observation and must be included in stratum, county, and state calculations. Also note that no within-flight line biomass variances can be estimated because the covariance calculations are intractable (DeVries 1986).

Stratum Estimates within County:

For purposes of clarity, let

$L_{i\bullet k} = \sum_{j=1}^{8}\sum_{s=1}^{n_{ijk}} l_{ijks}$, i.e., the length of the k[th] flight line in county i, across all strata., and let

$L_i = \sum_{j=1}^{8}\sum_{k=1}^{n_i}\sum_{s=1}^{n_{ijk}} l_{ijks}$, i.e., the length of all flight lines flown over county i.

biomass (tons) in stratum j, county i::

$$\hat{b}_{ij} = \frac{\sum_{k=1}^{n_i}(w_{i\bullet k})(\hat{b}_{ijk})}{\sum_{k=1}^{n_i} w_{i\bullet k}} = \sum_{k=1}^{n_i}(w_{i\bullet k})\,(\hat{b}_{ijk}) \qquad (7)$$

where $w_{i\bullet k} = \frac{L_{i\bullet k}}{L_i}$ and $\sum_{k=1}^{n_i} w_{i\bullet k} = 1.0$.

variance:

$$\hat{\mathrm{var}}(\hat{b}_{ij}) = \frac{\sum_{k=1}^{n_i}(w_{i\bullet k})(\hat{b}_{ijk} - \hat{b}_{ij})^2}{(n_i - 1)} \qquad (8)$$

and $\mathrm{SE}(\hat{b}_{ij}) = \sqrt{\hat{\mathrm{var}}(\hat{b}_{ij})}$, with 95% confidence limits: $\hat{b}_{ij} \pm t_{n_i-1}^{0.975}\sqrt{\hat{\mathrm{var}}(\hat{b}_{ij})}$

These calculations do not account for the residual error associated with the regression-based estimate of biomass per hectare, i.e., $\hat{b}'_{ijks}$, on each segment within a flight line. The variance formula (eqn. 8), then, underestimates the actual variances of the biomass estimates. Although the contribution of regression error to the overall estimation error is expected to be small (Ståhl, 2004, personal communication), efforts are ongoing to quantify the effects of regression error and to incorporate that and other sources of error into the final variance estimates.

Estimates of biomass per hectare are calculated by dividing the total biomass in stratum j, county i, by the stratum area in county i. Stratum area can be calculated using LIS techniques, or the user can utilize areas reported in the GIS used to stratify the laser pulses initially. Since LIS-based areas are estimates and GIS-based numbers are considered "truth", we suggest that GIS areas be used to convert totals to per-hectare estimates.

County Estimates within State:

total biomass: $$\hat{b}_i = \sum_{j=1}^{8} \left(w_{ij}\right)\left(\hat{b}_{ij}\right) \qquad (9)$$

where $w_{ij} = {a_{ij}}/{a_i}$ *and* $\sum_{j=1}^{8} w_{ij} = 1.0$

a_{ij} = area (hectares) of stratum j in county i,

variance: $$\hat{\text{var}}\left(\hat{b}_i\right) = \sum_{j=1}^{8} \left(w_{ij}^{\,2}\right)\left(\hat{\text{var}}\left(\hat{b}_{ij}\right)\right) \qquad (10)$$

State Estimates:

total biomass: $$\hat{b} = \sum_{i=1}^{3} \left(w_i\right)\left(\hat{b}_i\right) \qquad (11)$$

where: $w_i = {a_i}/{a}$ *and* $\sum_{i=1}^{3} w_i = 1.0$

a = area of the state.

variance: $$\hat{\text{var}}\left(\hat{b}\right) = \sum_{i=1}^{3} \left(w_i^{\,2}\right)\left(\hat{\text{var}}\left(\hat{b}_i\right)\right) \qquad (12)$$

LIS techniques were employed to estimate impervious surface and open water area. PALS videography was used to document start and stop points in the airborne laser data where the flight transects crossed impervious surface or open water. Roof crossings, asphalt/concrete crossings, and water crossings were noted. On a given flight line within a county, estimates of percentage of roof, asphalt/concrete, and water were developed as simple ratios. For instance, the percentage of area under roof in Kent County can be estimated on a particular flight line by dividing the length of roofs intercepted by the total length of the flight line in Kent County. A county roof estimate and the variance of that estimate may be calculated as a weighted mean and variance of the individual flight line estimates. Percentages are converted to area by multiplying these LIS estimates by the county area as reported by the GIS.

Of all of the work done in this project, this documentation of impervious surface and open water crossings was most time consuming. Although simple, the work was labor-intensive. The video record was matched with the laser height and amplitude profiles to identify specific pulses where the particular surface started and stopped. The minimum mapping unit, i.e., the minimum distance considered, was 1 m, or about the width of a typical residential sidewalk.

Accuracy Assessment

The forest inventory estimates were compared with U.S. Forest Service - Forest Inventory and Analysis (FIA) estimates of volume and biomass at the county and state level. The FIA is the US federal agency charged with measuring and monitoring forests nationally, by state, and by county within state. Prior to 2000, the USFS-FIA was mandated to provide decadal updates of the forest resources of each state. They inventoried Delaware forests by measuring 215 systematically located points in 1999. So as not to make allometry an issue, the same allometric equations employed by the FIA in Delaware (Scott 1979, 1981 Wharton & Griffith 1993) were employed in this study to estimate volume and biomass on the laser ground transects.

Laser profiling estimates of impervious surface area were compared with county and state estimates developed by Smith et al. (2003). They used sub-pixel mixture models to deconvolve impervious surface from porous materials in Landsat ETM 30m pixels. Though no accuracy figures are reported for the ETM-based results, this product is the only one available against which laser results could be compared. Laser estimates of open water were compared with the University of Delaware GIS estimates of open water area (http://www.udel.edu/FREC/spatlab, la=August 12, 2004). Although this GIS was used to stratify the airborne laser data into eight different land cover types, it was not used or consulted as laser open-water distances were measured. Rather, the PALS video record was used to determine where along a given laser transect open water was intercepted. The University of Delaware GIS open water estimates, then, are used to validate the PALS open water estimates.

Results

Numerous stratified and non-stratified linear and multiplicative (i.e., log-log) models which related ground-measured volume and biomass to simulated laser measures were developed and cross-validated. Comparison of models developed for Delaware forests indicate that (1) considering all cover types collectively, stratification does not consistently improve accuracy; (2) considering conifer and hardwood models specifically, conifer volume and biomass predictions are significantly more accurate than hardwood estimates; and (3) multiplicative models, e.g., ln(biomass) = b_0 + b_1 (ln($height_{laser}$)), consistently fit better (i.e., have higher regression-R^2 values) but perform worse (i.e., have significantly lower cross-validation R^2) than explicitly linear models.

With respect to comparison of airborne laser estimates to USFS-FIA results, no particular model - stratified versus non-stratified, linear versus natural log models, presence or absence of a y-intercept, parametric versus nonparametric - performed consistently better that the others. Most of the laser models produced estimates that were within 20% of USFS estimates. However, one combination of model characteristics performed poorly with respect to predicting total above-ground dry biomass. Non-stratified logarithmic models, i.e., log-log models where one generic equation was applied to all of the strata, reported laser-USFS differences of 50% to 100%. Stratified log-log models, on the other hand, did as well as both stratified and non-stratified explicitly linear regressions. Based on these findings, laser-based estimates of merchantable volume and total above-ground dry biomass are developed using explicitly linear models, e.g., equations 2-5. Laser-based estimates are compared with USFS-FIA estimates of volume and biomass, by county and state (Table 1).

Table 1. Percent difference between USFS-FIA and airborne laser estimates total merchantable volume and total above-ground dry biomass, by county and state. Non-stratified and stratified results for Models 1 and 2 are compared to USFS-FIA estimates. Model 1 is parametric; model 2 is developed using nonparametric techniques.

Dependent variable	Model	Stratification	Difference (%)*		
			New/Kent	Sussex	Delaware
Merchantable Volume	1	no	21.1	9.4 ‡	14.5 ‡
		yes	14.6 ‡	-3.6 ‡	4.2 ‡
	2	no	7.2 ‡	-5.9 ‡	-0.3 ‡
		yes	6.6 ‡	-13.2 ‡	-4.7 ‡
Total Above-Ground Dry Biomass	1	no	-14.1‡	-17.4	-15.9
		yes	-10.0 ‡	-20.8	-16.0
	2	no	-17.4 ‡	-21.3	-19.6
		yes	-10.5 ‡	-19.6	-15.5

* [(laser-FIA)/FIA] x 100. Negative percentages indicate a laser underestimate.

‡ Laser estimate is within ±2 standard errors of the USFS-FIA estimate.

The FIA combines Kent and Newcastle County results to reduce standard errors of estimate in the smaller counties. Due to the ambiguous nature of the findings regarding the merits of stratification in this study and in studies done by others, both stratified and non-stratified results are considered. It must be noted that, due to differences between FIA - GIS cover type definitions and FIA - laser sampling methods, the FIA and laser estimates of volume or biomass are not directly comparable, i.e., one cannot expect exact agreement. FIA timberland estimates for all Delaware tree species are compared with laser estimates for the four land cover classes considered forested in the University of Delaware GIS - hardwood, mixedwood, conifer, and wetlands.

Although it is certainly arguable as to which of these models is "best" due to the aforement-ioned incompatibilities between FIA and laser estimates, the results in Table 1 indicate that laser- based transect sampling methods can be used to develop large area forest volume and biomass estimates. Laser-based merchantable volume estimates are consistently within 2 standard errors of the USFS-FIA estimates at the county and state level. Laser biomass estimates fall just outside the FIA 95% confidence bounds at the state level, this due to relatively large discrepancies between laser and FIA biomass estimates in Sussex County. The basis for this difference in Sussex County is not known.

Per-hectare estimates of biomass developed using an explicitly linear, nonstratified, parametric model (Model 1 – nonstratified) are combined with areal estimates from the University of Delaware GIS to estimate statewide carbon allocations, by land cover type and county (Table 2). A generic conversion factor of 0.5 is used to convert above-ground dry biomass to carbon (Gower et al. 1997, Houghton et al. 2000; Nelson et al. 2000, Table 2).

Table 2. Airborne LiDAR profiling estimates of above-ground carbon, in thousands of metric tons, by land cover, county, and for the entire state. SE=standard error of estimate.

	Newcastle	Kent	Sussex	Delaware
Hardwood	1250.7	446.0	143.5	1840.1
SE	101.4	88.8	32.5	138.7
Mixedwood	61.8	601.6	2304.5	2968.0
SE	21.6	88.8	159.1	183.5
Conifer	10.7	85.1	484.5	580.2
SE	5.0	37.0	98.3	105.2
Wetlands	364.4	1518.9	2304.7	4187.8
SE	74.5	350.1	253.8	438.6
Forestland	1687.6	2651.6	5237.1	9576.3
SE	127.8	373.8	317.1	506.3
Agriculture	335.9	489.3	782.1	1607.6
SE	52.7	42.1	70.3	96.9
Residential	780.0	326.9	659.2	1766.0
SE	185.7	55.1	84.4	211.4
Urban	234.1	69.9	149.3	453.3
SE	64.4	27.6	27.4	75.3
Nonforest	1349.9	886.3	1590.4	3827.2
SE	203.5	74.4	113.4	245.2
Water	17.6	7.3	18.0	42.8
SE	7.2	2.7	4.7	9.1
Total:	3054.8	3545.1	6846.3	13445.6
SE	240.6	381.0	336.4	562.2

The importance of measuring carbon stores on land cover types that are typically considered "nonforest" is highlighted by the numbers presented in Table 2. Statewide, approximately 28% of the above-ground carbon resides on lands identified as agricultural, residential, and urban areas, approximately half of that (13.1%) in residential areas alone. Approximately one-fourth of Newcastle County (24.3%), an urban/suburban county just south of Philadelphia which includes the large city of

Wilmington, is residential. That residential area collectively supports one-fourth (25.5%) of the County's above-ground carbon.

The variances reported in Table 2 are underestimated. The degree of underestimation is unknown, but may be on the order of 10% (Phillips et al. 2003) or more. The standard errors report Line Intercept Sample variance, i.e., flight line to flight line variability, but the SE calculations ignore other important sources of variation, including:

- ground-laser regression error, i.e., that error associated with uncertainty in the volume and biomass predicted for each airborne laser segment based on airborne laser height measurements;

- laser height errors, i.e., that error associated with imprecise laser measurements of canopy height due to, for the most part, imprecise location of the ground line beneath a forest canopy by the analyst;

- field sampling variance, i.e., that sampling error associated with the ground LIS estimates of volume or biomass along the 40 m ground transects;

- allometric regression error, i.e., that error associated with uncertainty in the per-tree estimate of volume or biomass based on published, species-level allometric equations;

- field measurement errors, i.e., that error associated with imprecise measurement of individual tree diameter (dbh) and height.

Phillips et al. (2003) developed an error budget for a ground-based inventory of a five-state region in the southeastern US and found that sampling error, equivalent to the SE's reported in Table 2, accounted for 90-99% of the total error. Regression error accounted for the bulk of the remainder. We expect that, in this laser study, sampling error will make up a smaller portion of the total error (i.e., the other five sources of unaccounted-for variation will make up a larger proportion of the total error) because 1) our sampling design incorporates two sources of regression error, and 2) one of those regression error sources, i.e., laser-ground regression error, will be large due to an inherently noisy relationship between ground-measured volume or biomass and laser-measured canopy height.

Although the primary reason for flying the laser flight lines over Delaware was to develop and test procedures associated with a laser-based, large-area forest inventory, it became apparent that the same data set could be used to estimate the areas of a variety of land cover types, completely apart from those described by the Delaware GIS used to stratify the state. Line Intercept Sampling techniques were applied to all 1304 km of the airborne laser profiles acquired statewide. Each pulse was identified as belonging to one of the following classes, based on pulse height, pulse return amplitude, and/or based on the video record - forest, nonforest, roof, asphalt/concrete, water. Any pulse which measured a target over 3m tall, not manmade, was considered a measurement of a tree. Nonforest pulses were those over natural targets less than 3m tall. [Note: 3m was used as a cut-off to prevent mature corn from being identified as forest. This cut-off is slightly less than the USFS definition of a tree - 12 feet, or 3.7m (Griffith & Widmann 2001).] Roof, asphalt, and concrete crossings were identified via the video record and aided by noting changes in the strength of the return laser signal. Water crossings were

obvious in the laser profile since water generally absorbed the 0.905 μm, near-infrared laser pulse.
Forest, nonforest and open water estimates are compared with the University of Delaware GIS estimates. As in Table 1, there are, in Table 3, issues concerning comparison of estimates that are not exactly comparable. For instance, the laser survey defines a forest pulse based on height; the photointerpreters who produced the GIS map define a wetland (considered a forested cover type) based on drainage and wetlands cover, not necessarily on the presence/absence of trees. Much of the GIS wetlands category is forested, but there are extensive areas along the Delaware Bay and Atlantic Ocean that support marsh grasses and which are devoid of trees. Also, whereas the laser/video sample separates impervious surfaces from pervious forest and nonforest, the GIS does not. So some unknown proportion of the GIS forest and nonforest polygons are, in fact, impervious. Despite these differences, GIS and laser estimates of forest area agree within 9% at the county level and within 4% for the State. Nonforest differences, the compliment of forest results, are similar. Open water estimates should be directly comparable, though the minimum mapping unit (mmu) for the laser was much smaller (1m transect crossing length) than the mmu of the photointerpreters (4 acres, or 1.62ha). Laser and GIS open water estimates differ by ≤0.5% at the county level and <0.05% at the state levels.

Total impervious surface area is compared with estimates developed by Smith et al (2003). They used a mixture model to parse each 30m Thematic Mapper pixel into impervious and pervious surface percentages. Given the level of detail pursued in the delineating laser transect crossing distances, and given the total length of the flight transects considered, i.e., 1304 km, we would argue that the laser estimates are more accurate than the mixture model results. Absent more accurate ground reference data, however, there is no way to tell. Satellite mixture model estimates and airborne laser profiling estimates agree within 2.2% at the county level and within 0.2% at the state level. It does bode well for both analysis techniques that the county and state estimates are close.

Table 3. Forest, nonforest, impervious surface, and open water percentage estimates based on airborne laser profiling data (from Nelson et al. 2003b, Table 2). Independent estimates are provided for comparison directly below the laser table. SE = standard error of estimate (in percent). Percentages may be converted to area by multiplying the table entries by the following areas: Newcastle - 112412 ha, Kent - 154234 ha, Sussex - 253896 ha, Delaware - 520543 ha.

	Laser Profiling Estimates of Land Cover (%)							
	Newcastle		Kent		Sussex		Delaware	
	mean	SE	mean	SE	mean	SE	mean	SE
Forest	27.49	1.63	26.85	3.69	33.66	2.14	30.31	1.26
Nonforest	58.57	2.65	67.83	2.85	58.92	1.99	61.49	1.36
Pervious Surface	86.06	2.84	94.68	0.99	92.58	2.82	91.80	1.90
Roof	3.40	0.98	1.13	0.31	1.04	0.20	1.58	0.17
Asphalt/Concrete	7.50	2.00	2.21	0.43	1.77	0.33	3.13	0.34
Impervious Surface	10.90	2.96	3.35	0.72	2.82	0.51	4.71	0.49
Water	3.04	0.62	1.97	0.63	4.61	2.52	3.49	1.78
TOTAL:	100		100		100		100	

	Independent Estimates of Land Cover (%)			
	Newcastle	Kent	Sussex	Delaware
Forest [1]	27.60	35.64	36.04	34.10
Nonforest [1]	69.78	62.29	59.18	62.39
Impervious Surface [2]	8.76	3.50	3.88	4.90
Water [1]	2.62	2.07	4.79	3.51

1. The land cover percentages are derived from University of Delaware GIS used to stratify the airborne lidar data. The GIS land cover percentages total to 100%.
2. Estimates of impervious surface area are taken from Smith et al. 2003.

Impervious surfaces are non-point pollution sources, and monitoring impervious surface area is important from a pollution monitoring and mitigation standpoint. Goetz et al. (2003) analysed IKONOS data over a 1313 km^2 area in central Maryland (the state which abuts Delaware to the west) and found that stream health ratings could be described as a function of impervious surface area and forest cover. For instance, they found streams in watersheds with impervious surface area comprising less than 6% and riparian forest cover exceeding 65% had stream health ratings of "excellent". "Good" streams had impervious surfaces comprising less than 10% of the watershed, with 60% forest cover in the riparian areas. Laser transect data, whether profiling or scanning, could be used to develop such watershed-level measurements as one way to predict stream quality in developed areas.

Discussion

A statistical framework has been developed and tested whereby systematic, airborne LiDAR profiling measurements of forest canopy height, height variability, and crown closure are converted into estimates of forest merchantable volume, total above-ground dry biomass, and above-ground carbon. Using linear parametric and nonparametric models, laser-based estimates of merchantable volume differed from U.S. Forest Service-Forest Inventory and Analysis estimates by less than 15% statewide and by less than 22% at the county level. Seven of the eight merchantable volume models were within 15% at the county level, and three of the four merchantable volume models produced estimates within 5% of USFS-FIA state estimates. Biomass estimates differed by ≤20% at the state level and ≤22% at the county level. Certainly the agreement isn't perfect, nor is perfect agreement a reasonable expectation given differences in land cover definitions and sampling procedures The USFS-FIA estimates are based on 215 systematically sampled plot clusters which are post-stratified based on tree species encountered on the plots. The laser inventory is based on (1) 142 - 40 m ground sample transects used to develop the regression relationships used to calculate volume and biomass, (2) an existing photointerpreted land cover map comprised of eight general land cover types (i.e., hardwood, mixedwood, conifer, wetlands, agriculture, residential, urban/barren, and water); and (3) 1304 km of airborne lidar flight data. Though final judgement of the goodness of agreement is left to the reader, the authors are encouraged by the level of agreement between the two disparate inventory techniques.

Dry biomass estimates were converted to above-ground carbon estimates by using a generic multiplier of 0.5 t C/1 t dry biomass, and tallied by stratum, county, and for the State. The itemized carbon allocation for Delaware (Table 2) is provided as an example of the type of detail that can be extracted from airborne laser profiling data. The carbon table also highlights the importance of residential and urban areas with respect to C stores in developed areas.

The results also support the fact that an airborne laser profiler in conjunction with a video camera can be used to estimate the areal extent of forest, nonforest, impervious surface area, and open water area. Impervious surface area can be divided into area under roof and area under concrete or asphalt based on the height characteristics of the surface.

PALS was designed to inventory large forested areas in out-of-the-way places, places such as the Amazon, the Congo, Madagascar, and the circumpolar boreal forests where relatively little is known about biomass and carbon stores. The lidar system, transported in two large suitcases, is designed to be flown aboard locally-based, rotary or fixed-wing aircraft. At this point, the system has been used on a Bell 206 JetRanger helicopter, a UH-1 "Huey" helicopter, a twin-engine, fixed-wing Twin Otter, and a single engine, fixed-wing Cessna-207 Skyvan. It is currently being configured for a Cessna-182. It's nominal operational envelope is from 100m to 300m above terrain.

Future work will involve efforts in a number of different areas with the overall objective being to develop an real-time, laser-based, airborne forest inventory system which can be flown on many different types of small aircraft. Research areas include the following:

1. Improve regressions used to predict volume and biomass. Some of the stratified predictive equations, most notably the hardwood and mixedwood equations, were weak, with R^2 values typically less than 0.5. We believe that longer field transects, on the order of 100m, need to be considered in order to improve regression fits. Natural variation in the Delaware forests is high and regression outliers common. Future studies will key on the use of nonparametric techniques to develop the explicitly linear, predictive equations in order to mitigate the effects of outliers. Future investigations will also look at the acquisition of leaf-off data over hardwood forests as one way of strengthening predictive models (E. Næsset, personal communication).

2. Develop the flight hardware needed to fly PALS on other types of aircraft (e.g., smaller Cessnas).

3. Replace the first-return laser transmitter/receiver with a first/last return transmitter to facilitate identification of ground beneath canopy (in progress).

4. Develop automatic ground-finding and roof-finding algorithms so that the laser data stream can be processed in-flight. If heights can be reliably measured, i.e., if ground can automatically be tracked, and if roofs can be automatically excluded, then an airborne laser profiling system can be flown such that the laser and GPS data are stored and simultaneously processed to tally volume, biomass and carbon on-the-fly. Automated ground and roof finding algorithms have been developed and will be improved. It is realistic to expect that, in just a few years, airborne laser profiling systems will be flown such that the volume, biomass, and carbon inventory will be completed when the aircraft touches down after flying the final flight line. Automated scanning systems will follow soon after.

Without doubt, the future of airborne laser remote sensing belongs to airborne and spaceborne laser scanners, not to airborne profilers. Currently, however, laser scanning systems are expensive and the data streams are dense. Profilers offer technical simplicity, transportability, and a manageable data stream that allow researchers to consider processing real-time in remote areas. They also duplicate, at a much finer spatial scale, the data acquisition attributes of spaceborne laser profilers currently flying (the Geosciences Laser Altimeter System - GLAS, aboard the Ice, Clouds, and Land Elevation Satellite - ICESat) and proposed multi-beam profilers. The use of an airborne laser profiler such as PALS should be considered in situations where volume, biomass, and carbon need to be measured over large, remote regions where little or no forest inventory information exists. The results of this study provide a quantitative assessment of the estimation accuracy which might be expected when an airborne laser profiler is employed for regional assessment.

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The Analysis of Forest Structure using Laser Scanner Data

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Introduction

When using airborne scanning laser (LiDAR) sensors with small footprint diameter (10 to 30 cm) it is possible to get accurate height information on the forest canopy (e.g. Næsset 1997a, b, Magnussen and Boudewyn 1998, Magnussen et al. 1999, Means et al. 2000). The two main approaches in deriving forest information from laser scanner data have been regression based and individual tree based approaches. In regression based methods, quantiles (percentiles) of the distribution of laser canopy heights are used to predict forest characteristics. For example, Næsset (2002), Lim et al. (2003a) and Holmgren and Jonsson (2004) have shown that this approach produces highly reliable stand variable estimates. If the number of laser pulses is increased to more than, say, 5 measurements per square meter individual trees can be recognised (Brandtberg 1999, Hyyppä and Inkinen 1999, Persson et al. 2002, Popescu et al. 2002). It is also possible to recover individual trees or theoretical diameter classes from sparse laser data using probability models for the canopy hits (Magnussen et al. 1999) or percentiles of diameter distribution functions (Gobakken and Næsset 2003).

The most obvious stand characteristics to be produced using laser scanning are different height metrics. The results of tree height estimation are quite often presented by using different mean height characteristics (e.g. Magnussen et al. 2001, Næsset 1997a, 2002, Popescu et al. 2002, Holmgren et al. 2003). However, laser scanning based heights of individual trees have been compared to the field measured heights, e.g. in the studies by Hyyppä and Inkinen (1999), St.-Onge (2000), Lim et al. (2001) and Persson et al. (2002).

In addition to height metrics, timber volume characteristics are considered as well. When using regression based approach laser based height quantiles are related to stand volume (e.g. Næsset 1997b, 2002, 2004, Lim et al. 2003a). In the case of recognised individual trees, it is possible to calculate tree volume by using single tree models. Firstly, tree diameter is predicted by using tree height and segmented crown area (e.g. Hyyppä and Inkinen 1999, Persson et al. 2002, Maltamo et al. 2004a) and, secondly, tree volume is calculated by using standard volume equations for individual trees.

Many LiDAR studies also consider other stand characteristics such as crown height, biomass, canopy closure and LAI (e.g. Næsset and Økland 2002, Lim et al. 2003a). All these stand variables can be considered as characteristics of stand structure (see e.g. Lim et al. 2003b). However, the definition of stand or forest structure is not fixed in the same manner as for example basal area. It seems to be varying from one application to another. Forest structure on stand level is of interest from an ecological point of view, for example when considering gap dynamics (disturbance dynamics), successional and growth stages, biomass and for identifying wildlife habitats (biodiversity issues) (e.g. Clark et al. 2004, Lee et al. 2004). Stand structure includes different components such as vertical (e.g. number of tree layers) and horizontal (e.g. tree groups, spatial pattern) structure as well as species richness (e.g. Zimble et al. 2003). In addition to that, forest structure is quite different in different vegetation zones around the world and also affected by silvicultural operations. For example, in tropical conditions species diversity is very high and characteristic such as number of multiple-stemmed trees can be used (e.g. Dunphy et al. 2000). All in all it can be said that variables such as stand volume, basal area or mean height may not characterize properly stand structure of forests with great vertical heterogeneity. Correspondingly, in the cases where individual trees are considered they are usually recognised only in the dominant tree layer which gives a poor description of multilayered forests (Persson et al. 2002, Maltamo et al 2004a).

It is, however, possible to analyze vertical stand structure using laser scanner data since the quantiles of the height distribution of laser data are related to the vertical structure of the tree canopy (e.g. Magnusseen and Boudewyn 1998, Næsset 2002). Furthermore, some of the laser pulses will also penetrate under the dominant tree layer. Reviews of laser scanning in forestry aspects have been earlier presented e.g. by Lim et al. (2003b), Hyyppä et al. (2004) and Næsset et al. (2004). In this paper, I will review some of the airborne laser scanning studies – including analysis of vertical stand structure. The main emphasis is on discrete return small footprint laser data but some other approaches are presented as well. In addition to that, the studies considered are related to boreal forest conditions.

Characteristics and description of boreal forests

In Finland, managed boreal forests are structurally rather homogeneous due to silvicultural operations and low tree species diversity. The planting of trees has favoured coniferous tree species and silvicultural operations have removed suppressed trees and tree groups. These operations have usually caused a uniform stand structure. However, unmanaged boreal forests are often more heterogeneous.

According to Esseen et al. (1997) natural boreal forests include structural characteristics such as mixed stands, understorey of tree saplings, multi-layered tree canopies, patchy distribution of trees and uneven-aged stand structures. In addition to this also single old trees and dead standing trees and downed logs can be found. In Finland, forests with such characteristics are nowadays rare. However, their importance for the biodiversity of forests and the protection of endangered species is undisputable. Some natural structural characteristics may, however, still be found from old managed spruce forests whereas pine dominated forests are usually rather homogeneous.

In Finland, the traditional stand description of field inventories by compartment was based on measurements of basal area and stand mean height (Nyyssönen 1954). Stand volume was then calculated using so-called relascope tables. This approach is very close to the current regression based laser approach. During the last two decades inventory by compartments has been improved to include assessment of stand mean characteristics by tree species and tree storeys. This modification was done to get more accurate results by tree species (e.g. Maltamo 1997). If this kind of stand description is related to laser scanning based stand inventory it can be said that estimates of forest variables can be derived by tree species (Holmgren and Persson 2004). Furthermore, it would be important to separate and also quantify different tree storeys using laser scanner data. In the case of unmanaged forests the recognition of multilayered forest structures would be of interest.

Laser remote sensing of forest structure

Until now, most of the laser scanning studies have concentrated on estimating basic stand variables. The studies have also focused on analysing single-layered forests or vertical structure has not been mentioned. Although the main aim of the study was practical large-scale forest stand inventory, Næsset (2004) also visualised the relationship between different stand structures and laser point height distributions (Fig. 1). Correspondingly, the ability of laser scanner data to reflect stand structure can be seen from the laser data based profiles of canopy (Hyyppä et al. 2000, see also e.g. Parker and Russ 2004) (Fig. 2.) In the following, some studies concentrating especially on forest structure are presented.

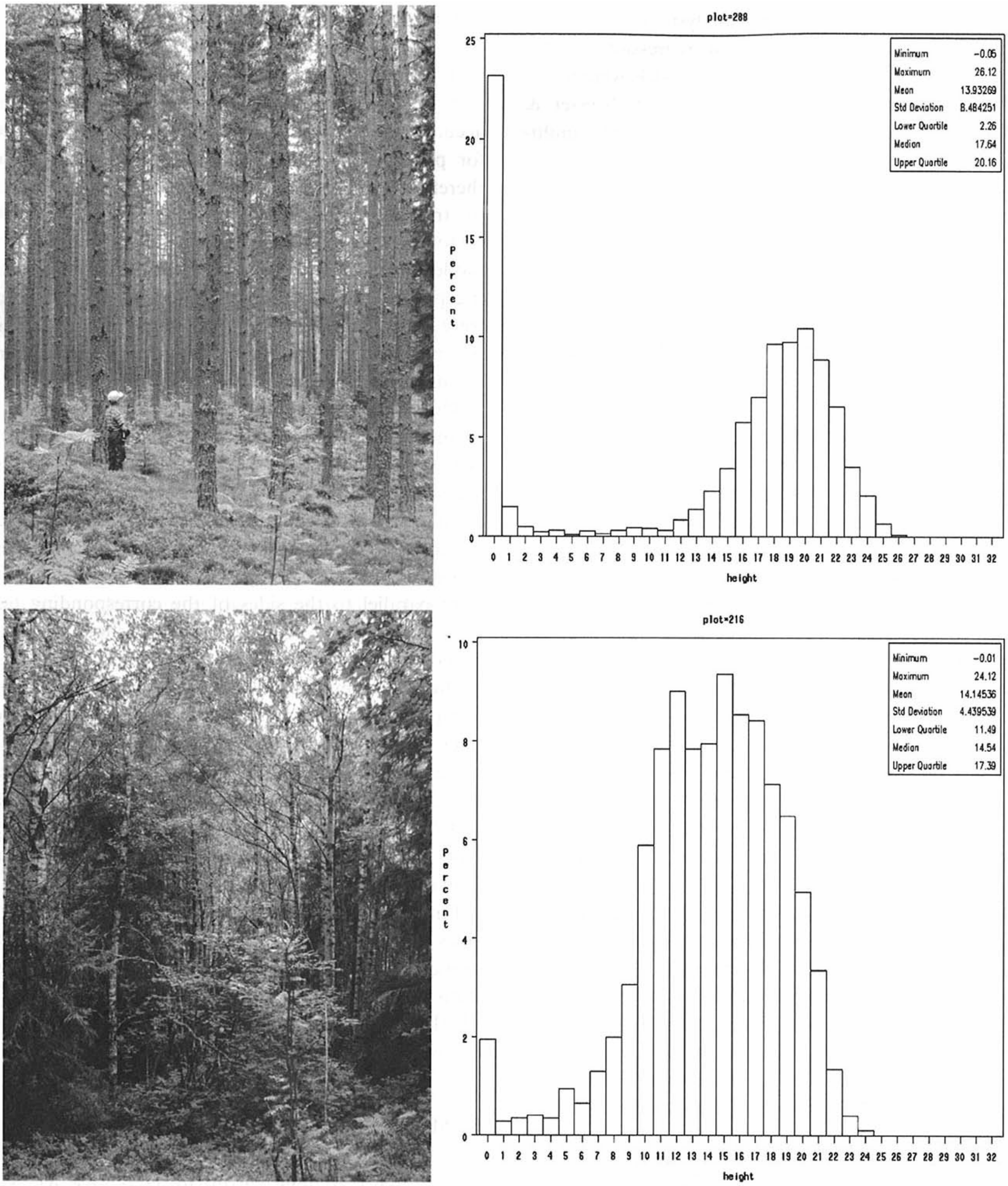

Fig. 1. The relationship between different forests and corresponding laser based canopy height distributions (Næsset 2004).

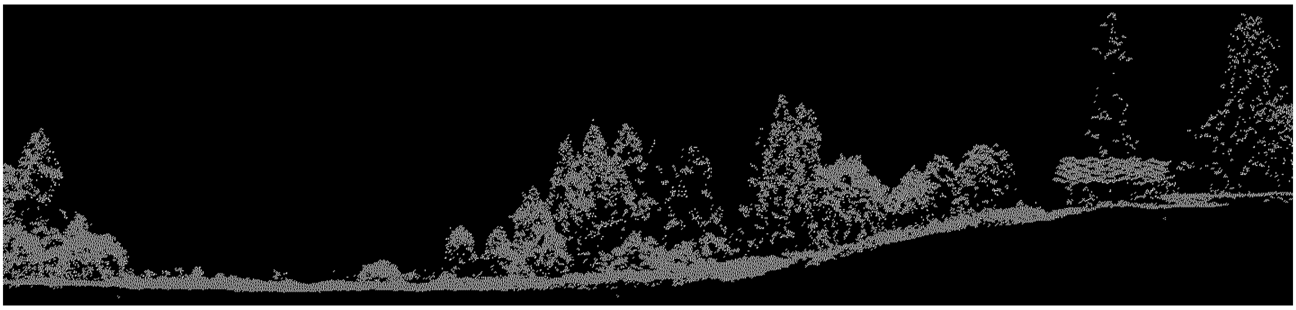

Fig. 2. Canopy height profile of boreal forest (Hyyppä et al. 2000). Copyright A. Samberg. 2000.

In the study by Zimble et al. (2003), LiDAR derived tree height variance was successfully used to determine differences between single-storey and multi-storey vertical structural classes. The used LiDAR was a small-footprint, multireturn system and the study area was located in Idaho, USA. Correspondingly, Blaschke et al. (2004) used standard deviation and variation coefficient of laser height points as indicators of forest structure in south-eastern Germany. The used point density was about 10 pulses per square meter.

The existence of understorey trees is of remarkable interest also for fire behaviour models. Riano et al. (2003) used laser scanner data (pulse density 5.6 per square meter) to construct a fire behaviour model in south-western Germany. They separated over- and understorey layers by using cluster analysis. Although their data included forests where there were gap between these layers, the authors state that the system can be applied even when there is no gap between these layers. However, in present form their algorithm can separate only two layers.

Hirata et al. (2003) used two separate laser scanning surveys – one was conducted in the full-leaf and the other in leafless season – in temperate deciduous forests in Japan. The used point densities were 25 and 31.9 pulses per square meter. The authors state that first and second canopy layer as well as gaps in the canopy can be interpreted and distinguished from the full-leaf data. On the other hand, understorey vegetation can be identified only from the leafless dataset.

Hashimoto et al. (2004) tried to identify indices of forest structure (foliage height diversity, sum of vegetation coverage, crown patchness) which are important for bird habitats. Laser scanner data included 4 pulses per square meter and both first and last pulses were used. The study area was temperate mixed forest in Japan and the survey was conducted during winter. The results showed that the laser scanner managed to reproduce the sum of vegetation coverage. There were difficulties to obtain return pulses from the middle layers of the canopy but these values were interpolated from the return pulse data captured. After that also the other indices were able to be estimated from laser data.

In Finland, Maltamo et al. (2004b) analysed highly heterogeneous boreal forest structures using laser scanner data. In the laser data the average number of laser pulse hits per one square meter was 12 and only first pulse data were used. The existence and number of suppressed trees was examined by analysing the height distributions of reflected laser pulses. The existence of lower canopy layers, i.e. suppressed trees, was firstly analysed visually by viewing the 3D-images of laser scanner based canopy height point data (Fig. 3) and, secondly, examining distributions of canopy densities which were computed as the proportions of laser hits above different height quantiles. Correspondingly, Parker and Russ (2004) used vertical profiles and canopy height distributions to characterise different forests.

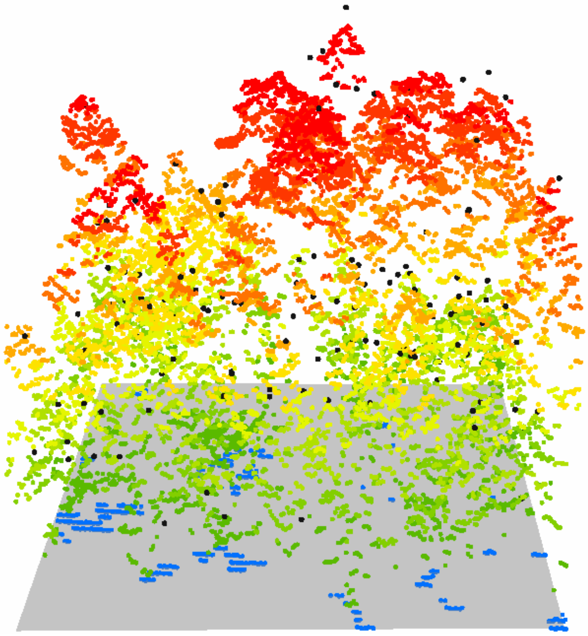

Fig. 3. An example of 3D-laser canopy height point cloud in multi-layered sample plot. Field measured tree tips (black dots) are also shown (Maltamo et al. 2004b).

Furthermore, in the study by Maltamo et al. (2004b) a developed histogram thresholding method (HistMod) was applied to the height distribution of laser hits in order to separate different tree storeys (Fig. 4). The classification succeeded in 24 sample plots and failed in 4 sample plots. Finally, the number and mean height of suppressed trees were predicted with estimated regression models. The results showed that multi-layered stand structures can be recognised and quantified using quantiles of laser scanner height distribution data. However, the accuracy of the results is dependent on the density of the dominant tree layer (Maltamo et al. 2004b).

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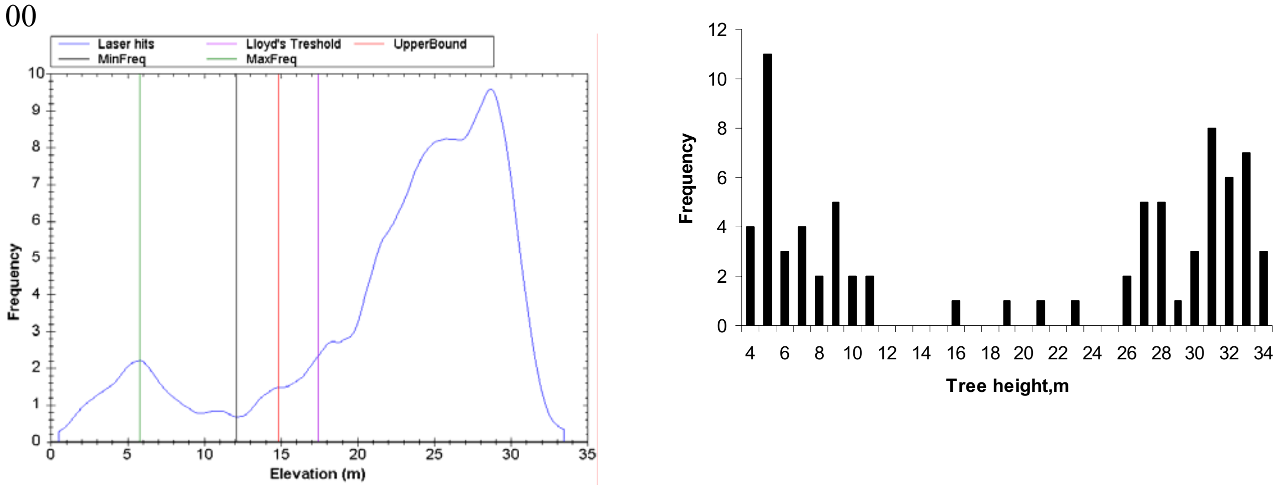

Fig. 4. Left: An example of the HistMod algorithm procedure used to define the number of tree layers in smoothed laser hit height distribution in multi-layered stand (see details in Maltamo et al. 2004b). Right: Corresponding field measured tree height distribution.

In tropical conditions Clark et al. (2004) analysed estimation of tree heights and sub-canopy elevation in Costa Rica. The used pulse density was about 9. Correspondingly, in subtropical open forests and woodlands in Australia Lee at al. (2004) characterised vertical forest structure. They simulated 3D representation of forest structure by using voxels (volumetric pixels) of one square meter based on both field measurements and LiDAR returs. Vertical distributions generated from these 3D generalisations were used to compare the results. It was found out that LiDAR profiles match with field measurements but field and ancillary data are needed to calibrate and validate LiDAR based results.

One possibility to characterise forest structure is to combine measurements of airborne and ground-based laser (Lowell et al. 2003, Chasmer et al. 2004). This kind of approach produces accurate results but it is very difficult to compare these results with applications based solely on airborne systems.

Instead of using discrete return laser systems it is possible to utilise different systems such as the waveform-recording laser altimetry (see e.g. Lefsky et al. 1999). Harding et al. (2001) characterised closed-canopy broadleaf forests using the scanning LiDAR imager of canopies by echo recovery (SLICER). The study material included also old-growth multi-layered forest. It was found that it is possible to capture structural variations of different forests using this approach. Recent improvements in LiDAR technology also include waveform-digitizing systems (Hug et al. 2004). This kind of approach seem to be very interesting alternative to detect vertical structure including multiple layers and ground vegetation.

Conclusions

In this paper, laser scanning studies related primarily to forest structure has been reviewed. To the best of my knowledge, very few reviews of this kind has been made so far. Forest structure has been considered in relation to many different aspects, such as e.g. wildlife habitats, fire behaviour and biomass content. Correspondingly, different indicators have been calculated from laser scanner data and various methods have been applied to compare laser data with reference measurements of forest structure.

Technical parameters of the considered laser scanning surveys have also varied a lot. Point density of reflected pulses has varied from about one to over 30 per square meter. Some other parameters where there has been much variation are, for example, flight altitude, footprint diameter and scanning angle. Both first and last pulse information has been used and also the intensity of the image can bring new information – at least on recognition of species. Instead of using small footprint discrete return systems, it is possible to utilise different technologies as well as combining airborne and terrestrial LiDARs. Finally, also the season is an important factor when scanning deciduous forests.

When relating these studies to boreal conditions one should keep in mind the specific features of boreal forests. However, the structural diversity of boreal forests is rather low when compared to e.g. temperate and tropical forests. In Finland, stand level inventory has been based on aerial images (stand delineation) and field measurements (assessment of stand mean characteristics). Recently it has been proposed that next generation inventory system should consist of digital aerial photographs and low density (point density about 1 hit per square meter) laser images. Such information would provide accurate results in relation to stand variables (volume, timber sortiments) (see e.g. Næsset 2004) but it would also make it feasible to map and analyse at least some structural characteristics at the stand level. For research purposes and in nature conservation areas considerably higher point densities could be used. However, it should be remembered that the development in laser technology is currently very rapid and after a couple of years the situation can be quite different and thus much more effective or even completely new scanners may be in use.

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Laser Scanning at Stand and Tree Level – Experiences in Sweden

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1. Introduction

The scope of this paper is limited to briefly presenting some ongoing airborne laser scanning projects in Sweden. For earlier activities in Sweden and elsewhere, one can find information in the proceedings from the ScandLaser conference held September 2-4, 2003 in Umeå, Sweden (Hyyppä, et al., 2003). To the knowledge of the organizers, ScandLaser was the first international meeting of its kind in Europe. A subset of contributions to the conference was recently published in a special issue of Scandinavian Journal of Forest Research (Vol. 19, No. 6, 2004), including the review article entitled "Laser Scanning of Forest Resources: The Nordic Experience."

2. Large area laser scanning for forest inventory

The first large area airborne laser scanning project in Sweden for the purpose of forest inventory was started in 2003 by a regional forestry board in central Sweden (Dalarna-Gävleborg forestry board, www.svo.se). The objective was to compare an airborne laser scanning based method with traditional operational methods for forest variable estimations. The objective field methods that exist today for estimation of forest variables are too expensive to use for all forest land. Therefore, forest companies are using several subjective estimation methods that typically give standard errors of about 10% (proportion of mean value) for mean tree height estimation, 6 to 17% for mean diameter estimation, and 15 to 25% for stem volume and basal area estimations (Ståhl, 1992). One common method is to use manual interpretation and tree height measurements from stereo models of aerial photos combined with a field survey (Åge, 1985).

Laser data were acquired for a 5000 ha forest area in central Sweden with approximately 1.2 laser measurements per square meter. Mean tree height, mean stem diameter, basal area, and stem volume were predicted using regression functions with variables extracted from laser data. Field plots that were GPS-positioned were used as training data. Three separate regression functions were built for each predicted variable; one for Scots pine (*Pinus sylvestris*), one for Norway spruce (*Picea abies*) and one for deciduous dominated forest stands. Which regression function to apply for a certain forest stand was decided based on information from manual interpretation of aerial photographs. A validation inventory of 29 forest stands was performed with approximately 10 field plots within each forest stand. The RMSE values at stand level were 5.0% (0.8 m) for mean tree height, 8.9% (1.9 cm) for mean stem diameter, 12.5% (3.0 m^2ha^{-1}) for basal area, and 14.1% (28 m^3ha^{-1}) for stem volume estimations. The results imply that estimations of forest variables using laser scanning yield higher accuracies compared with the traditional methods presently used in Swedish forestry. More details of the first phase of the project can be found in Holmgren & Jonsson

(2004). One problem with the evaluated laser scanning based method is that it relies on manual photo interpretation for stand delineation and for stratification. Future research will therefore concentrate on reducing the need for field work and manual photo interpretation, for example, by using semi-automatic stand delineation.

3. Imputation study for forest planning application

Research concerning remote sensing based imputation is motivated by the need to deliver input data into long term forest resource planning systems. Imputation is regarded to be suitable for optimization because several variables, including variables associated with individual trees, are needed. Also, the relationships between the variables on a plot need to be conserved.

In order to obtain the necessary variables for all forest stands, field plots are imputed using different remote sensing data. Imputations were made using data from bands XS2, XS3 and XS4 from the SPOT optical sensor and plot summary measures of canopy height laser measurements. Both sensors were used in combination and separately. Primarily, results show that imputations using laser data were overall superior to those based on SPOT data alone, as well as the combination of both sensors. This was evaluated using ranking of errors in distribution summary statistics as well as error in stem volume estimations. For each stand, plots were imputed by selecting the most similar plot of the plots in other forest stands in feature space using the Mahalanobis distance. Further work is needed in order to validate the accuracy for imputation with other distances besides the Mahalanobis distance, in order to efficiently use several data sources. This work is a part of the ongoing research project Heureka (http://heureka.slu.se/eng/index.shtm).

4. Predicting stem volume at stand level

Possible solutions for updating the Swedish national Digital Elevation Model (DEM) are presently being investigated and airborne laser scanning is being considered as a data source to cover large areas of Sweden. The acquisition of laser scanning data is associated with a high cost for large areas. In order to reduce cost, the flight altitude or flight speed can be increased, resulting in low-resolution laser data. It is possible that very low resolution laser scanning data is enough for modeling stem volume at stand level if the laser data is combined with medium resolution satellite image data.

In an ongoing project, the accuracy of forest stem volume estimation at stand level using a combination of optical SPOT-5 satellite and laser scanner data has been investigated. The stem volume for the selected stands was in the range of 30-620 m^3 ha^{-1} with an average stem volume of 288 m^3 ha^{-1} and an average size of 2.9 ha. Regression analysis was used to develop stem volume functions for each sensor and for the combination of the data sources. For the combined stem volume function, the satellite image data was combined with measures of the height distribution of laser reflections in the canopy. Thus, only height information was utilized from the laser data. The accuracy in terms of relative root mean square error (RMSE) was 30.8% of the average stem volume using SPOT-5 data alone and 15.7% for the combination. Thus, compared to using SPOT-5 data alone, the improvement was found to be 49%. The result implies that the combination of multi-spectral optical satellite and laser derived tree height data can be used for stand wise stem volume estimation in forestry applications. One can find a more detailed description of the first phase of this project in Fransson et al. (2004). The next step will be to investigate the sensitivity of laser measurement density on the estimations. The hypothesis is that a low number of laser measurements per forest stand are sufficient for achieving a similar accuracy for stem volume estimation.

5. Identifying tree species of individual trees

Airborne laser data with high resolution can be used to first detect individual trees and then measure the detected trees (e.g., Hyyppä & Inkinen, 1999; Hyyppä et al., 2001; Persson et al., 2002; Schardt et al., 2002). Position and tree height of individual trees can be estimated with sub-meter accuracy. The next step is to identify the species of the detected trees. Properties of laser data within segments of individual trees have been used for separation of Norway spruce and Scots pine, the two most common tree species in Sweden, with 95 % accuracy (Holmgren & Persson, 2004). Furthermore, information can be achieved by fusion with data from other sensors. High density laser data is a powerful tool for tree canopy delineation and for assessing canopy shape, while spectral properties can be extracted from multi-spectral images.

Ongoing research is investigating the possibility of combining near-infrared images and laser data in order to classify individual trees. Digital images were recorded using the Z/I Digital Mapping Camera (DMC). Three multi-spectral cameras were used that were sensitive in the spectral bands B1 (500-650 nm), B2 (590-675 nm), and B3 (675-850 nm). Three forest stands, each dominated by Norway spruce, Scots pine or deciduous trees, were used for the first tests. The position of each tree was measured on the ground in order to automatically link a field measured tree to the corresponding laser measured tree.

The method to classify trees has the following steps: (1) individual tree crowns are delineated using laser data, (2) the height and crown diameter are measured for each tree, and finally (3), the tree species are classified. In the first tests, the classification was based on DMC data only. Delineations of individual trees, which also results in a laser measured tree height and crown diameter, were performed using an earlier developed method (Persson et al. 2002).

For these first tests, the classification was based on data from the DMC camera only. To avoid re-sampling of the images, each pixel within an extracted crown segment was back-projected to the image. The three tree species classes could be separated with an accuracy of 90% only using spectral data for the classification. In order to make conclusions about expected accuracy in an operational case, the validation needs to be extended to also include separate stands not used in the training dataset (Persson et al. 2004). Future work will concentrate on combining variables derived from laser data and near infrared images for the classification.

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The Role of LiDAR for Forest Health Monitoring

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Abstract

Forest damage will result in two general effects: defoliation and/or discolouration. The two available techniques in remote sensing of forests today, LiDAR and spectroscopy, are promising tools for monitoring these two, respectively. Merging data on foliar mass, estimated by LiDAR, with data on chlorophyll concentrations, estimated by spectroscopy, can provide data on chlorophyll mass pr area unit. Monitoring the temporal changes of this is likely to be a very good measure for variations in forest health.

In order to check out the possibilities for this, we are now working on building relationships between foliar mass data and LiDAR data for single spruce trees. In total we have measurements of position and stem diameter on about 2000 trees distributed on 16 plots, where 64 trees are intensively sampled for estimating foliar mass, as well as crown size. We need to parameterize a relationship between the LiDAR data for each of these trees and their foliar mass (or leaf area). If we succeed to build this relationship, we will scale it up to provide foliar mass (or leaf area) estimates for every 10x10 m pixels in two SPOT images of the area. Together with a similar up-scaling of chlorophyll concentrations, based on spectroscopy, we will test the possibility of estimating chlorophyll mass per area from SPOT or other satellites. In addition, we have visually assessed data on crown density for all the trees, being a rough, but valuable data-set for validating the relationship. The work, being in progress now, includes several tasks: a) finding an appropriate canopy surface model, b) segmentation of trees, c) estimating crown volume, and evt d) handling of smaller trees standing below (this is a heterogenous canopy layer forest) and e) handling of the relative influence of stem and branches.

Additionally, we see some other benefits from using LiDAR together with airborne hyperspectral data and satellite data in general. Firstly, the combination of high resolution LiDAR and hyper-spectral data, is a good basis for separating the signals from ground vegetation and from the tree canopy. Secondly, LiDAR provides both a DTM and a canopy surface model, and they are two alternative surface models for the geo-referencing of other data, and for appropriate handling of effects of shadowing and obstacles from tall trees.

Introduction

Extensive monitoring of forest health in Europe has been carried out for two decades, based mainly on defoliation and discolouration. Together these two variables reflect chlorophyll amounts in the tree crown, i.e. as an indicator of foliar mass, and chlorophyll concentration in the foliage, respectively. In a current project we try to apply remote sensing techniques to estimate canopy chlorophyll mass, being a suitable forest health variable. So far, we limit this to Norway spruce only. LiDAR data here play an important role, together with optical and spectral data, either from survey flights or from satellites. We intend to model relationships between foliar mass and LiDAR data for sample trees, and then scale up this to foliar mass estimates for the entire LiDAR area. Similarly, we try to scale up chlorophyll concentrations in sample trees, by modelling a relationship between sample tree chlorophyll and hyper-spectral data. The estimates of foliar mass and chlorophyll concentrations are then aggregated to every 10x10 m pixel of a SPOT satellite scene which is also covered by airborne data, providing an up-scaled ground truth. If we are successful with this, it might be a starting point for developing a new nationwide forest health monitoring system in Norway.

The ground truth

The area for this study is located in Østmarka, south-eastern Norway. The size of the area is 6 km2, comprising mainly Norway spruce and some Scots pine. We subjectively selected 16 spruce sites for sample plots, being in the four age-classes with the Norwegian labelling II; III; IV and V with corresponding tree heights in the plots being around 0.5-6; 7-14; 15-20; and 21-35 m, respectively. Ground data were gathered in 2003. We used differential GPS for determining plot coordinates. On each plot, the diameter at breast height (dbh) was callipered for all trees with dbh ≥3 cm. Also, for each tree we recorded defoliation, discolouration, polar co-ordinates from the plot center, social status according to Schotte, and tree species. The number of trees on each plot ranged from 76 to 239, with the highest numbers in the younger stands. The total number of trees callipered was 2202.

On each plot four sample trees of the non-suppressed trees were systematically sampled as sample trees, being the first tree found going clockwise around the plot after each main cardinal direction. On these 64 sample trees were measured height; crown base; and crown width in four cardinal directions. By climbing the trees, all living branches were callipered and counted in 0.5 cm classes, separately for the lower, middle and upper crown parts. In the middle of each crown part, four sample branches were cut, - one to each cardinal direction. These sample branches were measured for fresh weight, basal diameter and length. The sampled branches were used for determination of foliar mass and chlorophyll concentration. The foliar mass of the sample branches was up-scaled to each of the sample trees, based mainly on a) relationships developed for sample branch foliar mass and branch basal area, and b) the counts of branches by branch basal area.

Airborne laser scanning

A helicopter-based laser scanning was carried out in October the same year, and the deciduous trees still kept the foliage on. The scanning included approximately 37 million pulses, each having two returns. The operating firm, BN-Mapping, did post-processing of the first and last pulse data, providing a DTM, geo-referencing of each return observation in the point cloud, and the height of each point relative to the ground.

Modelling of LiDAR-data and foliar mass

This part of the work is on-going, and preliminary methods and results are presented. The LiDAR data were assigned to the sample trees by developing crown projections in the horizontal plane: Firstly a digital canopy model (DCM) in a 10x10 cm grid was developed for each sample plot, using the gridding procedure “minimum curvature” in the SURFER software (Anon. 2002). This as based on first returns only, after using a max-z filtering within 50 cm radius around each return point. Secondly, this DCM was polished running a 3x3 gaussian filter 10-20 times, in order to try to retain only one local maximum per tree. A local maximum was then identified as any grid node being higher than its nearest eight neighbours.

After developing crown projections, LiDAR data were assigned to the sample trees. The foliar mass of a sample trees were then fitted to a LiDAR function, being the natural logarithm to the fraction of ground hits. The idea is that the ability of a laser pulse to penetrate the entire crown is related to the crown density, or foliar mass, of the tree. And further, that the amount of laser pulses penetrating is decreasing logarithmically with increasing foliar mass.

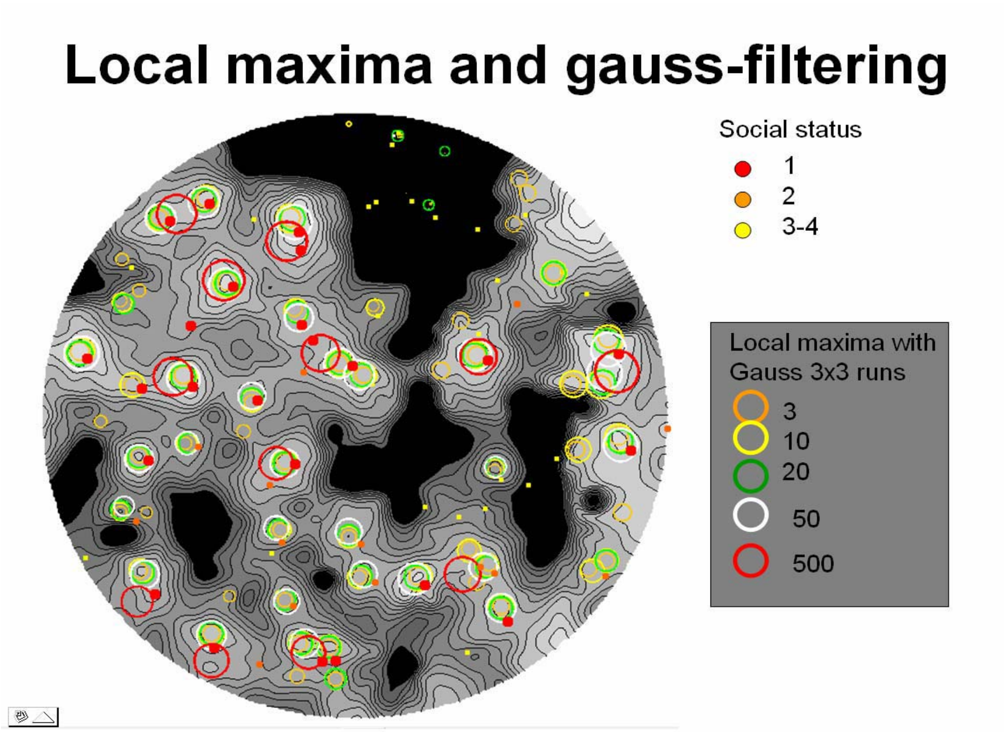

Fig. 1. The DCM shown as a contour plot and the number of local maxima (circles) relative to the number of Gauss filterings. Ground truth positioning of the trees is given as colours indicating their social status. Black = canopy gaps (DCM lower than 7 meters).

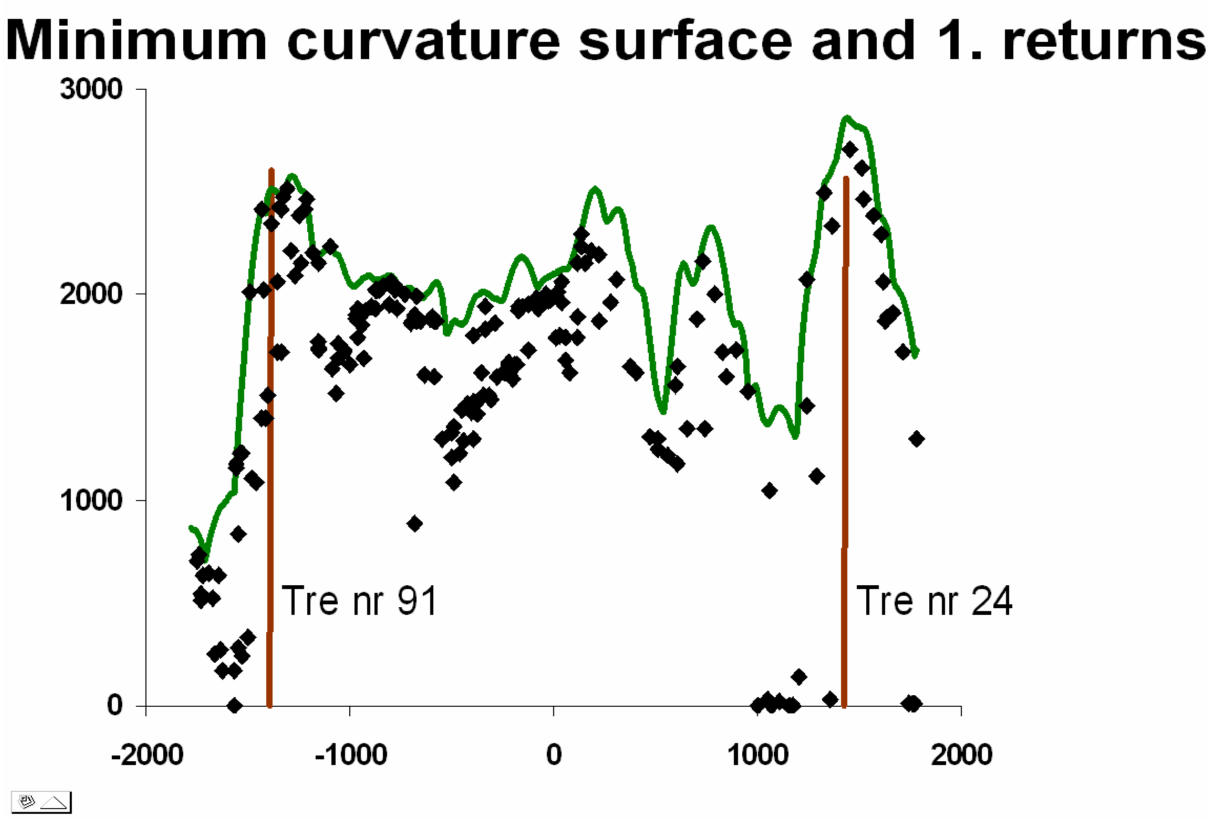

Fig. 2. DCM: First Lidar returns and mean canopy surface in a one m wide belt across plot 1 (old spruce forest) after using a minimum curvature model. The stems of two trees are included, - their positions and heights from ground measurements. Scale unit = cm.

In conclusion, LiDAR appear to be a promising tool for monitoring of foliar mass, or similarly crown density or LAI, all being key variables in forest health monitoring. Airborne LiDAR can be used for the up-scaling of ground truth for developing satellite based health surveys, as in the current project. In addition, airborne LiDAR have the potential to produce objective reference data for the subjective crown defoliation assessments carried out across Europe since the mid 1980s.

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Percentile-based Diameter Distributions in Uneven-aged Spruce Stands

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Abstract

A model for prediction of stand basal area and diameters at 10 percentiles of a basal area distribution was estimated from various canopy height and canopy density metrics derived by means of a small-footprint scanning laser over primeval conifer forest using partial least squares regression. The regression explained 44-80% of the variability of the observed values. The predicted percentiles, scaled by the predicted stand basal area, were used to compute stand volume, and cross-validation revealed a standard deviation between predicted and observed volume of 11%.

Introduction

The empirical diameter distribution holds significant information about the stand properties and can be utilized descriptively as well as provide input in growth projections and other computations. The diameter distribution is particularly interesting in uneven-aged forest, where traditional stand variables characterizing the mean values of the stand (i.e mean height, mean diameter and basal area) may neither be applicable to serve as a description of the stand properties, nor be relevant for computation of stand volume, stand growth or economic value.

It is labour-intensive and expensive to obtain reliable estimates of the diameter distribution by conventional field-based inventory of entire forest stands. However, data from airborne laser scanning have in the last years shown to be efficient in order to derive stand-based estimates of tree heights, mean diameter, stem number, basal area, and timber volume, at least for tree species with a regular crown shape (Næsset, 2002, 2004). Hence, it is likely that there exist a strong relationship between diameter distribution and canopy surface depicted by laser scanning.

The aims of this study were to estimate diameter distributions in uneven-aged conifer stands using area-based metrics derived from laser scanner data, and to assess the accuracy of the estimated models by cross-validation.

Materials and methods

The data used to estimate the diameter distributions were collected on 20 circular field plots of 0.1 ha in a boreal nature reserve of 1,400 ha in southeastern Norway (59º 50´N, 11º 02´E, 190–370 m a.s.l).

On each plot all trees with diameter >3cm where callipered. Volume of each plot was computed as the sum of individual tree volumes by means of volume equations for individual trees (Braastad, 1966; Brantseg, 1967; Vestjordet, 1967). Heights were calculated by means of multiplicative diameter-height equations estimated from field values of sample trees.

A helicopter carried the ALTM 1233 laser scanning system produced by Optech, Canada. The average flying altitude was approximately 600 m above the ground. The average footprint diameter for individual plots was approximately 18 cm. The mean number of pulses transmitted was 5.0 per m^2. First and last returns were recorded.

First and last pulse height distributions were created from the laser canopy heights of each 0.1 ha sample plot. Various variables were derived from these distributions, such as percentiles and canopy densities for various vertical canopy layers (Næsset 2004).

The plot diameter distribution was derived as the number of callipered trees in predefined 2 cm diameter classes, where the specific value of each class corresponds to class center. Stand basal area (G) was computed from the diameter measurements. To describe the plot diameter distributions, diameters at 10 percentiles of stand basal area defined an empirical cumulative probability density function. Partial least squares regression (PLSR) (Wold et al., 1983; Martens, 2001) was used to establish the relationships between the 10 percentiles, G, and the laser variables.

In predictions using the estimated model, the cumulative percentage of G in each diameter class was found by linear interpolation between percentiles. Furthermore, the number of trees in each diameter class was found by scaling the relative basal area to the predicted stand basal area.

To assess the accuracy of the derived model a cross-validation were carried out. The criterion for model appraisal was the difference between the plot volume computed from the predicted diameter distributions and observed plot volume. The predicted percentiles were used to compute the number of stems in each diameter class by means of the predicted values of G. Plot volume was derived from the resulting diameter distribution by using single-tree volume equations to compute the volume of the centre tree in each diameter class, multiplied by the number of trees in each diameter class.

Results and discussion

This study was aimed at assessing the ability of airborne laser scanning to provide data for modelling diameter distributions in uneven-aged conifer forest stands. The model was calibrated on data from uneven-aged sample plots that had reverse-J and multi-modal diameter distributions. Differences between predicted and observed volume was the basis for model evaluation. A cross-validation showed no significant bias in the volume prediction.

Table 1. Mean difference ($\overline{D}$) between observed plot volume (V) and predicted volume according to the predicted distributions, and standard deviation for the differences (SD) from cross-validation (CV).

Validation method	Number of obs.	Observed mean V	$\overline{D}$ (%)[a]	SD(%)
CV	20	360.7	-3.3ns	11.0

[a] Significance level: ns=not significant (p>0.05).

In conclusion, this study has demonstrated that multi-modal diameter distributions of large sample plots can be derived from laser scanner data with a precision of predicted volume of approximately 11%. This research was focused on methods to estimate and predict diameter distributions of fixed sample plots. Future work should focus on procedures to implement these methods in operational forest inventory where entire forest stands are the target units.

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Towards a Laser-Scanner Based Biomass Monitoring System

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Extended abstract

The advantage of scanning laser systems as compared to profiling lasers, is the ability to provide a continuous coverage of data suitable for "wall-to-wall" mapping of the forest. In large-area biomass surveys covering counties or states only profiling systems have been used so far (e.g. Nelson et al., 2004). These surveys have been designed as sampling-based inventories considering the profiling transects as a sample of lines applying the Line Intersect Sampling framework. However, even scanning systems can be used in regional, state- or nation-wide surveys by considering the flight-lines as part of a strip sampling design. It is our goal to design and implement such a scanning-based sampling design for biomass assessment and monitoring at county-level in Norway. The approach is illustrated in Figure 1.

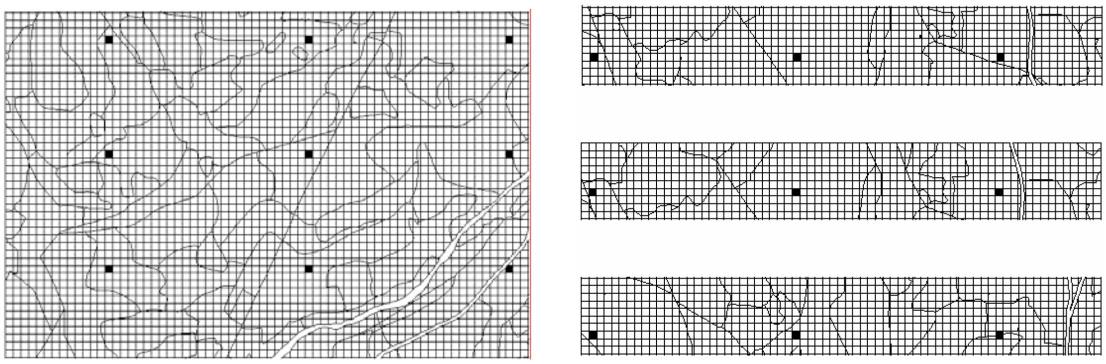

Figure 1. Illustration of laser scanner-based strip sampling scheme (right) and wall-to-wall inventory of forest stands (left). The area covered with laser data is divided into regular grid cells – the primary unit of the estimations. The black cells indicate systematically distributed field sample plots used as training data. Stratification according to land-use classes or stands (irregular solid lines).

Figure 1 (left) displays the method used in wall-to-wall mapping of forest stands for management planning. This method is described in Næsset & Bjerknes (2001) and Næsset (2002, 2004a), and it is now used in operational inventories in Norway (Næsset, 2004b). More than six such projects are currently under contract (Næsset et al., 2004). In this method, a complete coverage of laser data is provided for the entire area in question. The area is divided into forest stands by photo-interpretation (irregular, solid lines). Each stand is then divided into regular grid cells. Field sample plots (black cells) are measured, and by regression analysis timber volume, mean tree height and other biophysical variables of interest are regressed against explanatory variables derived from the laser data. The estimated regressions are finally used to predict the biophysical

variables of interest for every grid cell, and stand estimates are provided as aggregates of cell estimates with the individual stands.

The idea is to use a similar approach for regional sampling-based monitoring. In Figure 1 (right), the laser only provides single flightlines of data – not a wall-to-wall coverage. Within each strip, the same procedure is followed as outlined above. However, since only a sample of strips is provided, the biomass or volume estimates of the area of interest have to be based on estimated values where either the sampling proportion or the total area of different land cover classes is known. Thus, several different estimators may be considered.

Biomass has been one of the main target variables of laser research over the last 20 years, but much of the research has dealt with the ability to estimate above-ground forest biomass in hardwood forests. Only a few studies have addressed the coniferous species that occur frequently in the boreal forest in Scandinavia, such as Norway spruce and Scots pine. Preliminary results indicate that biomass of coniferous species can be estimated with a similar or even better accuracy as compared to deciduous species. Based on 300-400 m^2 sample plots where the ground-reference biomass has been estimated according to standard allometric equations, I have estimated regression models for different above-ground and below-ground biomass fractions (Næsset, 2004c). The analysis indicates that a similar and even higher degree of explained variability (86-92%) can be expected as compared to other biophysical variables, such as stem volume and mean tree height.

In regional-scale, sampling-based biomass monitoring a certain amount of variance will be associated with the biomass estimates. In repeated sampling over time, it is important to identify a reasonable time period over which it can be expected that lasers can provide reliable and significant change estimates. We have analyzed the kind of metrics derived from laser scanner data that usually have been applied in forest inventories, to see if these metrics change significantly due to growth over a two-year growth period in an untouched forest. Preliminary results indicate that the values of many of the height-related metrics at plot and stand level are significantly increased due to growth (Gobakken & Næsset, 2004).

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Conditioning Inference on Line Orientation in Line Intersect Sampling

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Conditioning Inference on Line Orientation in Line Intersect Sampling [1]

1 Introduction

The literature on line intersect sampling (LIS) spans many decades and disciplines dating back at least to 1898 in an article by Rosiwal discussing the ascertainment of the quantitative contents of the mineral constituents in rocks. Of course, its similarity to the famous needle problem posed by Buffon in the 1770's is well known.

It was introduced to ecologists in a 1936 monograph by Bauer, but Canfield's 1941 "Application of the Line Interception Method in Sampling Range Vegetation" in a forestry journal is widely credited as the first quasi-statistical look at LIS within the field of ecology.

The probabilistic properties of LIS can be deduced geometrically, per the famous monograph by Kendall and Moran (1963) and appreciated by the renowned Swedish forest-statistician Bertil Matérn in his 1964 note on estimating the total length of roads by means of a line survey.

Our assessment of the literature on LIS (a bibliography with 164 entries is posted at http://www.yale.edu/forestry/gregoire/biblo.html) is that the basis of inference following its use to estimate descriptive parameters of a population is often unclear. This lack of clarity has resulted in abundant confusion to applied scientists who may not be aware of the distinction between design-based and model-based statistical inference. Indeed, a confusion is apparent in published works by forest biometricians, which was one motivation behind the 1998 article by Gregoire: "Design-based and model-based inference in survey sampling: appreciating the difference" published in the *Canadian Journal of Forest Research.*

Our remarks on conditional inference are prefaced with this historical overview in order to credit Kaiser (1983) properly as the conduit to our understanding of estimation following LIS from the design-based perspective. We have recently investigated the statistical properties of estimators – proposed or implicit – when using line transects with two or more segments (Gregoire and Valentine, 2003, henceforth GV03; Affleck, Gregoire, and Valentine, 2005, henceforth AGV05). [2]

[1] This research was supported by funds from the USDA Forest Service, Northeastern Research Station, RWU-4104, through a cooperative agreement between the School of Forestry and Environmental Studies at Yale University.

[2] We would be remiss if we neglected to mention current and very intriguing work being done in this area by L. Barabesi and colleagues at the University of Siena, Italy. At the Seventh International Meeting on Quantitative Methods for Applied Sciences, Siena, September 23-24, 2004, Barabesi and Marcheselli will present "Improved strategies for coverage estimation by using replicated line-intercept sampling". A pdf version of this paper can be obtained by emailing barabesi@unisi.it.

Our remarks today are restricted, however, to an inferential nuance made explicit by Kaiser (1983) which has gone under-appreciated, indeed barely noticed by many users of LIS.

2 LIS sampling design

Let the population of interest consist of discrete and stationary objects (trees, bushes, logs, rocks, dens, scat, etc.) which we call particles for sake of generality. Using the notation adopted in AGV04, the population is the collection $\mathcal{P} = \{P_1, P_2, \ldots, P_N\}$ of discrete particles distributed over a region whose projection onto the horizontal plane is $\mathcal{A}$, the area of which is denoted by A. Each particle must be connected in the sense that any two points in P_i can be joined by a path contained entirely in P_i. In other words, a disjoint object constitutes one distinct particle. Particles can have any shape: they need not be circular nor needle-shaped with a central axis; particles need not be convex; and can be forked or have void interior regions. Furthermore, nothing about the spatial distribution of $\mathcal{P}$ on $\mathcal{A}$ is assumed: particles may be spread and oriented in any manner physically possible over $\mathcal{A}$ and may overlap in their projections onto $\mathcal{A}$.

Let y_i be a fixed, measurable characteristic of P_i that is independent of whether or how that particle is intersected by a transect. The target parameter to be estimated may be the aggregate quantity

$$\tau_y = \sum_{i \in \mathcal{P}} y_i \ ,$$

or perhaps the amount per unit area:

$$\lambda_y = \frac{\tau_y}{A}.$$

Evidently, when $y_i = 1, \forall i$ by definition, $\tau_y = N$, and hence population size and density are encompassed as special cases of τ_y and λ_y.

The sample design consists of M replicated transects on $\mathcal{A}$, the m^{th} of which is indicated by $T_m, m = 1, \ldots, M$. The total length of each transect is L. For the moment, assume each transect comprises a single straight-line segment. The location of T_m is referenced by the coordinate pair (x_m, z_m) on the horizontal plane of $\mathcal{A}$. By convention (x_m, z_m) is usually the midpoint or an endpoint of the transect. Transect locations are presumed to be selected independently and uniformly at random in $\mathcal{A}$. Systematic location introduces the usual limitations on variance estimation, but otherwise no essential incumbrances.

Relative to some reference direction, say $\theta = 0$, let θ_m denote the orientation of T_m. The orientation of T_m may be selected at random from a defined distribution, such as the uniform ($\theta_m \sim U[0, 2\pi]$). We allow for the possibility that transect orientations are selected independently for each of the M transects, or for the simpler case where an orientation is selected randomly and used for all transects. In the latter case, $\theta_m = \theta, \forall m$, say. Alternatively, the orientation of the transect may be fixed purposefully in advance of sampling, in which case $\theta_m = \theta, \forall m$, necessarily.

Irrespective of the choice of transect orientation, let $w_i(\theta_m)$ denote the width of P_i in a direction perpendicular to θ_m.

If P_i is intersected by T_m, P_i is included into the sample. Nothing precludes the intersection of P_i by two or more transects, although this event can be expected to have small probability of occurrence. We have dealt with partial and multiple intersections of P_i earlier (GV03, AGV04). Gregoire and Monkevich (1994) presented the reflection method to deal with reduced sample support near the edge when using LIS with single, straight-line transects. We currently are working on solutions to the boundary overlap problem when using radial and polygonal transects with two or more segments.

3 Estimation following LIS

When transect orientations are not randomly selected, estimation of τ_y is necessarily conditional on the choice of transect orientation. This arises when sampling logging slash, as in Warren and Olsen's (1964) motivating example, and one deliberately fixes the transect orientation perpendicularly to the predominant orientation of the felled needle-shaped tips. The conditional inclusion probability, denoted by $\pi_i^{\mathrm{c}}(\theta_m)$, is

$$\pi_i^{\mathrm{c}}(\theta_m) = L w_i(\theta_m)/A, \tag{1}$$

as shown by Kaiser (1983). Based solely on the sample tallied at T_m, the Horvitz-Thompson (HT) estimator of τ_y conditionally on transect orientation is thus

$$\begin{aligned} \widehat{\tau}_{ym}^{\mathrm{c}} &= \sum_{i \in \mathcal{P}} \frac{t_{im} y_i}{\pi_i^{\mathrm{c}}(\theta_m)} \\ &= \frac{A}{L} \sum_{i \in \mathcal{P}} \frac{t_{im} y_i}{w_i(\theta_m)}, \end{aligned} \tag{2}$$

where $t_{im} = 1$ if P_i is tallied by T_m, and $t_{im} = 0$, otherwise. At the conclusion of sampling, τ_y is estimated by

$$\widehat{\tau}_y^{\mathrm{c}} = \frac{1}{M} \sum_{m=1}^{M} \widehat{\tau}_{ym}^{\mathrm{c}}. \tag{3}$$

When transect orientation is randomly selected, the unconditional inclusion probability is

$$\begin{aligned} \pi_i^{\mathrm{u}} &= E_\theta\big[\pi_i^{\mathrm{c}}(\theta_m)\big] \\ &= L c_i / A, \end{aligned} \tag{4}$$

where $c_i = E_\theta\big[w_i(\theta_m)\big]$. For any connected particle, c_i can be computed by measuring the circumference of the convex hull of P_i and dividing by the mathematical constant

π. The HT estimator of τ_y unconditionally on transect orientation is thus

$$\begin{aligned}\widehat{\tau}^{\mathrm{u}}_{ym} &= \sum_{i\in\mathcal{P}} \frac{t_{im}y_i}{\pi^{\mathrm{u}}_i} \\ &= \frac{A}{L}\sum_{i\in\mathcal{P}} \frac{t_{im}y_i}{c_i}, \end{aligned} \tag{5}$$

and at the conclusion of sampling, τ_y is estimated by

$$\widehat{\tau}^{\mathrm{u}}_{y} = \frac{1}{M}\sum_{m=1}^{M} \widehat{\tau}^{\mathrm{u}}_{ym}. \tag{6}$$

A point to be emphasized is that when transect orientations are selected at random, one can choose to estimate τ_y (λ_y) conditionally on the orientations that were chosen, or unconditionally over all possible orientations. Indeed, it seems reasonable to choose to condition, or not, based on a consideration of which estimator, $\widehat{\tau}^{\mathrm{c}}_{y}$ or $\widehat{\tau}^{\mathrm{u}}_{y}$, is more precise.

The variance of $\widehat{\tau}^{\mathrm{c}}_{y}$ is

$$V\left[\widehat{\tau}^{\mathrm{c}}_{y}\right] = \frac{1}{M^2}\sum_{m=1}^{M}\left[\sum_{i\in\mathcal{P}} y_i^2 \frac{1-\pi^{\mathrm{c}}_i(\theta_m)}{\pi^{\mathrm{c}}_i(\theta_m)} + \sum_{i\in\mathcal{P}}\sum_{\substack{i'\neq i\\ i'=1}} y_i y_{i'} \frac{\pi^{\mathrm{c}}_{ii'}(\theta_m) - \pi^{\mathrm{c}}_i(\theta_m)\pi^{\mathrm{c}}_{i'}(\theta_m)}{\pi^{\mathrm{c}}_i(\theta_m)\pi^{\mathrm{c}}_{i'}(\theta_m)}\right], \tag{7}$$

where $\pi^{\mathrm{c}}_{ii'}(\theta_m)$ is the joint conditional inclusion probability of P_i and $P_{i'}$.

Similarly, the variance of $\widehat{\tau}^{\mathrm{u}}_{y}$ is

$$V\left[\widehat{\tau}^{\mathrm{u}}_{y}\right] = \frac{1}{M}\left[\sum_{i\in\mathcal{P}} y_i^2 \frac{1-\pi^{\mathrm{u}}_i}{\pi^{\mathrm{u}}_i} + \sum_{i\in\mathcal{P}}\sum_{\substack{i'\neq i\\ i'=1}} y_i y_{i'} \frac{\pi^{\mathrm{u}}_{ii'} - \pi^{\mathrm{u}}_i\pi^{\mathrm{u}}_{i'}}{\pi^{\mathrm{u}}_i\pi^{\mathrm{u}}_{i'}}\right], \tag{8}$$

where $\pi^{\mathrm{u}}_{ii'}$ is the joint unconditional inclusion probability of P_i and $P_{i'}$.

Regrettably, these expressions provide little guidance as to whether $\widehat{\tau}^{\mathrm{c}}_{ym}$ is preferable to $\widehat{\tau}^{\mathrm{u}}_{ym}$, or not. Clearly, when dealing with particles that project circles onto $\mathcal{A}$, $\pi^{\mathrm{c}}_i(\theta_m) = \pi^{\mathrm{u}}_i$, and there is no distinction between the variances of the conditional and unconditional estimators. But for a collection of arbitrarily shaped particles haphazardly arranged on $\mathcal{A}$, it is difficult to deduce analytically whether one is apt to be more precise than the other. The combined effect on estimation variance of the joint inclusion probabilities, $\pi^{\mathrm{c}}_{ii'}(\theta_m)$ and $\pi^{\mathrm{u}}_{ii'}$, strikes me as especially difficult to discern. we are unaware that anyone has studied this matter either analytically or empirically.

The notion of conditioning inference on the transect orientations actually observed, rather than over all possible orientations that could have been observed, is not unlike poststratifying the sample and then conditioning inference on the observed post-strata sizes. Also, conditional inference is familiar to all of us in a model-based setting: having fitted a regression model, subsequent inference is conditioned on the set of predictor variable values used to estimate the parameters of the model. These familiar activities notwithstanding, conditioning after having randomly selected transect orientation is a course of action that many may find difficult to reconcile in the setting presented here. Unfamiliarity aside, there is nothing perverse about so doing.

Two questions seem relevant in this regard, however:

① Does the choice between the conditional versus unconditional estimator make much of a difference on the precision of estimation?

② Does choosing one or the other based on which has smaller estimated variance introduce bias?

In our view, the answer to the latter question is emphatically, NO. One is always free to choose a preferred estimator after sampling has been concluded and based on what has been observed in the sample, without risk of insinuating a design-based bias.

Our answer to the former question is more equivocal, because we suspect that it permits of no answer in complete generality, as it is too dependent on particle shape and pattern of distribution on the plane. Moreover, no study has been undertaken to provide empirical evidence to guide one's choice.

4 Incorporating an Auxiliary Variate into LIS

Let $q_i(\theta_m)$ be an auxiliary variate measurable on P_i whose value may depend on the angle of orientation, θ_m, of T_m. Therefore, when θ_m is a random variable, then $q_i(\theta_m)$ is random, also, whenever its value changes with θ_m.

Consider the conditional estimator

$$\widetilde{\tau}_{ym}^{\mathrm{c}} = \sum_{i \in \mathcal{P}} \frac{t_{im} q_i(\theta_m) y_i}{E\big[t_{im} q_i(\theta_m) \,|\, \theta_m\big]}. \tag{9}$$

The corresponding unconditional estimator is

$$\widetilde{\tau}_{ym}^{\mathrm{u}} = \sum_{i \in \mathcal{P}} \frac{t_{im} q_i(\theta_m) y_i}{E\big[t_{im} q_i(\theta_m)\big]}. \tag{10}$$

When $q_i(\theta_m) = 1, \forall i$, then (9) is identical to (2) and (10) is identical to (5). When this condition does not hold, then (9) and (10) are not HT estimators. For a judicious choice of the auxiliary variate, $q_i(\theta_m)$, the actual measurement of y_i may be obviated, as in the following example adapted from Kaiser (1983).

Example 1

Suppose y_i is the "coverage" onto $\mathcal{A}$ of P_i, so that one is interested in estimating the total area of $\mathcal{A}$ covered by $\mathcal{P}$. For irregularly shaped particles, y_i is difficult to measure directly. Define $q_i(\theta_m)$ to be the length of interception of P_i by the line in $\mathcal{A}$ which contains T_m as a subset ($q_i(\theta_m)$ may be longer than just the interception length of T_m in P_i). In this case, $E\big[t_{im}q_i(\theta_m)\,|\,\theta_m\big] = y_iL/A$, so that

$$\begin{aligned} \widetilde{\tau}^{\,c}_{ym} &= \sum_{i\in\mathcal{P}} \frac{t_{im}q_i(\theta_m)y_i}{y_iL/A} \\ &= \frac{A}{L}\sum_{i\in\mathcal{P}} t_{im}q_i(\theta_m) \end{aligned} \tag{11}$$

In other words, one has replaced the tedious measurement of coverage area with the comparatively simpler measurement of its interception length.

Because $E\big[t_{im}q_i(\theta_m)\,|\,\theta_m\big] = y_iL/A$ does not involve the orientation of T_m explicitly, $E\big[t_{im}q_i(\theta_m)\big] = y_iL/A$, too. Therefore the estimator of coverage area unconditionally on orientation, $\widehat{\tau}^{\,u}_y$, is identical to $\widehat{\tau}^{\,c}_y$. We emphasize that this result, which does not hold in general, obtains here because of the particular choice of auxiliary variate to estimate coverage area. The auxiliary variate thus achieves two purposes: obviation of y_i and elimination of the dilemma between conditional versus unconditional estimation of τ_y.

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National Forest Inventory

Photo: John Y. Larsson
Picture from Sjodalen, Oppland.

The New Swedish National Forest Inventory

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Introduction

In Sweden, the National Forest Inventory (NFI) commenced in 1923, twelve years after a large-scale testing of methods had been conducted in the county of Värmland (Segebaden 1998). The first inventory cycle was completed in 1929. At that time a belt sampling design was used, with survey lines traversing entire counties (Thorell & Östlin 1931).

Over the time, the NFI has changed both regarding target variables and sampling design. For quite a long time, the main emphasis was set on the timber resources. Detailed assessments of soils started in the 1960s. From the 1980s onwards, substantial demands for new variables have emerged, e.g. information about forest health and biodiversity. Regarding sampling design, statistical evaluations led to a shift from the original belt sampling approach to a sample plot design (Matérn 1960). Thus, from about 1950 onwards, a cluster-plot system has been used, with circular plots allocated along a square or rectangular "tract". Permanent plots were introduced in 1983 (Hägglund 1985; Ranneby *et al*. 1987) in order to improve both the estimation of state and changes, as well as providing time series data for forest research.

The NFI is the responsibility of the Swedish University of Agricultural Sciences, but it is partly financed also by the Swedish Environmental Protection Agency. Nowadays the results are part of Sweden's official statistics and thus the NFI to some extent is regulated by law.

Major changes in the NFI historically have occurred with about 10-20 years intervals. For example, the introduction of permanent plots in 1983 was one such change. At that time, a partly independent soil and vegetation survey also was initiated and set to run parallel with the NFI, utilizing the same permanent plots. In 1993, only some minor changes were introduced in the field inventory, although many new techniques for the data computations were introduced. Thus, when a new cycle of the Swedish NFI started in 2003, twenty years had passed since the last major revision.

The objective of this paper is to provide an overview of the changes that were introduced in the Swedish NFI in 2003. Further, the objective also is to describe the main features of the current inventory, which is scheduled to continue until 2012 in its present form.

Revisions in 2003

In is commonly acknowledged that revisions of NFIs as far as possible should be avoided due to the negative effects changes tend to have when trends are to be interpreted and evaluated. Thus, major revisions in principle should only be made if (i) there are significant changes in information demands, or (ii) if major improvements in cost-efficiency can be achieved by using new survey designs or assessment methods. Of course, parts of an inventory also may need to be revised due to poor data quality although the underlying information requirements have not changed.

The main motivation for the revision of the Swedish NFI in 2003 was changes in information demands rather than the availability of new, more cost-efficient, methods.

The trend from the 1980s towards demands for data providing a more holistic view on sustainable forestry has continued. Thus, nowadays and in the foreseeable future, forests and forestry in Sweden need to be monitored and described from the point of view of many other aspects that wood production. Moreover, recently introduced Swedish forest and environmental policy largely is based on clearly specified targets and continued monitoring of whether or not the development leads towards the specified targets. In addition, there is an increased demand for data on county and sub-county levels and in this specific case new methodology, based on remote sensing, is available. Internationally, an increasing number of conventions and other agreements require information on forests, for example the Framework Convention on Climate Change and its Kyoto Protocol, with very detailed requirements of forest information.

Although a guiding principle during the revision of the NFI was to maintain the basic structure and make as few changes as possible, a number of changes were found to be motivated. These involved:

- The scope of the inventory was modified. New variables were introduced, some variables were modified, and other variables were dropped.
- The design of the inventory was modified.
- Remote sensing was introduced in order to provide local level estimates.
- New infrastructure in terms of computer programs for data acquisition and map production was developed and implemented.

Changes in the scope of the inventory

As pointed out above, the trend towards demands for information about multifunctional forestry has continued. Thus, the revision in 2003 implied a continued development towards providing data on a wide range of forest goods and services to meet these demands. New variables for assessing biological diversity were introduced, and some of the existing ones revised. Some variables were introduced in order to enhance the monitoring of forest carbon pools and in order to assess the recreational aspects of forests. However, regarding the carbon pools it was found that the former NFI contained most of the variables needed for the assessments. New variables also were introduced also in order to better describe some aspects of the timber production function of forests, e.g. variables describing the timber quality on sample trees. A number of revisions were made in order to improve the assessment of forest damages. These involved assessments at both stand and sample tree level, as well the procedures for assessing moose browsing damages. The regeneration survey within the NFI was dropped. The reason was the ambition of the Swedish Forestry Board to increase their activities within this field and thus this part of the NFI was dropped in order to avoid duplication of work. Moreover, the selection and measurement of top height sample trees was dropped.

Changes in the design

The basic principle of combining permanent and temporary plots has been found to work well in Sweden. Thus, it was decided to maintain this basic survey principle. However, due to increased demands for data on changes it was decided to increase the proportion of permanent plots and to move back from a practice with variable and rather long intervals between re-measurements to a system with a five years re-measurement cycle. From 2003 onwards, the proportion of permanent plots will be about 2/3. Changes also have been introduced at the plot level. The major ones involve the introduction of large plots (20 m radius) for the survey of sparse populations and small plots for the assessment of regeneration and vegetation. The regeneration plots have a 1 m radius and the new vegetation assessment plots a radius of 0.28 m. To be able to introduce new variables without breaking the time constraint that a team of three people should be able to complete a survey tract within one day, a separation of the permanent plots into two different types were made. On all permanent plots a core set of variables are assessed and thus re-assessed with a five years interval. The remaining variables are divided into two different groups corresponding to two different plot types; these variables are re-assessed with a ten years interval. This separation of the variables into different types makes sense also from the point of view that the changes in conditions in some aspects are very slow and thus a ten years re-assessment interval is sufficient.

Combination with remote sensing for providing local level estimates

There is an increased demand for local level information about forests in Sweden, mainly from local and regional administrative agencies. As is well known from Finland (e.g. Tomppo 1992) that such information can be made available at reasonable cost and accuracy by combining NFI plots with satellite remote sensing. Contrary to the case in Finland the principle used for deriving this type of statistics in Sweden is post-stratification (Nilsson *et al.* 2003). The main motivation for the selection of this technique is that its theoretical properties ensure unbiased estimates, whereas techniques such as kNN estimates may be biased. However, complete cover maps based on the kNN principle also have been developed.

New NFI infrastructure

New infrastructure for the NFI in terms of, e.g., software supporting the data acquisition and the production of maps also has been developed. The main motivation for the change in data acquisition software was that the old one could not easily be transferred to new hardware. Also, the old system was close to its maximum capacity regarding inclusion of new variables and thus further development of that system was found to be impossible. No system was previously available for the map production and thus the new system has made the process of planning the fieldwork simpler.

Organisation

Organisationally, the NFI continues to be linked with a separate soil survey, financed by the Swedish Environmental Protection Agency. The ambition during the revision has been to merge the two parts further, and in order to mark this the two inventories from 2003 onwards share a common umbrella name: the Swedish National Inventory of Forests (Riksinventeringen av Skog). However, the NFI and the Soil Survey remain as independent parts under this umbrella.

Overview of the new Swedish NFI

Given the changes described above, an overview of the basic components and features of the new Swedish NFI is presented in this section.

Design

The basic design of the inventory remains the same as before, i.e. a combination of permanent and temporary plots allocated in tracts, corresponding to one day's work for a field crew of three people (or half a day's work in the southern part of the country). As is well known, a combination of permanent and temporary plots is efficient both for estimating state and change (e.g. Schreuder *et al.* 1993). In addition, the permanent plots can be utilised for a number of different research purposes. So far in Sweden, no permanent plots have been replaced (except those that cannot be found), and thus the Swedish NFI so far has not used the principle of sampling with partial replacement (SPR), which has been suggested by some authors (e.g. Scott & Köhl 1994).

The country is divided into five different strata based on forest conditions and size of the counties for which accurate precision of the estimates is required. For each stratum, an optimal tract design has been developed based on the spatial autocorrelation features of major forest variables, like timber volume (Ranneby *et al.* 1987). This means that the size of tracts – and the number of plots within a tract – is smaller in the southern part of the country.

Each plot consists of a number of concentric circular plots, varying in size between 0.28 m and 20 m radius (a further description is given below). Basic measurements of trees are carried out within a 10 m radius on permanent plots and a 7 m radius on temporary plots.

The permanent tracts from 2003 onwards are of two different kinds: permanent tracts with assessments of soils and vegetation and other permanent tracts. These two types share a common basic set of measurements and assessments, whereas a number of variables are specific for the tract type. A "soils and vegetation" tract will be an "other tract" five years later (and so on) which means that the re-measurement interval for a core set of variables is 5 years, whereas for a number of other variables (e.g. variables based on soil sampling) it is 10 years.

All land (and water) in principle is included in the inventory. Thus, in case a plot falls outside the forest it is assessed what land cover and land use class it belongs to. In case a plot is divided by a boundary between different cover or land use types, each part of the plot is separately described. Thus, no mirage or similar methods (Schmid 1969, Ducey *et al.* 2001) are required in order to obtain a correct representation of boundary zones.

Observation and measurements

All definitions and measurement instructions are provided in a certain field manual (Anon 2004), and modern equipment is used as far as possible to avoid measurement errors and in order to make the fieldwork efficient. For example, the registrations are made on field computers; electronic hypsometers as well as distance meters are used. GPS equipment is used to locate the plots in the field. However, in case of temporary plots (or newly laid out permanent plots), the instruction is that a point a least 20 m from the plot should be located with the GPS, from which measurement with compass and tape is made. This procedure is practiced in order to avoid bias due to the location of plots in the field. Poor GPS receiving conditions in dense forests might otherwise lead to a bias in plot locations towards open parts of a forest.

A plot consists of a number of concentric measurement/assessment units, as outlined in the text below.

Stand level descriptions: It is well known that data from small plots cannot be used to correctly estimate areas of stands of different kinds, provided that the stands should be classified based on their stand level average parameter values. In this case estimates based on plot level data will overestimate the areas of stands with extreme conditions. To avoid this, some basic assessments in the inventory are made at the stand level. However, since a stand is a loosely defined concept and since the area it covers generally is far too large to allow for accurate measurements and assessments, only some very basic variables are registered at this level, e.g. forest management activities, stand development class, and the approximate size of clear-cut areas.

A loosely defined plot with 20 m radius: As a substitute for stand level descriptions, a loosely defined plot with 20 m radius is used for the description of "stand level" information such as basal area, mean height, tree species composition, mean age, and stand level damages. During these assessments, which to some extent are based on subjective judgement, an area up to 20 m from the plot centre is considered provided there is no stand boundary within this distance – in that case only the area up to the boundary is considered. This type of assessments is made on both permanent and temporary tracts. During the assessments, no strict measurements of the exact plot boundary are needed, since the larger area mainly is a conceptual framework for assessing stand level mean values.

A strictly defined plot with 20 m radius: Sparse objects in the forest require that a larger area be used for searching for them in order to obtain sufficient precision in the estimates. For this reason, a number of variables are measured/assessed in a plot with a – strict – 20 m radius. This concerns coarse trees, overstory trees in regenerations, and signs of past cultural activities. However, the features to search for must be very "obvious" so that they can readily be observed in a plot with 20 m radius, which is rather large.

A plot with 7/10 m radius: The core part of the inventory is carried out on plots with 10 m (permanent tracts) or 7 m (temporary tracts) radius. Here, all trees above 10 cm diameter are callipered and a certain number of sample trees are selected using a random mechanism. On the sample trees, a large number of variables are assessed, ranging from damages to height, crown height, and age. In addition, a bore core is taken from each tree on temporary tracts; the core is sent to the lab for detailed measurement of age and growth. On temporary plots, callipered trees are clearly marked in order to assure that each and every tree on a plot is measured exactly one time. The same basic principle is used on permanent plots, although in this case the marks on the trees are applied in a discreet manner, so that they should not be easily observed in case the forest is managed.

A plot with 5.64 m radius: Rather detailed assessments of vegetation cover and presence/absence registrations of species and species groups are made on a plot with 5.64 m radius. The reason for this exact size is that it equals 100 m^2 and thus cover assessments, which may often be made in terms of square-metre-coverages, can easily be transformed to percentages. More than 200 species and species groups are covered by the inventory. With the 5.64 m plot, description of soils and soil sampling also is made on some of the permanent plots. Soil samples are sent to the lab for further analysis and storage. The soil assessments are part of the Soil Survey (and thus formally not a part of the NFI).

A plot with 3.5 m radius: Small trees (4-10 cm radius) are measured on plots with a 3.5 m radius on both permanent and temporary plots. The reason for the smaller plot size is that small trees may be far more abundant than large trees, and thus registrations on a large plot would be both time consuming and potentially lead to poor quality due to missed trees.

Two plots with 1 m radius: Regeneration (trees between 0.1 m height and 4 cm diameter) is measured in two plots, each with 1 m radius. These two small plots are located 2.5 metres, diagonally opposite to each other, from the centre point of the plot system.

Two plots with 0.28 m radius: In the centre of each regeneration plot, the presence or absence of a limited number of common forest species is registered (in addition to the registrations in the 5.64 m plots). The reason for this is that the quality of the presence/absence registrations on the large plots has been found to be poor for some species; moreover, in principle, changes in occurrence for common species require small plots to be detected with reasonable accuracy. On the small plots, additional measurements of edible berries (Vaccinium myrtillus and V. vitis-idaea) and lichens of importance for reindeer herding are made as well.

Only a few of all variables assessed in the NFI have been mentioned above. A full list would require several pages space, and is not within the scope of this paper.

Considering methods used for assessing the different variables, it can be concluded that a mix of strict measurements and subjective judgements are used. During the analysis it is important to know what variables have been assessed according to strict measurement routines and which have been ocularly assessed. It is only for variables of the first kind that it is really meaningful to study short-term changes. Variables of the latter kind generally are subject to assessment bias that may change between years and thus indicate changes that have not occurred in reality.

Information management

elow, information management is treated in a “narrow sense”, restricting the presentation mainly to applications of information technology in different parts of the inventory programme. The discussion follows a sequence from inventory planning to analysis and dissemination of results.

In the planning phase, GIS routines are implemented for studying the layout of permanent and temporary tracts, and for producing different kinds of maps helping the field crews to locate the plots in the field. The field maps are produced within a GIS system overlaying different map and remote sensing data (satellite images or aerial photographs) to tailored field maps.

The next step in the planning of the inventory is to store selected parts of old inventory data – and map data – to the field computers that the field crews use for registering data in the field. The major issue in this case is the selection of data from permanent plots visited 5-10 years earlier. This involves data about trees and tree locations, to be updated during the re-measurements of the permanent plots.

During the fieldwork, all data are registered in field computers and submitted to the coordinating office at regular intervals on CDs. Many data consistency checks are implemented directly in the field computers. Further checks are made at the office when the CDs are received, and potential data problems are reported back to the field teams.

Two different databases are used, one in which preliminary field data are stored, and one where the final data from each year’s inventory are stored. Thus, there is a clear separation between preliminary – not yet fully checked data – and the checked “final” data. During the transition from preliminary field data to final data, there is also a number of computations to be conducted, e.g. for deriving volumes for all living and dead trees from the basic measurements of diameters, heights, etc.

The final databases are very large, since all data from all previous years in principle need to be available during analyses. Regular backups are made of these databases. Currently, data from 1953 onwards are available in digital format, and the long-term ambition is to make also the previously collected data available in such format.

Since the inventory changes over time it requires great knowledge and skill to use the “raw” databases for various kinds of analyses. To overcome this problem, a semi-automated analysis program – using SAS macros – has been developed for use within the NFI group. This program automatically handles a large number of details (e.g. shifts in design and definitions) that need to be considered during analyses in order to avoid erroneous results. Thus, this program facilitates analyses of the material to be made in a controlled manner.

Every year, standardised results are produced in a yearbook (“Skogsdata”) from the NFI. These data also are made available over the Internet. In addition to this, interactive web-systems have been developed. For soils and vegetation data, a separate Internet system ("MarkInfo") has been developed.

Modelling for estimation and monitoring

Standard results from the inventory are of different kinds. Some main types of output are:

- Estimates of present state
- Time series (series of present state estimates)
- Change estimates
- Forecasts of future conditions

Each of these types is treated in a separate section below, regarding models and estimation principles used.

Estimates of present state: The standard procedure for deriving estimates of present state for a certain variable within a certain region is that separate estimates for a specific year is estimated using (i) data from permanent plots from that year, (ii) data from temporary plots from that year, and (iii) data from past inventories of temporary plots, updated using difference estimates from permanent plots. Thus, three different estimates are obtained, and these are then combined using principles of weighting inversely proportional to the variances - considering also covariances between the estimates – see e.g. Raj (1968). Some variations on this theme exist, regarding the use of data from temporary plots inventoried in the past. In general, at least for estimates within restricted areas, moving averages over several years are required in order to obtain estimates with reasonable standard errors. Thus, to obtain an estimate for year 1995 (e.g.) a standard procedure would be to make estimates for 1993-1997 according to the principles above, and then compute an average figure, which would correspond to the state in year 1995.

Time series: Since data are available from 1953 in digital format, presentations of time series for different variables are popular. The standard approach to this – although in some cases questionable (see "change estimates" below) – is to compute a series of moving averages present state estimates.

Change estimates: Change estimates between two time points may be taken as the difference between present states according to the principles outlined above. However, from a theoretical point this would give far too much weight to the information from temporary plots in relation to the information from permanent plots. Thus, in principle another estimation procedure should be adopted when changes between two specific time points are being estimated. If we consider an idealised case where the time difference for the change estimate corresponds to the re-measurement interval for permanent plots, two separate estimates of the change can be computed: (i) the difference in state based on the permanent plots, and (ii) the difference in state using the temporary plots. Thus, two different estimates are obtained, and these are weighted inversely proportional to the variances. However, in general the weight given to the permanent plots in this case will be much higher than the weight given to the temporary plots, i.e. the permanent plots are very powerful for the estimation of changes.

Forecasts of future conditions: Although state and change estimates are very important outputs, the most powerful output from the Swedish NFI probably is the results produced with the forecasting system Hugin (Lundström & Söderberg 1996). This system utilises NFI data as input and estimates future forest conditions and resource utilisation potentials given different scenarios. The main dynamic part of the modelling system is the growth and yield functions for single trees derived by Söderberg (1986). Hugin starts by updating the NFI data to a certain reference year and then produces modelled output every 10th year in an arbitrarily long forecasting period. Currently, the research programme Heureka aims to build new systems for long term forecasting of Swedish forests. The main difference in comparison to Hugin is that Heureka will be able to model the conditions for a large number of forest goods and services whereas Hugin has mainly been targeted on timber. Heureka is likely to be functional in year 2006.

Outputs

A large number of national and international users use data and information from the Swedish National Inventory of Forests for a large number of different purposes. The main outputs from the inventory are:

- Standardised results presented yearly in a statistical yearbook as well as over the Internet. In the yearbook, each year a specific theme is covered in addition to the standard results.
- Interactive presentation of results over the Internet, see e.g. www-markinfo.slu.se and www-riksskogstaxeringen.slu.se
- Regular reports to international conventions and organisations, such as the United Nations Framework Convention on Climate Change (UNFCCC) and UN/ECE's and FAO's Forest Resource Assessments. For the reporting under UNFCCC, a certain reporting subsystem is currently being developed.
- Scenario analyses using the Hugin system, e.g. in connection with regular evaluations of Swedish forest and environmental policy conducted by Swedish Governmental Agencies.
- Regular follow-up of the Swedish Environmental Quality Objectives.
- A large number of analyses and reports prepared on demand every year in response to inquires from forest companies, national and international organisations, and researchers.

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The Finnish NFI10: Changes in Design and Measurements

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Abstract

The field plots of the 9th National Forest Inventory of Finland (NFI9) were measured in years 1996 – 2003. The sampling design of NFI9 was following the design of previous inventories: each year measurements were concentrated in 1 or 2 Forestry Centers. Thus, for some parts of the country we have very new data (e.g. Lappland measured in 2003) whereas some parts of the country have field data from the year 1996. When planning the 10th NFI we decided to change our system similar to the design applied in most countries: we measure field plots in the whole country each year. At the same time, we decided to shorten the inventory cycle down to 5 years so that the NFI10 field plots should be measured in years 2004 – 2008.

Naturally, these changes have caused increase in the annual costs. To reduce the costs of field work, we have slightly reduced the sampling intensity and measured variables. The major changes are that 1) dead wood is measured on permanent plots, only and 2) key biotopes are not observed. Few other variables have been dropped.

On the other hand, we have increased the accuracy of basal area measurements in thinning and mature stands. The number of seedlings in seedlings stands is measured in more detail, and there are some other minor changes, also. With these changes we aim at improving the feasibility of NFI data in estimating quality of recent silvicultural operations and need for future operations.

Plan for Inventory of Forest and Woodland Resources in Iceland

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Abstract

Icelandic Forest Research has launched a project titled Icelandic Forest Inventory (IFI), mainly to meet the requirements of the Kyoto protocol concerning greenhouse gas accounting of the forests and woodlands of Iceland. The main emphasis will be on carbon accounting measures for the first commitment period of the Kyoto Protocol, 2008-2012. A total of 4 to 5 million seedlings are annually planted by the forest sector in Iceland. Relatively good statistics are available on the number and rough location of planted seedlings. On the other hand, information about the size and exact location of afforestation sites is poorly documented. Accordingly the first task of IFI is to compile a database about size (area), geographic location and contours of all afforestation sites (plantations). For this purpose IFI will rely heavily on the use of geographical information systems (GIS). Each plantation will be an independent polygon situated in the official geographical co-ordinate system of Iceland.
To date, sufficient data have been compiled for approximately 3/4 of afforestation sites planted during the period 1990-2002. In 2003 IFI established a routine for compiling these data on an annual basis. These data have now been used to recalculate the area of the plantations. Data concerning plantations established before 1990 will also be compiled, but with lesser stratification. To update the database of the native woodlands IFI will use results from previous inventories carried out in the 1970s and 1980s, complemented with results analysed from remote sensing data. The next step will be to create a systematic sample of permanent mensuration plots where carbon and wood stock, among other valuable data, will be sampled. In the spring of 2005 IFI will be prepared to start the first measurements on permanent plots. This will be finished in the autumn of 2009 and in 2010 re-measurement will start. The differences in carbon stock between these inventories will form the basis for an estimate of mean annual change in carbon stocks, among other things, during the first commitment period of the Kyoto protocol.

Keywords: National forest inventory, carbon stock change, Iceland.

Introduction

Before the 9th century settlement the Icelandic lowlands were dominated by birch (*Betula pubescens*) woodlands (Sigurðsson S. 1977), which is in accordance with the classification of Iceland as a part of the northern boreal zone (Tuhkanen 1993). At that time the birch woodland cover is estimated to have been 28,000 km^2 or about 27% of the total land area of Iceland. After settlement severe degradation of both the birch woodlands and the vegetative cover in general was induced by human activities (grazing, cutting and burning) and accelerated by the cooling climate and frequent volcanic eruptions.

In modern times the cover of the native birch woodlands has been estimated at only 121 km^2 or approximately a 96% decrease since the time of settlement 1,100 years ago (See fig. 1).

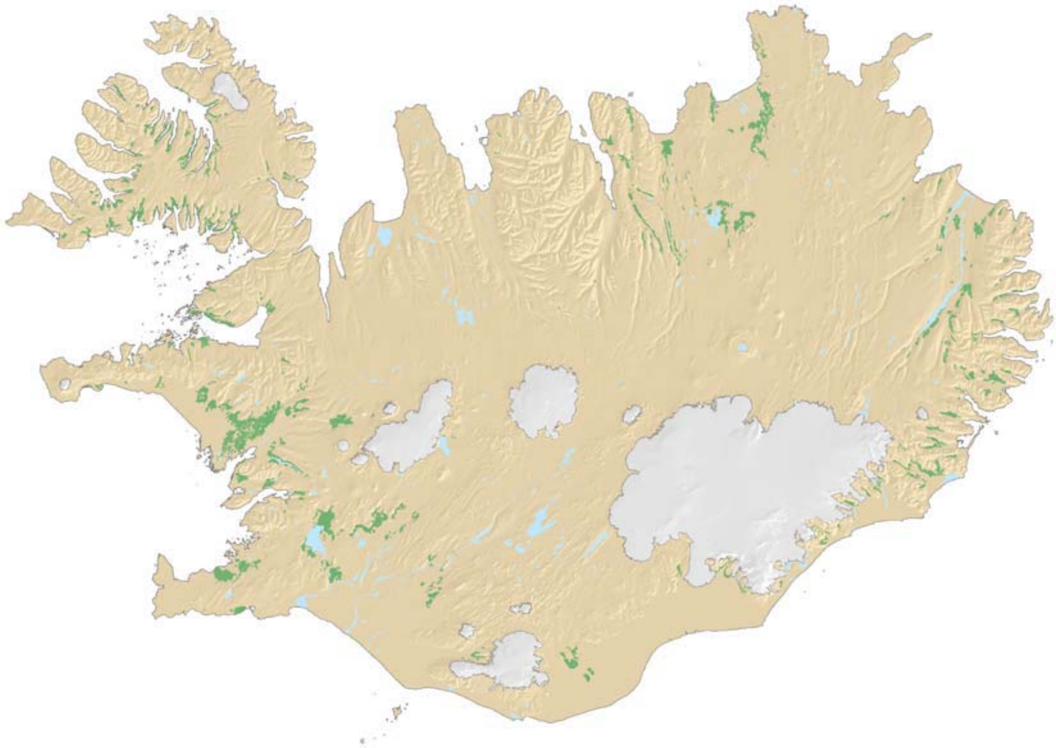

Figure 1. Map of the native birch woodlands in Iceland, based on two inventories in the 1970s and 1980s.

Experiments with exotic tree species started in Iceland in1899 (Blöndal S. 1977). Afforestation of treeless areas, both with exotics and native species, gradually increased throughout the 20th century, with a big jump upward first in the 1950s and again in the ‘90s, as seen in figure 2 (Pétursson 1999).

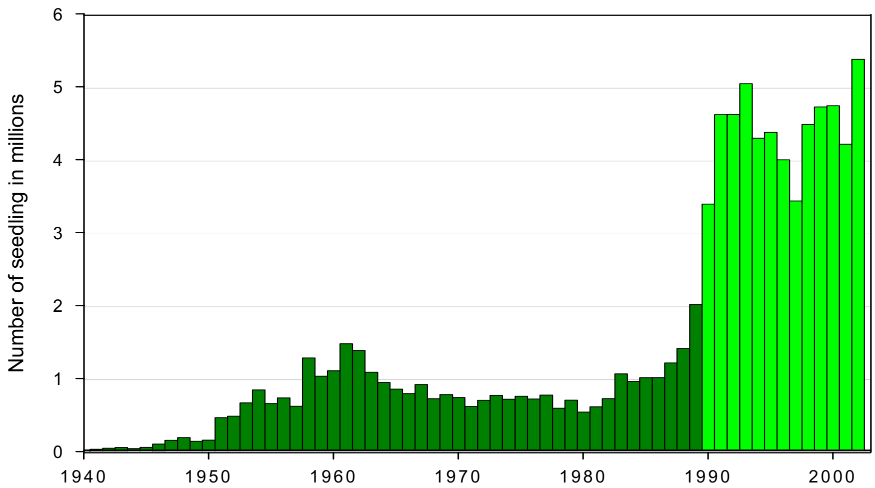

Figure 2. Number of seedlings planted each year from 1940 to 2002.

The Kyoto Protocol was ratified by the government of Iceland on May 23, 2002 (The Ministry of Environment 2003). The Ministry of Agriculture is responsible for greenhouse gas accounting in the sector of land use, land use change and forestry (LULUCF). As a response to requirements and guidance from the international arena the Ministry decided to initiate a national forest inventory. Icelandic Forest Research, i.e., the research branch of the Iceland Forest Service, has launched a project named Icelandic Forest Inventory (IFI) to carry out this task.

Former inventories of forests and woodlands

Relatively good national statistics are available on the number of planted seedlings and the approximate location of plantations. These data have been used to estimate the area of plantations. On the other hand, information about the size and exact location of afforestation sites varies in quality (Sigurdsson & Snorrason 2000). In 1998 data about the majority of afforestation sites established before 1985 were collected. For each site area, mean height and species ratio were assessed subjectively. However, these data have not been analysed or compiled as an inventory subject.

The focus has mostly been on the native birch woodlands. Two national surveys have been conducted. In the first one, carried out in 1972-1975, all woodlands were mapped on aerial photographs and divided into homogenous units or polygons. For each unit a set of variables was collected, for example mean height and crown cover (Sigurdsson & Bjarnason 1977). The latter survey was carried out in 1987-1991 and was a more in-depth field inventory on sampled transects (Aradóttir et al. 2001). A new inventory of the area was not completed but the area data from the first inventory were partially improved with new data from mapping of vegetation and field mapping. A map of the woodlands was digitised, projected in an official geographical co-ordinate system for Iceland known as ISNET93 and published as part of a vegetation map of Iceland (Gudjonsson & Gislason 1998). A final reporting and publishing of the latter inventory of the native woodlands has not yet been completed.

The IFI inventory scheme

The project "Icelandic Forest Inventory" (IFI) was launched in 2001 and from the outset it was clear that the main effort would be on carbon accounting measures that would affect the national greenhouse gas inventories for the first commitment period of the Kyoto Protocol, 2008-2012.

Carbon stock changes, both emissions and removals of afforestation after 1989 (defined under Art.3.3 of the Kyoto protocol) will be involved (Kyoto protocol 1997). Older afforestation fields will, on the other hand, only affect national greenhouse gas inventories in the case of emission, i.e., if these plantations will be deforested during the first commitment period (UNFCCC 2001). The same is the case for the native birch woodlands; only human induced deforestation will affect the national greenhouse gas inventories under the Kyoto protocol.

Accordingly, the priority of IFI is to compile a database about size (area), geographic location and contours of all plantation areas defined as a Kyoto-afforestation area. For this purpose IFI relies heavily on the use of geographical information systems (GIS). Each plantation will be an independent polygon projected in the Icelandic co-ordinate system. Because of the young age of these plantations they cannot be remote sensed and IFI will have to rely on information from forest managers. The main constituents are six independent regional and one national afforestation project, the forest associations, the Iceland Forest Service and the Soil Conservation Service of Iceland. In 2001 these constituents planted about 98% of the forest tree seedling production (Petursson 2002).

The main effort in the project is to consult with the personnel of the afforestation projects and to encourage them to use standardized variables and methods with the help of GIS to get an overview of the afforestation sites planted each year on numerous farms and properties in each region of Iceland. To date, sufficient data have been compiled for approximately 3/4 of the afforestation sites planted during 1990-2002. IFI has established a routine for compiling these data on an annual basis. Data for 2003 and the coming years are compiled as a matter of annual routine and published in the following year. Figure 3 shows an example of a Kyoto afforestation project on a farm in North Iceland where necessary geographical and tabular information have been placed in the IFI geographical information system.

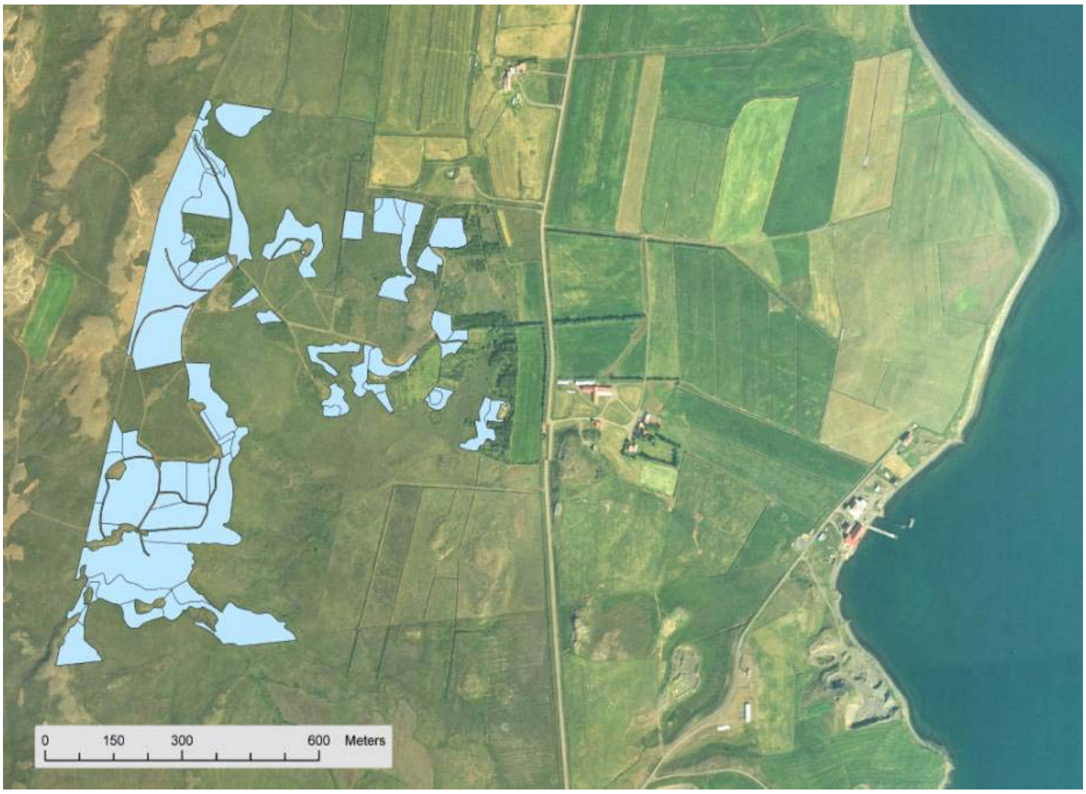

Figure 3. Colour air photo of a farm in North Iceland where Kyoto afforestation registered in the IFI GIS database is highlighted (in light blue).

Data concerning plantations established before 1990 will also be compiled but with lesser stratification. To identify and locate these plantations we will use remote sensing based on both SPOT-5 satellite images and colour flight images complemented with the inventory data from 1998 and information from forest management maps. As Figure 4 shows that middle-aged conifer plantations are clearly discernable on SPOT-5 images.

Figure 4. SPOT-5 satellite image of a recreation forest south of Reykjavik. 40 year old conifer plantations are very distinctive with their dark green colour and can easily be remote-sensed.

For the native birch woodlands, results from previous inventories, in combination with the analysis of remote sensing data, will be used to monitor changes in area. Compilation of data about direct human induced deforestation will go through official institutions, e.g., the Public Roads Administration and the Planning Agency, which supervise or are responsible for processes that can lead to deforestation. These institutions have been and will be informed about the importance of these data.
The Agricultural Research Institute is presently running a project called "The Icelandic Farmland Database" where remote sensing of vegetation of all land areas in Iceland is the main objective (Arnalds & Barkarson 2003). One of the ten vegetation classes analysed is “woodland and forest”. This class will cover both plantations and native woodlands that can be recognised with the remote sensing technique. The results of this work will provide an excellent reference for the work of IFI on further divisions of plantations and native woodlands.

The other main approach to the estimate of the forests and woodlands will go through a systematic sample of permanent mensuration plots where carbon and wood stocks, among other valuable data will be sampled. In the spring of 2005 IFI will be prepared to start the first measurements on permanent plots, which should be completed in the autumn of 2009, and then in 2010 re-measurement will start. The stock change calculations in the beginning will be built on the difference between increment and drain estimates. Increment will be estimated with tree growth during the five years preceding the last measurement, and drain with stump and dead wood measurements. After re-measurement the differences between past and present stocks will be used. Measurement plots will be laid out both in plantations and native birch woodlands. Variables sampled and sample intensity will partially differ but the output for the main group of variables will be fully comparable. All C-stock and C-stock change measures for managed forests and woodlands will be analogous and fulfil the quality and uncertainty standards provided by the Good Practice Guidance for Land use, Land-use change and Forestry (IPCC 2003).

Estimate for present afforestation, reforestation and native woodlands cover in Iceland

IFI classifies the forests into three categories: (1) Afforestation before 1990, named Pre-Kyoto-Afforestation. Its area is estimated only by the number of seedlings planted annually to 6,600 ha. and with a mean age of 34 years. (2) Afforestation from 1990 to 2003, named Kyoto-Afforestation, is estimated to at 19,000 ha with a mean age of 8 years. In this case IFI used the results from the new area inventory for plantations in 2003, together with data on the number of planted seedlings (Snorrason & Kjartanssson 2004). (3) Remnants of native birch woodlands are still assumed to be unchanged in area from former surveys but the digital maps have recently been skimmed for errors so that latest update for the total area is 120,600 ha or about 1.2 % of total land area.

In coming years these estimates will be improved with more scientifically approved methodology, as described earlier.

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Nordic Biodiversity Indicators Based on National Forest Inventories: Methods, Results and Further Development

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In 1998 the Nordic Council of Ministers initiated a project with the aim to establish common statistics for the variation in forest types and states in the Nordic countries. The project should classify and quantify the natural variation as well as the variation caused by forestry. The databases from the national forest inventories (NFI) should be the empirical basis for the project. On the basis of the analyses the project should establish a common proposition of field parameters, data analysis methods and indicators for forest biodiversity monitoring. The results should thereby contribute to a more comprehensive forest management through connecting biodiversity monitoring to existing monitoring of natural resources and resource use in forest ecosystems. The project was called Biodiversity and forestry in the Nordic countries (BioNord) and it produced a report in the TemaNord series of Nordic Council of Ministers (Stokland et al. 2003).[1]

The underlying motivation for the project was increased importance of biodiversity in the context of sustainable forest management in the early 1990-ies. At the United Nations Conference on Environment and Development in 1992, the topic of biodiversity received much attention that led directly to two resolutions on sustainable forestry and biodiversity conservation on the second MCPFE conference in Helsinki in 1993. These two resolutions have generated much subsequent work on indicator development to assess the sustainability of European forestry. The project report related directly to this work and presents the results of an attempt to harmonize and quantify a set of biodiversity indicators on the basis of NFI data in three Nordic countries (Finland, Norway and Sweden).

Forest biodiversity

The project report adopts the definition of biodiversity put forward by the Convention of Biological Diversity in 1992. In a separate chapter it gives a brief description of the biological diversity in the Nordic countries at the ecosystem, species and genetic level.

Harmonization methodology

The project needed to develop a methodology to process data from individual NFI databases to a common set of harmonised and explicitly defined indicators. This methodology was applied for all indicators and comprised the following elements: a) description of the data source and comments on data pre-processing, b) harmonised classification categories for the parameters being used in the indicator, c) area basis,

[1] On behalf of the project, see acknowledgements.

i.e. which part of the forest area that has been used to calculate the indicator value, and d) unit of measurement to quantify the indicator.

Results of the indicator work

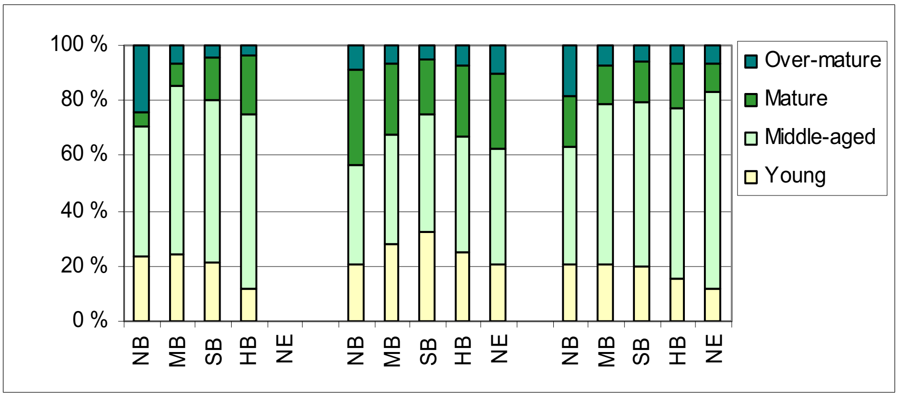
The project defined and quantified 24 indicators that are relevant for the state and development of forest biodiversity. NFI data is the empirical basis for 19 indicators, and 5 indicators are based on other data sources. In addition, we have suggested several potential indicators for which data is not available (at least in some countries) or we have not given the potential indicator priority in our work.

The indicators are grouped in the following major themes (concept areas):

1) Forest area and land cover, quantifying the forest area as a proportion of the total land area in each country.
2) Resource management, quantifying the growing timber stock and the balance between increment and felling.
3) Forestry methods and land use, quantifying the extent of various methods and practices that are adopted in the Nordic countries.
4) Forest dynamics, quantifying the extent of different natural disturbances that affect the forest states.
5) Forest states, quantifying tree species composition, age distribution, dimension of living trees, tree mortality and dead wood, important substrates, and landscape patterns.
6) Species diversity and threatened species, enumerating the number of forest species in different organism groups.
7) Conservation measures, quantifying the amount of protected forests. As a general rule, the project has subdivided the indicators in 5 climatic zones according to the established system of vegetation zones for the Nordic countries.

The results are presented in the format of tables, histograms and maps in order to exhibit a detailed picture of the forest states (fig. 1). Each indicator is commented to highlight the main finding(s), similarities and differences between the countries as well as weaknesses or sources of errors to consider when interpreting the results.

	Young			Middle-aged			Mature			Over-mature		
	F	N	S	F	N	S	F	N	S	F	N	S
North boreal	1170	352	780	2305	602	1618	240	579	713	1207	154	694
Mid boreal	1767	760	2006	4528	1079	5618	577	699	1345	493	185	715
South boreal	1530	584	624	4250	763	1828	1109	351	461	329	96	173
Hemi boreal	65	270	977	347	450	3840	115	272	1038	20	79	399
Nemoral	0	25	64	0	51	376	0	33	53	0	13	37
Total area	4532	1991	4451	11430	2945	13281	2040	1934	3610	2048	527	2018



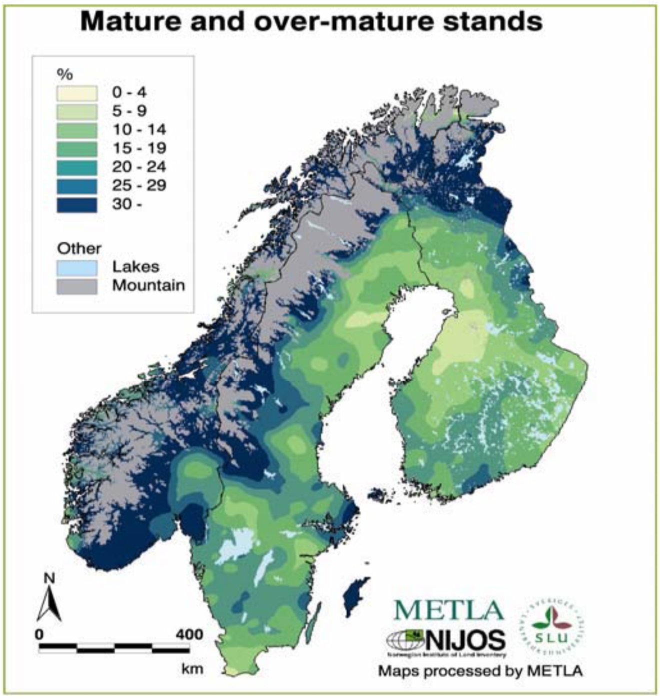


Figure 1. Example of result presentation from the report. Area of different development classes presented in format of table, histogram and map.

Results of prognosis work

For a selected number of indicators (growing stock, annual increment and fellings, proportion of old forest, big trees, annual mortality, and protected area), we have made prognoses of 100 years future development. Three scenarios are used: a) continuation of forestry practices from the 1990s, b) slightly increased stand rotation cycle and less removal of broad-leaved trees, and c) increased stand rotation cycle and amount of forest reserves. One province in northern Sweden and another in southern Sweden have been used as example areas. The scenarios demonstrate that the forest state may develop quite differently under alternative management regimes.

Evaluation of the NFI

The national forest inventories in Finland, Norway and Sweden consist of 10 000 – 70 000 individual plots distributed in a regular grid throughout the forest area in each country. These grids are sufficiently dense to quantify reliable indicator values for the majority of the indicators on a national and regional level adopting the system of vegetation zones. The field methods and parameters vary somewhat between the three countries, but they are sufficiently similar to produce harmonized indicator values. For most indicators it was impossible to produce comparable statistics from Denmark. The main reason is the lack of a NFI in Denmark (prior to the project period). Although much forest statistics has been produced in Denmark, this database comprises aggregated data without the flexibility to be recalculated according to a specified set of parameters and measurement units.

For some rare phenomena (e.g. large standing dead trees), the area basis was too small to produce reliable results, especially when the indicator was disaggregated to a regional level. It is possible to circumvent this problem by expanding the census area (e.g. by expanding the plot area, introducing transect lines between plots or increasing the number of plots).

The NFI plots in their current format are inadequate to quantify indicators describing landscape patterns because of the small plot size (typically 0.1 ha or smaller). It is not efficient to increase the field plot size for this purpose. A more promising approach would be to apply sample based remote sensing (airborne or satellite-borne) in combination with calibration data from the NFI field plots.

Some biodiversity indicators should or must be derived from other data sources than the NFI. In the project we have defined and quantified a few such indicators. Examples are *number of threatened forest species and total number of forest species, area with forest fire, and area of strictly protected forest.* Thus, although NFI data are highly relevant for establishing biodiversity indicators, other data sources must also be utilized.

The BioNord indicators are compared with three indicator systems: the MCPFE indicators for sustainable forestry in Europe, the BEAR indicators suggested for the “Environment of Europe” process, and the general DPSIR system adopted by EU. These systems have several features and specific indicators in common, but they also complement each other in important ways. The BioNord indicators have largest similarities with the MCPFE indicator system.

Need for future development

Based on the work carried out in this project we suggest that future development of NFI and the associated production of indicators should follow three lines:

1) Data acquisition methods. Field methods should be harmonized further by revising measurement units or classification categories of existing parameters (e.g. canopy cover percentage classes for different trees, decay classes of dead wood), and by introducing new parameters (e.g. standardized habitat classes, a limited set of indicator species, breakage class of dead wood). It is highly relevant to develop sample-based methods using remote-sensing data for indicators on landscape patterns. This development work includes both interpretation challenges for identifying relevant forest types and states, as well as assessments of different scales or plot sizes (1 to 100 km^2 and more) to identify different patterns.

2) Indicator development. Considering the number of parameters in the NFI, the number of parameter combinations and possible indicators is very large. It is a challenge to develop a relatively small set of indicators that a) are complementary to each other, b) comprise the most important key factors for forest biodiversity and c) can be measured in a standardized manner across different forest types and regions.

3) Biological validation of indicators. It is an underlying assumption that the indicators really say something about forest biodiversity. This assumption has rarely been explicitly validated. Thus, it is necessary to establish data sets that simultaneously quantify different indicator states (several indicators simultaneously) and direct measurements of biodiversity components (e.g. species composition, number of species in different organism groups, number of endangered species). On this basis it is possible to sort out the importance of different indicators for biodiversity states.

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Ulf Söderberg, Hans Toet, Torben Riis-Nielsen.

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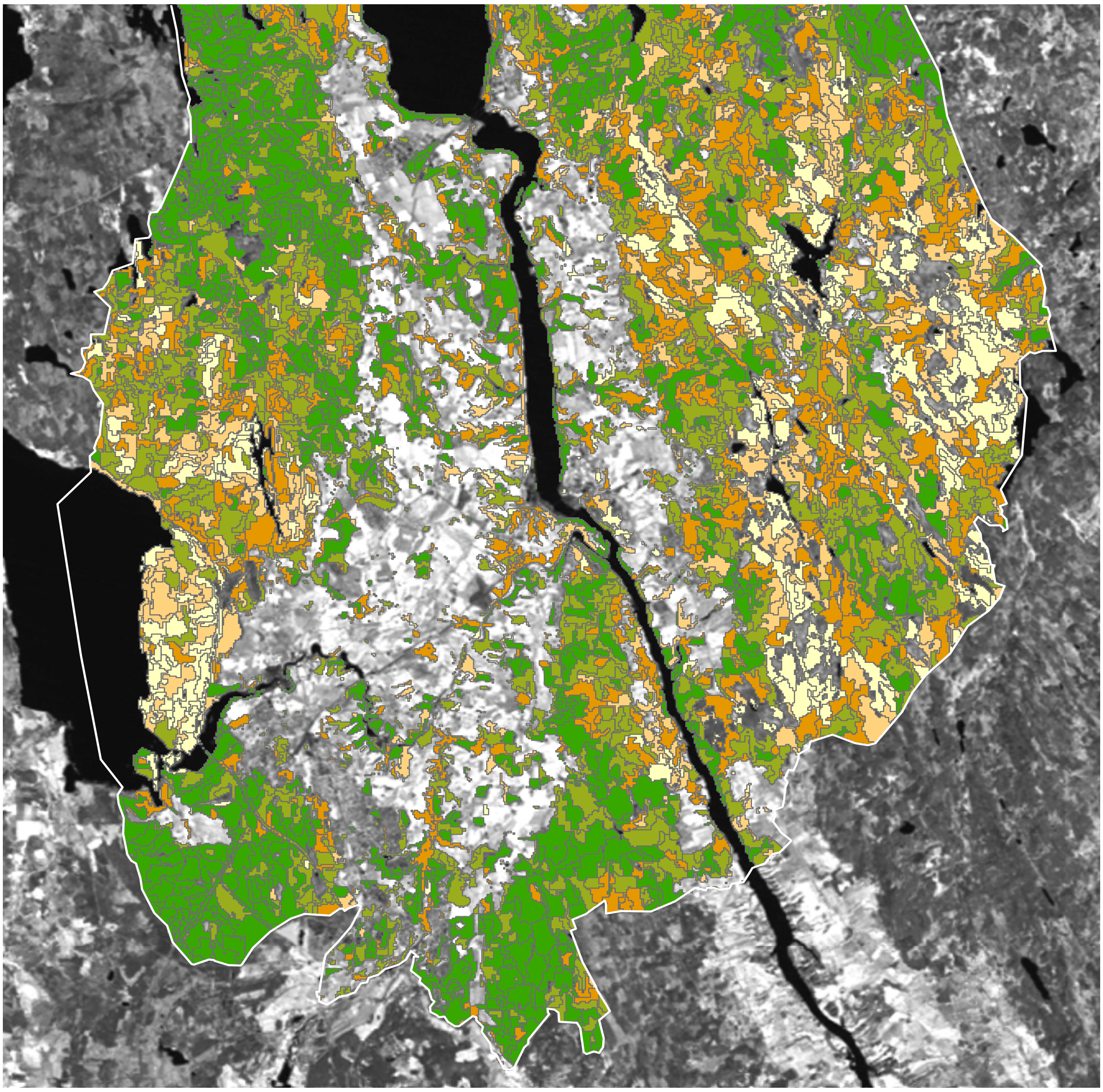
Remote Sensing Studies



Satellite image from Eidsvoll. Akershus.

Supply of Earth Observation Data beyond Landsat and SPOT

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Abstract

The Landsat and SPOT satellites currently used operationally by for example the National Forest Inventories in Finland and Sweden, and the Swedish Forest Administration, are the last in their respective series. Early planning for new series of operational medium resolution satellites is presently ongoing in USA and France. However, these new sensors could, if at all realised, not be operational until at the earliest 2010. In this paper is therefore other possible satellite missions that, if needed, could fill the gap between now and year 2010, discussed. In conclusion, there will most likely be medium resolution satellite data available also before 2010, but it is difficult to tell which candidate sensors that will be practically available for forest monitoring in Scandinavia. These candidate sensors from nations outside EU and USA also have in common that the scenes are generally smaller than for Landsat; and the short wave infrared band (which is of high importance for forestry applications) is missing.

Introduction

For more than 30 years, the forestry community has had good access to medium resolution satellite imagery. Landsat 1 with the MSS sensor producing 80 m pixels was launched 1972; Landsat 4 with the TM sensor producing 30 m pixels was launched in 1982; SPOT 1 with 20 m colour and 10 m pan pixels was launched 1986; and the IRS 1A with 36 m pixels was launched 1988. The availability of data from these satellites and their followers in the respective series, has formed the basis for nationwide operational applications among forest authorities in Scandinavia. Examples are the kNN estimations carried out by the Finnish and Swedish National Forest Inventories (NFI) and the nationwide and annual mapping of clear felled areas which is carried out by the National Board of Forestry in Sweden. Also the national forest inventories in some other countries, for example in the USA and India, are using satellite data as part of their inventory methods.

However, there is now a risk for interruption in this data flow. Since May 31, 2003, there has been a permanent failure in the Scan Line Corrector in the ETM+ sensor onboard the Landsat 7 satellite, resulting in severely degraded images. The US Government has not given priority to the construction of a new ”Landsat 8”, thus there is currently no replacement in place. Furthermore, the current SPOT 5, which was launched in May 2002 and has a design lifetime until about 2007, is the last in the SPOT series. The next generation of French satellites, the Pleiades, will have small pixels (0,7 m) and only 20 km wide scenes, and will thus not be suitable for large area forest monitoring. The Indian Space Research Organisation has so far provided an uninterrupted series of operational land remote sensing satellites. The most recent, IRS P6, launched in October 2003, is number 10 in the IRS series. It receives images with down to 6 m pixel size and up to 70 km wide swaths. However, the next three satellites in the IRS series are less useful for large area forestry purposes; what is planned next is one stereo imaging satellite with only 30 km wide scenes (Cartosat-1), one high resolution satellite with only 10 km wide images (Cartosat-2), and one Radar satellite named RISAT.

Thus, there is a serious risk of interruption in the data flow from the series of remote sensing satellites currently most used for operational forest monitoring in Scandinavia. The aim of this paper is to outline some of the alternate options that might be available in the future as temporary substitutes, as well as more long term permanent solutions.

Satellite data needs

This paper addresses the need for satellite data for nationwide forestry applications, for example large area estimates of forest variables of the “kNN-type”, where data from National Forest Inventory field plots are combined with satellite data, or the nation-wide mapping of clear-felled areas carried out by the Swedish Forest administration. For those types of applications, the experience is that there is a requirement for data with basically the following features:

- *pixel size 10 m – 20 m*, (which might be extended to 5 m – 30 m), thus we get a “many trees per pixel and many pixels per stand” imaging situation;
- a few *multispectral bands* in the visible and Near Infrared region, and preferably also in the Short Wave Infrared (SWIR) region, where the correlation with forest biomass and forest stem volume is strongest;
- *large scenes*, preferably with a swath width on the order of 200 km, in order to get many NFI plots per scene and a limited number of scenes per country;
- *good geometric properties* are important in order to enable good matching between image data from different dates, and also between image data and geo-located NFI plot data;
- *good radiometric properties* are also preferable, especially registration of several grey levels in the interval 0 – 5 % ground reflectance, since the boreal forest is a very dark object.

Above all, besides the above technically oriented whish list, there is a need for continuity in the data supply, as well as ground receiving, pre-processing and distribution of the data.

Even if the products from the above described type of “medium resolution” satellite data are useful for the overviews needed by authorities, they do not generally contain enough information for being used alone as a data source for operational forest management planning. For such applications more information rich data are needed. One step in this direction would be to use Ikonos and Quick Bird type of satellite imagery with one meter pixel size or better. In that case, we get a “many pixels per tree” imaging situation, which provides additional information about for example tree-size. However, at present, such imagery covers very small areas and are not cost efficient for the nationwide applications addressed in this paper.

In the next two sections, different candidate missions for supply of medium resolution satellite data beyond Landsat and SPOT are listed. In addition there exists a large number of "one-time" more or less experimental sensors sent up by different nations. Preference has therefore been made here to include sensors that are expected to be reasonably operational and preferably also operated as a series of satellites rather than single missions.

Candidate missions, possible long term solutions from USA and Europe

NPOESS OLI

During year 2004, the lack of data continuity for medium resolution satellite data, has been given attention in USA and Europe. The maybe most important sign of this was a letter from the office of the president in USA, August 13, 2004, expressing the US commitment to provide a continuity of Landsat-type of satellite data (the letter is available at: http://ldcm.nasa.gov). This was followed by the release of the plans to place a sensor called Operational Land Imager (OLI) onboard the future generation of US weather satellites, NPOESS (Irons and Ochs, 2004). The use of NPOESS as sensor carrier is a very appealing solution, since it would mean that the future replacement for Landsat would be sensors onboard a truly operational series of satellites which at present are planned until at least 2019. However, the launch of the first operational NPOESS will not take place until earliest late 2009. There is therefore also a current discussion in USA about the need for sending up a "gap-filler mission" with a sensor that could provide Landsat-like images already before 2009 (Irons and Ochs, 2004). However, no firm news about that option has been announced yet.

"GMES mission on land surfaces", early activities by CNES and ESA

In Europe, the need for a continuation of operational medium resolution satellites of SPOT / Landsat – type, has become especially evident during the work within the GMES program (http://www.gmes.info/). The French Space Agency, CNES, is therefore currently running a project where definitions for a *"GMES mission on land surfaces"* is being worked out. Current discussions are to send up a constellation of 3 – 6 mini or micro satellites with sensors providing 10-20 m pixels in at least four bands in the range visible – NIR – SWIR. The scene-width for the images would be in the order of 160 - 390 km. It looks like such a system would fulfil the above indicated forestry needs very well. However, due to the early stage of this project, it is unlikely that it, if at all realised, could provide images to end users before 2010.
Also the European Space agency (ESA) has observed the need for future medium resolution optical satellites. ESA has proposed a sensor called "superspectral imager" as part of a future GMES system, however, this project is in an even earlier phase than the French project and will need approval at the next ESA council at ministerial level, scheduled for the summer 2005.

Candidate missions, possible new satellites in the period 2005-2010

It is likely that there will be a time gap between the currently used satellites Landsat, SPOT, and IRS, and the introduction around 2010 of new operational capacity owned by USA and Europe, respectively. A selection of missions that could fill this gap is therefore listed below and in Table 1b. ALOS is a scientific satellite that not is part of a series, but it is included because of its timeliness (launch planned late 2005), the very relevant high quality instruments, and the fact that reception of ALOS imagery over Europe already is agreed between ESA and the Japanese space agency JAXA. The other three are series of operational satellites. Only satellite series with announced launches between 2005 and 2010, and with sensors producing optical imagery with 5 – 40 m pixel size are included. In addition to the once listed below, there are also other systems under discussion for launch during this period, for example satellites from Russia and Ukraine. The main sources for the text below are Kramer (2002), the web pages that are included in Table 1, and the persons listed in acknowledgements.

CBERS
CBERS stands for Chinese-Brazil Earth Resource Satellite. The multispectral images have 20 m pixel size and should be of relevance for forestry. With two already successfully launched satellites (CBERS 1 & 2) and two more planned (CBERS 3 & 4), CBERS presently appears to be one of the more reliable and operational earth observation satellite programmes. So far, CBERS images have only been received over China and Brazil (where they are free of charge!). China and Brazil are however considering starting international distribution of the images. Furthermore, ESA is planning to negotiate receiving of CBERS data over Europe as an ESA "third party mission".

ALOS
ALOS is a large Japanese remote sensing satellite that will be launched at the earliest September 2005. Images for ordinary users will be available 9 months after launch. ALOS is an experimental satellite in the way that it has several sensors that also can be operated in different modes and that it is not part of a series of satellites. It is however included here, because it might be a timely complement between SPOT and the more operational missions expected after 2010, and because the ambition is to cover the earth with cloud free images yearly. For Scandinavia and northern Europe, it is planned that colour images from the AVINIR-2 sensor will be received yearly between July 15 and August 31.

RapidEye
RapidEye is a planned constellation of five small (150 kg) satellites. The company with the same name is German, but also industry from UK and Canada is involved in the project. The aim is to target the commercial market, primarily for agricultural applications. It is thus one of the very few (or maybe the only) planned commercially oriented medium resolution satellite image projects. ESA will try to get access to Rapid Eye Imagery to be distributed to the scientific community. With 6,5, m pixel size and an image size of maximum 78 km * 1500 km, the images should be of great interest for forestry as well. The SWIR band, which is important for forestry, is however missing.

DMC
The Disaster Monitoring Constellation (DMC) is a formation of micro satellites which is launched by the UK company Surrey Satellite Technology Ltd (SSTL). The project has several purposes. A technology transfer effect is reached since the satellites are owned by different countries and training of staff from these countries at Surrey are included in many of the satellite projects. The first four satellites have been financed by UK, Algeria, Nigeria and Turkey, respectively. A fifth satellite owned by China is planned for launch 2005 and negotiations with more countries are ongoing. A second purpose is to obtain an at-least daily global coverage with optical imagery to be used

for disaster monitoring. Third, the data might also be suitable for resource surveys, such as for example forestry. However before the use of DMC data for forestry can be recommended, the data have to be benchmarked and compared with other data sources, since this was not the prime intended use for these low cost satellites. The large scene size (600 km) is an advantage, but the coarse resolution (32-36 m) and the limited number of spectral bands (green, red, NIR) are limitations. Also the geometric and radiometric quality of the imagery has to be evaluated. DMC images are distributed through the company DMC International Imaging (DMCII).

Conclusions

It is a large risk that it will be a gap in the supply of medium resolution optical satellite data from USA and Europe. New long term operational solutions are planned from about year 2010, which is beyond the design lifetime of currently used satellites. As listed above, and in Table 1, section b, there are a number of satellites that might serve as gap-fillers during this period, and also as add-on's to the operational supply beyond 2010. Some common conclusions regarding these possible gap-fillers are:

- it is very likely that some medium resolution data will be practically available for the forestry end users, but it is more difficult to say from which satellites, since this is dependent on successful launches (e.g. ALOS); negotiations of terms for receiving data over Europe (CBERS); commercial prices (RapidEye); and evaluation of the feasibility for forestry (e.g. DMC);
- none of the "gap-fillers" in Table 1b, has a medium resolution short wave infrared (SWIR) band; this wavelength band (e.g. Landsat TM band 5) has been shown to be the band that is best correlated with forest stem volume and forest biomass, and all the currently used sensors listed in Table 1a have SWIR bands. Thus we will probably face a drop in the quality in some types of forestry estimates derived from these types of medium resolution satellite data;
- with the exception of DMC, and OLI, all other sensors listed in Table 1, provides significantly smaller images than Landsat TM; since a large number of NFI plots per satellite scene is critical for example for the kNN estimation method used in Finland and Sweden, the currently used kNN procedures might have to be developed further in order to work well also with a smaller number of plots per scene.

Finally: forest authorities are one of several user categories that have a need for a continuous supply of earth observation data. The need in each sector of society separately is often too limited to motivate operational remote sensing satellites, but taken together over sectors and between countries, the needs are obvious. The current situation has shown that single countries with space capacity might not always has a sustainable long term policy for earth observations, and that the coordination between countries has been limited so far. In order to obtain a secured future supply of imagery, there must either be a stable commercial market (which does not exist today), or agreements between nations. Hopefully, the GEO process, (http://earthobservations.org) which at the third Earth Observation Summit in Brussels, February 2005, will adopt a 10 year plan for global earth observation will be a step towards better future coordination of earth observation capacity between nations.

Acknowledgements

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Table 1, a) current medium resolution remote sensing satellites of high importance for operational forestry applications; b) candidates for filling the possible gap between current sensor series and new sensor series beyond 2010, only sensors providing optical images with 5 – 40 m pixel size, and which are onboard satellites with planed launch between 2005 and 2010, are included; c) candidate long term operational solutions from USA and Europe, (vis = visible light, NIR = Near Infra Red, SWIR = Shortwave infra red)

Satellite	Country	Sensor	Colour Bands	Pixel size colour	Pan band	Swath-Width	Comments	Launch date	Web site
a) Current medium resolution satellites of high importance for operational forestry applications:									
Landsat 5	USA	TM	6 vis-SWIR	30 m	-	185 km	Still working, but is much overdue the original 3 years design lifetime	1984	landsat.usgs.gov
Landsat 7	USA	ETM+	6 vis-SWIR	30 m	1 * 15 m	185 km	Only central parts of images usable, design life time 5 years has passed	1999	landsat.usgs.gov landsat.gsfc.nasa.gov
SPOT 5	France	HRG HRS	4 vis.SWIR	10, 20 m	2 * 5 m 2 * 5 m	2* 60 km	HRS:Along track stereo instrument	2002	www.spotimage.fr
IRS P6	India	LISS-III LISS-IV	4 vis-SWIR 3 vis-NIR	23 m 6 m	-	140 km 70 km		2003	www.isro.org
b) Possible gap fillers with launch of new satellites planned between 2005 and 2010:									
CBERS	China & Brasil	HRCC MUXCAM	4 vis-NIR 4 vis-NIR	20 m 20 m	1 * 20 m 1 * 5 m	120 km 60 km	ESA might start receiving CBERS data over Europe as a substitute for Landsat.	1999, 2003, 2008, 2010	www.cbers.inpe.br
ALOS	Japan	PRISM AVNIR-2	- 4 vis-NIR	 10 m	3* 2,5 m	35 km 70 km	Registration 1 June – 15 July, along track stereo 16 July – 31 Aug (AVINIR-2)	≥ Sept 2005	http://alos.jaxa.jp/ index-e.html
RapidEye	Germany		4 vis-NIR	6,5 m		78 km	Commercial constellation of 5 mini-satellites, mainly for agriculture	2007	http://rapideye,de
DMC	UK, Algeria Nigeria China		3 vis-NIR	32 - 36 m	- 1 * 4 m	600 km	Cooperation between a private UK company (SSTL) and several states. Aimed primarily at technology transfer & daily global disaster monitoring.	4 launched since Nov 2002 and more satellites planned ≥ 2005	www.dmcii.com www.sstl.co.uk
c) Possible long term operational solutions past 2010:									
NPOESS	USA	OLI	8 vis-SWIR	30 m	1 * 10 m	177*170		≥ 2009	http://ldcm.nasa.gov
GMES mission on Land surfaces	France + ?		≥ 4 vis - SWIR	10–20 m		160 – 390 km	Early pre-study	≥ 2010 ?	

The Finnish Multi-Source National Forest Inventory

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Introduction

1.1 Background

The first forest resource assessments were total cover inventories either with visual assessments or, in small areas, by counting all trees with a given minimum size. The development of statistically designed sampling based forest inventories began in the end of 1800s and the beginning of 1900s. The purpose was, and has been until now, to get accurate country level and sub-country level forest resource information. Nevertheless, some countries still base national forest assessments on covering stand level (or compartment level) inventories with visual assessment, possibly assisted by remote sensing data. One problem, in addition to possible biases in visual estimation, is the lack of methods to asses the errors of the estimates for large areas on statistical basis.

Forest decision making and data utilisation require information often for smaller units than what is possible to reach with sparse field measurements only. To meet this requirement with field sampling based method only, would require multi-fold sampling density and thus multi-fold measurement costs. One of the most expensive components, often the most expensive one, in sampling based forest inventories is just the field measurements.

The spatial variation of forests is often such that field measurements in a certain area can be utilised also in neighbouring areas when using a relevant extrapolation or 'information borrow' technique.

This need, that is, to get forest resource information for smaller areas than what is possible with field data only without increasing the costs of the inventory significantly was a driving force to start the development of the multi-source forest inventory method (MS-NFI) in the connection of the Finnish national forest inventory (NFI). Furthermore, new natural resource satellites images provided new possibilities to increase the efficiency of the inventories with relatively small additional costs.

One basic requirement, set to the method, was that it should be able to provide applicable information for forestry decision making. Thus, methods that often are applied in satellite image aided approaches, and that produce only maps about forest type or land use classes, were not considered satisfactory. The methods those are able to provide area and volume estimates, possibly broken down into sub-classes, e.g., by tree species, timber assortments and stand-age classes, were sought for. In an optimal case, the method had to be able to provide all the same estimates for the small areas as the field data based method provides for national and sub-national level. Note that the number of variables measured in the field is usually high, ranging typically from 100 to 400. Estimates of additional variables are calculated from these measured variables.

One possible approach had been separate or simultaneous regression models, or logistics regression models, for variables of interest (Trotter, Daymond, & Goulding, 1997, McRoberts, 2005, Tomppo, 1987, 1992). A disadvantage had been that models had to derive separately for variables or variable groups to be predicted wherefore the dependence in predictions had not correspond the original dependence of the field variables. Furthermore, this approach is somewhat laborious in practical applications because models had to derive for each satellite image set.

These were the reasons to select k-nn approach. It had been used during several decades in image analysis and pattern recognition tasks (e.g., Fix, & Hodges, 1951). A somewhat similar method, a grouping method, had earlier been applied in North Finland with aerial photographs and visual interpretation to reduce errors of the estimates (Poso, 1972), and was suggested by Kilkki and Päivinen (1986) with satellite images. A further advantage of the adopted and developed method is that it simultaneously produces wall-to-wall forest resource maps.

It became soon obvious that any digital map which could separate forestry land from other land use classes with a moderate accuracy could decrease the errors. Note that the maps don not need to be perfect in accuracy. The effect of the map errors on the estimates can partially be removed and handled in a statistically sound way (Katila, Heikkinen & Tomppo, 2000, Katila & Tomppo, 2002).

The input data of the Finnish multi-source inventory are thus NFI field data, satellite images and digital map data of different types, e.g., basic map data, soil data for stratifying between mineral soil, spruce mires, pine mires and open bogs, as well as digital elevation model.

The k-nn estimation method is non-parametric and thus avoids the need for explicit models. However, it presumes that the total variation of all forest variables is well represented by the field sample plots.

The method in which the entire field data vector are predicted simultaneously (one vector or the weighted mean of *k* vectors are the predictor of an un-known field data vector), also better preserves the covariance structure of field variables than the methods in which the prediction is made separately for each variable (to each element of the vector).

The pixel level predictions of the variables can be arranged into forms of wall-to-wall maps. These maps in which the covariance of the variables are near to that of field variables are more applicable to different forestry, ecological and environmental purposes than the maps in which the predictions have been done separately (Pakkala, Hanski, & Tomppo, 2002).

Pixel-level errors with k-nn method are typically high but this is the case with other methods as well with the space-borne satellite images with a spatial resolution of 20 - 30 m. The use of *k* field plots instead of one decreases errors caused by the random variation in the image data. Tokola, Pitkänen, Partinen, & Muinonen (1996) studied, among other things, the effect of the value of *k* on the errors. Pre-processing of images and image noise reduction decrease the errors and improves the quality of the estimates particularly at pixel level. Examples of other error sources are within-stand variation of the forest parameters together with dislocation of the field plots compared to the image coordinates, as well as numerous other factors affecting pixel level prediction errors (see error source discussion in the Conclusion Chapter of this article). A method to reduce the effect of the dislocation of the field plots compared to the image coordinates on the estimates is presented in Halme, & Tomppo (2001).

The k-nn method has been used or tested in forest inventories also outside of Finland. The favour of the approach is based on the simplicity of the basic method, and on the facts that there is no need to estimate any model parameters, and, particularly, the final calculation of the estimates returns near the calculation with the field data only. Franco-Lopez, Ek, & Bauer (2001) tested the method both for estimation and map production with the data from Forest Inventory and Analysis program (FIA) of the Forest Service, US Department of Agriculture. McRoberts, Nelson, & Wendt (2002), introduced an interesting stratified estimation method based on k-nn technique to decrease the errors of the forest area estimates in FIA program. Haapanen, Ek, Bauer, & Finley (2004) also tested k-nn method in forest area estimation with US FIA data.

The performance of k-nn method with different remote sensing data, also with simulated data for error estimation, and with Swedish national inventory was studied in the doctoral thesis of Nilsson (1997). The operative k-nn based Swedish system is described in Reese et al. (2003). The goal of the system is to produce forest maps both for forestry and ecological purposes.

The main goal in developing a Norwegian system is to be able to produce forest resource estimates for municipality level, like in the Finnish MS-NFI (Gjertsen, Tomppo, & Tomter, 1999, Gjertsen, & Eriksen, 2004). The possibilities to apply k-nn predictions in harvest planning in radiata pine plantations in New Zealand was studied in Tomppo, Goulding, & Katila (1999). The pixel level errors were high but could be reduced to using as ancillary information stand age and years since last thinning. These variables are known for planted forests. The method showed some promise.

The reduction of the estimation errors with multi-temporal images were tested with k-nn technique in small-area estimation in Nordrhein-Westfalen, Germany (Diemer, Lucaschewski, Spelsberg, Tomppo, & Pekkarinen, 2000). The entire inventory concept, from planning of field sampling design to calculation of estimates both with field data only for large areas and with k-nn based multi-source technique to small areas is presented Tomppo, Korhonen, Heikkinen, & Yli-Kojola (2001). The test area was in Heilongjiang province in North-East China.

1.2 Progress in the Finnish multi-source inventory

The development of the Finnish MS-NFI began in 1989. The first operative results were computed in 1990 (Tomppo, 1990, 1991, 1996). The method has been modified continuously and new features added (Katila, Heikkinen, & Tomppo, 2000, Katila, & Tomppo, 2001 and 2002). The core of the current method is presented in Tomppo, & Halme (2004).

Any digital land use map or land cover data can be used to improve the accuracy of the predictions (Tomppo, 1991, 1996). Methods to remove the effect of possible map errors from the predictions are presented by Katila, Heikkinen, & Tomppo (2000) and Katila, & Tomppo (2002).

The application of the k-nn estimation method presumes the selection of 'estimation parameters' for each satellite image and the other data applied with the image (Katila, & Tomppo, 2001). The operative application of the method has also shown that the predictions, particularly the predictions of volumes by tree species, may be biased if the area of interest is large and covers several different vegetation zones with different tree species compositions (Figure 2, Chapter 5). One reason for the bias is that the mapping from the field data vector space to the image data vector space is not necessarily an injection when the area in question is large. (A function, $f: A \rightarrow B$, is injective or one-one, or is an injection, if and only if for all a, b in A, $f(a) = f(b) \Rightarrow a = b$, that is no different inputs give the same output.). Varying imaging conditions within the area of a satellite image also change the covariance structure between field data and image data. The biases can be reduced if the set of potential nearest neighbours are somehow restricted.

In the first operative applications of the Finnish multi-source inventory (MS-FNFI), a sub-set of field plots has been selected for potential nearest neighbours in the image space for each image pixel, usually those field plots that are within a certain geographical distance from the pixel in question. The goal has been to find a sub-area in which a certain spectral vector would correspond a unique field data vector and vice versa. Methods and criteria for selecting (pixel-dependent) geographical area from which the nearest field plots (in the spectral space) for each pixel are selected, i.e., the maximum horizontal and vertical search distances, are studied in Katila, & Tomppo (2001). A regular shape search region, e.g. circle or rectangle, has previously been applied. Vegetation zone boundaries are more complex; the shape and size of the region typically vary with the location of the pixel on the image (ground element, Figure 2, Chapter 5).

Tomppo, & Halme (2004) presented another method to guide the selection of the field plots. It has been in an operative use since early 2000. It employs additional variables in the applied distance metric, i.e. additional elements in the distance metric vector to guide the selection of nearest neighbours. The elements are variables describing the large area variation of forest characteristics, e.g., mean volumes by tree species, and are map-form predictions of those variables. A relevant, practical variation scale for these variables and their predictions ranges between 40 km and 60 km. The variation of the variables on this scale can be computed from field data only, e.g., from field data of the current or preceding inventory of the area.

The method also employs bands transformations in addition to the original image bands. It is assumed that band ratios, e.g., improve the identification of tree species, although all information from the satellite images is already in the original bands. An optimization method, based on a genetic algorithm, was developed to find the weight vector. The method noticeably reduces the errors both at the pixel level and in areas of different sizes. The method is called ik-nn method (improved k-nn method) in Tomppo, & Halme (2004).

One of the still open problems related to k-nn method is the lack of an analytic method to estimate standard errors of any estimate for an area of an arbitrary size. This problem has been solved in the method by Taskinen and Heikkinen (2004). It is non-parametric local Bayesian regression method utilising the Markov Chain Monte Carlo (MCMC) estimation. Bayesian method with state-space model has also been applied by Wallerman, Vencatasawmy, & Bondesson, (2003).

2. Input data sets for the basic k-nn method and improved k-nn method

2.1 Processing of Field Data for Multi-Source Calculations

The core idea in employing multi-source data is to estimate new area weights for field sample plots. Furthermore, digital wall-to-wall thematic maps can be created, in principle for an arbitrary variable of the NFI. Examples of maps are spatial distributions of site fertility, mean age and diameter of stand, volumes by tree species and timber assortments and volume increment of growing stock by tree species.

The basic computation unit in image processing is a picture element, a pixel. The pixel size applied with Landsat TM images, e.g., is 25 m x 25 m. Therefore, it is more convenient to work with volumes per area unit than with volumes of tallied trees. Volumes per hectares are estimated for each sample plot by tree species and by timber assortment classes from tally tree volumes.

The estimation of volumes and volumes of timber assortments for tally trees from field measurements are described in Tomppo (2005a). The tree level volumes are transformed to volumes per hectare in MS-NFI using the basal area factor and the maximum radius of the plot. Otherwise, the field variables are in MS-NFI are similar to those in NFI calculations using field data only. Field measurements based result computation does not involve increment estimates of tally trees wherefore increment estimates are not usually computed with multi-source method.

2.2 Satellite images

The images from Landsat 5 TM or Landsat 7 ETM+ sensors are the most suitable images for operative applications due to fairly large coverage area of one image and still a moderate spatial and spectral resolution. These images are given the priority when covering an area with satellite images. If these images are not available, e.g., due to the clouds, either Spot 2 - 4 XS HRV images or IRS-1 C LISS images have been used so far.

Finland's land area is 30.4473 million hectares, and together with inland waters amounts to 33.8145 million hectares. In NFI8 and its up-dating in South Finland (field data from 1990-1994), 36 Landsat 5 TM images and 2 Spot 2 XS HRV images were applied. In NFI9 (1996-2003), 40 Landsat 5 TM or Landsat 7 ETM+ images and 4 IRS-1 C LISS images were applied.

Areas corresponding to the cloud-free parts of satellite images are utilised in operative applications. Forests under clouds and cloud shadows are assumed to be similar to forests on the average on cloud-free part of the computation unit (e.g. municipalities).

All applied images are rectified to the national coordinate system. Point type objects (e.g. small islands on water) are identified from both satellite images and base maps and to fit a regression model to the image coordinates and the map coordinates of the points. Second order polynomial regression models have usually been applied:

$$\begin{aligned} u &= a_l + b_l x + c_l y + d_l x^2 + e_l y^2 + f_l xy + \varepsilon_u \\ v &= a_c + b_c x + c_c y + d_c x^2 + e_c y^2 + f_c xy + \varepsilon_v \end{aligned} \qquad (1)$$

where u and v are the image coordinates, x and y the map coordinates and ε_u and ε_v the random errors. A typical number control points is some 50.

An image element, i.e. a pixel, can be assigned to each ground element with the estimated model. The nearest neighbour method has been applied for the re-sampling of the images to a pixel size of 25 $m \times 25\ m$. This pixel size is somewhat smaller than Landsat TM and ETM+ pixel size and a bit larger than Spot 2 -4 XS HRV pixel size. The pixel of 25 $m \times 25\ m$ was selected for practical reasons, more narrow objects (e.g. roads) are possible to separate than for instance with the original resolution of Landsat 5 TM. The absolute values of the residuals in the model estimation, i.e., $\hat{\varepsilon}_u$ and $\hat{\varepsilon}_v$, range typically from 0.3 pixels to 0.6 pixels.

2.3 Digital map data

The digital map data are used to decrease the errors of the estimates. The errors of the area estimates and total volume estimates can be decreased significantly in multi-source method, if distinguishing of forestry land versus non-forestry land can be supported by any digital map information, in addition to satellite images. The effect of possible map errors on the estimates can be reduced with statistical methods. Two different methods have been developed to remove the effects of map errors from the estimates (Katila, Heikkinen, & Tomppo, 2000, Katila, & Tomppo, 2002). The first method is a kind of calibration method utilising confusion matrix derived from land use class distributions based on field plot data and map data. The second method employs stratification of the field plots on the basis of map data. The map information is used to separate forestry land from other land use classes, such as arable land, built-up areas, roads, urban areas and single houses. Further, a map is used to stratify forestry land area and the corresponding field plots, into mineral soil stratum and peatland soil stratum (spruce mires, pine mires, open bogs and fens).

The digital map data purchased from the National Land Survey of Finland form one basic data source in the operative MS-NFI. The database called "Topo" is the most accurate digital map covering most of the country (Topographic, ..., 1998). It covers almost the entire Finland. For the rest of the area, the map data comes from several data sources, mainly provided by the National Survey of Finland (Katila, & Tomppo, 2001).

A digital elevation model is used in two different ways, for stratification on the basis of elevation data and to correct the spectral values by employing the angle between sun illumination and terrain normal. The later method is described in a detailed way in Tomppo (1992). Stratification in this context means a maximum vertical distance for the possible nearest neighbours applied with a pixel (see formula (5)). The selection of parameters for stratification and spectral correction has been studied in Katila, & Tomppo (2001).

The basic computation unit in multi-source inventory is a municipality. The number of municipalities in the entire country is about 500, and the land areas range from some 1000 hectares to some hundreds of thousands of hectares. Digital municipality boundaries are used to delineate the computation units (Tomppo, 1996).

2.4 Large area forest resource data

The basic k-nn method was applied in NFI8. The improved k-nn method, ik-nn method, was introduced during NFI9. It employs the coarse scale variation of the applied key forest variables in guiding the selection of the field plots from which the data are transferred to the pixel to be analysed. The variation is presented in the form of large scale digital forest variable maps (Figure 2, Chapter 5). These maps can be derived either from the current inventory data or from the data of the preceding inventory.

The data from the 9th Finnish NFI9 from South Finland were already available when the method was introduced. NFI9 progressed by regions. New large area maps were always created for MS-NFI calculation when the field data from a region were available. The number of the field plots on land in the NFI9 (1996-2003) in the entire country was 81 249, on forestry land 67 264, on forest and poorly productive forest land 62 266, and on forest land 57 457. All the plots on forest land and poorly productive forest land were used for the final large area maps.

The variables were selected in such a way that their values indicate the areas in which the covariance structure between field variables and image variables would be approximately constant. It is assumed that the mapping from field data to image data, conditional for large scale forest variables, is a bijection. A function, f: A $\rightarrow$ B, is bijective or a bijection or a one-to-one correspondence if it is both injective (no two values map to the same value) and surjective (for every element of the B there is some element of the A which maps to it), that is there is exactly one element of the A which maps to each element of the B. In the Finnish forest, tree species composition or vegetation zones may reflect these types of areas. Volumes by tree species on forest land and poorly productive forest land were therefore selected as variables. These variables also describe the average variation of the key inventory variables to be estimated in k-nn analysis. The maps were created as follows. The averages of plot level mean tree stem volumes (m^3/ha) were computed by field plot clusters. A map of Finland with a pixel size of 1 km × x 1 km was 'filled' with these cluster level averages using a nearest neighbour method, i.e. the values were taken from the nearest cluster (in geographical space). The map was filtered using a moving average filtering three times with a widow sizes of 20 *km* × 20 *km*, 11 *km* × 11 *km*, and 25 *km* × 25 *km* (Figure 2, Chapter 5).

3. Estimation with field data and standard errors

Estimates and error estimates based on field data only are used as standards for comparisons in assessing the quality of the other estimates wherefore field data based estimation is very briefly described. For more complete description, see, e.g., Tomppo (2005a) and error estimation Heikkinen (2005). The NFI estimators based on pure field data are ratio estimators. The goal is to estimate a parameter of the form

$$M = \frac{X}{Y} \ , \tag{2}$$

where X and Y are expectations of two random variables, x and y. Variable y can be, e.g., an indicator of land class (e.g. , pine dominant forest land) or the volume of a tree species (pine volume) and x the indicator of a stratum of interest, e.g., forest land. Let x_i and y_i be their observed values on sample plot i, then the ratio estimator of M is

$$m = \frac{\sum_{i=1}^{n} x_i}{\sum_{i=1}^{n} y_i} = \frac{\bar{x}}{\bar{y}} , \tag{3}$$

where n is the number of sample plots in the inventory area. This estimator is approximately unbiased. The estimation of its standard error is complicated, in addition to systematic sampling, by the spatial autocorrelation and possible trend-like changes of the target variables, in addition to a systematic sampling. Matérn (1947, 1960) suggested the error variance, $E(m-M)^2$, as a measure of reliability of the estimator and also proposed a model based estimator of the error variance. Cluster-wise residuals $z_r = x_r - my_r$, with $x_r = \sum_{i \in r} x_i$, $y_r = \sum_{i \in r} y_i$, and r a cluster of field plots i, are assumed form a realisation of a second order stationary (weakly stationary) stochastic process. Its variance can be estimated by means of quadratic forms. The use of four clusters with layout

r_3 r_4

r_1 r_2

and with equal weights yields to the estimator

$$s = \frac{\sqrt{k \sum_{g} T_g}}{\sum_{i} y_i} , \tag{4}$$

where

$T_g = (z_{r_1} - z_{r_2} - z_{r_3} + z_{r_4})^2 / 4$,

$z_r = (\overline{y_r} - \bar{y}) n_r$,

g refers to the groups of clusters in the stratum,

i refers to the relevant sample plots in the stratum,

$\overline{y_r}$ represents cluster mean,

$\bar{y}$ is a stratum mean,

n_r is the number of the applied sample plots in the cluster, and

k indicates how many clusters each cluster group represents.

For more details and the application of the method, see, e.g., Heikkinen (2005).

4. Basic k-nn estimation

As given in section 2.4, the basic non-parametric k-nn estimation was applied in the MS-NFI calculation during NFI8, and also in the beginning of NFI9. The basic principles of k-nn method are first described. Let us first recall that each field plot has a certain area representativeness, a plot weight, sometimes called also plot expansion factor when forest inventory estimates are computed from pure field data. This plot weight can be the total land area divided by the number of field plots on land if either systematic or systematic cluster sampling is applied (Kuusela, & Salminen, 1969, Tomppo, 2005). In the MS-NFI, new plot weights (not equal for each plot) are computed for each plot by computation units, e.g. by municipalities (Tomppo, 1996). The weights are computed for each field sample plot $i \in F$, where F is the set of field plots belonging to forestry land. These plot weights are sums of satellite image pixel weights over the forestry land mask pixels. The pixel weights, in turn, are computed by a non-parametric k-nn estimation method (Tomppo, 1991, 1996). The method utilises distance metric *d*, defined in the feature space of the satellite image data. The *k* nearest field plot pixels (in terms of *d*), i.e., pixels that cover the centre of a field plot $i \in F$, are sought for each pixel p under the forestry land mask of the cloud free satellite image area. A maximum distance is usually set in both horizontal and vertical directions in order to avoid selecting the nearest plots (spectrally similar plots) from a region in which the response of image variables to field variables is not equal to that of the pixel under consideration. This is necessary due to the fact that the mapping from field data to spectral data is not a bijection in a large area. One reason for this is that the covariance structure between field variables and image variables may vary between the vegetation zones and also between image sub-areas. Further, a stratification on the basis of soil information is also made for the same reason (Katila, & Tomppo, 2001). The feasible set of nearest neighbours for pixel p is thus

$$\{p_i \mid d_{p,p_i}^{(x,y)} \le d_{\max}^{(x,y)}, d_{p,p_i}^{z} \le d_{\max}^{z}, R(p_i) = R(p)\} \tag{5}$$

where $d_{p,p_i}^{(x,y)}$ is the geographical horizontal distance from pixel p to pixel p_i, d^z the distance in vertical direction, $d_{\max}^{(x,y)}$ and $d_{\max}^{z}$ their maximum allowed values, and *R(p)* is the indicator function of mineral soil/peatland soil (Tomppo, 1990, 1991, 1996, Katila, & Tomppo, 2001).

Denote the nearest feasible field plots by $i_1(p),...,i_k(p)$. The weight $w_{i,p}$ of field plot i to pixel p is defined as

$$\begin{aligned} w_{i,p} &= \frac{1}{d_{p_i,p}^{t}} \Bigg/ \sum_{j \in \{i_1(p),\ldots,i_k(p)\}} \frac{1}{d_{p_j,p}^{t}}, \text{ if and only if } i \in \{i_1(p),\ldots,i_k(p)\} \\ &= 0 \text{ otherwise.} \end{aligned} \tag{6}$$

The power t is a real number, usually $t \in (0,2]$. The distance metric d in the operative MS-NFI was earlier

$$d_{p_j,p}^2 = \sum_{l=1}^{n_c} (f_{l,p_j} - f_{l,p})^2, \tag{7}$$

where

$$f_{l,p_j} = f^0{}_{l,p_j} / \cos^r(\alpha) \tag{8}$$

is the normalised intensity value of the spectral band (or feature) l. The normalising is done on the basis of the slope and aspect variation, $f^0{}_{l,p_j}$ is the original intensity of the spectral band l, α the angle between terrain normal and sun illumination, r the applied power due to non-Lambertian surface and n_c the number of spectral features (Tomppo, 1996). Only original spectral bands with equal weights (=1) were applied in the old operative k-nn approach.

Practically, k-nn estimation means transferring field data vectors from k field plots to each pixel. The field plots are pixel specific. The k vectors are weighted inversely proportionally to the distance from the pixel in question with the applied distance metric.

For computing forest parameter estimates for computation units, sums of field plot weights to pixels, $w_{i,p}$ are calculated by computation units (for example, by municipalities) in the image analysis process over the pixels belonging to the unit. The weight of plot i to computation unit u is denoted

$$c_{i,u} = \sum_{p \in u} w_{i,p}. \tag{9}$$

Reduced weight sums $c^r_{i,u}$ are obtained from the formula (10), if clouds or their shadows cover a part of the area of the computation unit u. The real weight sum for plot i is estimated by means of the formula

$$c_{i,u} = c^r_{i,u} \frac{\hat{A}_{s,u}}{\hat{A}^r_{s,u}} \quad , \tag{10}$$

where

$\hat{A}_{s,u}$ = the estimate of the area of the forestry land of unit u, and

$\hat{A}^r_{s,u}$ = the estimate of the area of the forestry land of unit u not covered by the cloud mask.

The areas can be taken, e.g., from digital maps or estimated by means of field plot. It is thus assumed that the forestry land covered by clouds per computation units is, on average, similar to the rest of the forestry land in unit u with respect to the forest variables (cf. Tomppo, & Halme 2004).

The weights (9) and (10) are computed within forestry land separately for mineral soil stratum and peatland stratum. The weights are also computed to other land use classes, arable land, built-up land, roads and waters, if stratification based map correction method is applied (Katila, & Tomppo 2002). In the other method, statistical calibration and confusion matrix are used to reduce the effect of the map errors on the estimates (Katila, Heikkinen, & Tomppo 2000).

After the final field plot weights to computation units ($c_{i,u}$) have been computed, the ratio estimation is applied to compute the estimates (e.g., Cochran 1977). In this way, the estimation is similar to that using field plot data only. Volume estimates, e.g., are computed by computation unit u and reference unit s in the following way. Mean volumes are estimated by the formula

$$v = \frac{\sum_{i \in I_s} c_{i,u} v_{i,t}}{\sum_{i \in I_s} c_{i,u}}, \tag{11}$$

where $v_{i,t}$ is the estimated volume per hectare of timber assortment (log product) t for plot i and I_s the set of field plots belonging to stratum s. The corresponding total volumes are obtained by replacing the denominator in formula (11) by 1.

The forest variable estimators for computation unit u thus utilise information outside the unit u. The k-nn estimator is therefore a kind of a synthetic estimator (Gonzales, 1973).

Mean and total volume increments could be estimated similarly. However, the increments are not predicted in NFI to tally trees, or can be understood to be constant within increment computation strata, i.e., by tree species, diameter class and site factor classes over increment computation regions. These regions are usually so large that the within region variation in growth factors is high wherefore the constant predictions do not correspond the real variation between MS-NFI computation units (municipalities).

Some examples of estimates obtained with MS-NFI are given in Table 1. These estimates are from the 8th inventory, with field data and satellite images from year 1992, and concern the area of forestry Centre Kainuu (Tomppo, Katila, Moilanen, Mäkelä, & Peräsaari, 1998). The estimates are: Distribution of forestry land into sub-classes (Table 1a), Mean and total volume of growing stock on forest land, on forest and scrub land and on forestry land (Table 1b) and Total volume of growing stock by timber assortment classes on combined forest and scrub land (Table 1c). Forestry land (FRYL) consists in MS-NFI of forest land (FL), scrub land (SRCL) and waste land (WL). In national classification, forestry roads and depots, as well as some other minor areas belonging to forestry, are included into forestry land. Note that for the entire forestry centre, totals are given in two different ways in Table 1a) and Table 1b), based on on one hand on the MS-NFI and on the other hand on the field data based inventory only (NFI). The standard errors for forestry centre totals in Tables 1a) and 1b) are based on NFI. In addition to the previous tables, the following tables were given in MS-NFI8 for all municipalities in Finland: the areas of mineral soil and peatland soils separately on FL, SRCL and WL, tree species dominance separately on FL and on SRCL, areas of age classes on FL, mean volumes (m^3/ha) by age classes on FL, areas of development classes on FL; mean volumes (m^3/ha) by development classes on FL, mean and total volumes by tree species and timber assortment classes on FL and on combined FL and SCRL. Furthermore, some relative distributions for area and volume estimates were given.

Table 1. Examples of MS-NFI estimates from Forestry Centre Kainuu in NFI8: Distribution of forestry land into sub-classes (Table 1a), Mean and total volume of growing stock on forest land, forest and scrub land and forestry land (Table 1b) and Total volume of growing stock by timber assortment classes on combined forest and scrub land (Table 1c).

Table 1a. Distribution of forestry land into sub-classes.

		Forest land		Scrub land		Waste land		Forestry land, Total	
		ha	%	ha	%	ha	%	ha	%
105	Hyrynsalmi	113370	83,7	14435	10,7	7689	5,7	135494	100,0
205	Kajaani	92850	88,8	7798	7,5	3971	3,8	104619	100,0
290	Kuhmo	388155	83,7	49706	10,7	25737	5,6	463598	100,0
578	Paltamo	73713	89,0	6429	7,8	2708	3,3	82850	100,0
620	Puolanko	191331	80,7	30259	12,8	15389	6,5	236980	100,0
697	Ristijärvi	69148	87,7	6613	8,4	3120	4,0	78881	100,0
765	Sotkamo	222928	90,0	16846	6,8	7985	3,2	247759	100,0
777	Suomussalmi	389616	77,0	65185	12,9	50876	10,1	505677	100,0
785	Vaala	88493	75,6	18862	16,1	9661	8,3	117016	100,0
940	Vuolijoki	52272	82,3	8344	13,1	2921	4,6	63536	100,0
	Total, MS-NFI	1681876	82,6	224477	11,0	130057	6,4	2036410	100,0
	Total, NFI	1659701		222675		142749		2025124	
	Standard error of NFI	13895		8969		7863		8582	

Table 1b. Mean and total volume of growing stock on forest land, forest and scrub land and forestry land.

	Forest land			Scrub land			Forest and scrub land			Forestry land		
	ha	m^3/ha	1000 m^3	ha	m^3/ha	1000 m^3	ha	m^3/ha	1000 m^3	ha	m^3/ha	1000 m^3
105 Hyrynsalmi	113370	67,4	7638	14435	12,0	173	127805	61,1	7812	135494	57,7	7818
205 Kajaani	92850	68,8	6386	7798	11,1	87	100648	64,3	6473	104619	61,9	6476
290 Kuhmo	388155	74,9	29083	49706	11,4	567	437861	67,7	29648	463598	64,0	29670
578 Paltamo	73713	83,2	6133	6429	12,8	82	80142	77,6	6215	82850	75,0	6214
620 Puolanko	191331	69,7	13341	30259	13,2	399	221590	62,0	13741	236980	58,0	13745
697 Ristijärvi	69148	68,7	4748	6613	11,1	73	75761	63,6	4822	78881	61,1	4820
765 Sotkamo	222928	75,7	16870	16846	11,5	194	239774	71,2	17063	247759	68,9	17071
777 Suomussalmi	389616	66,1	25747	65185	10,4	678	454801	58,1	26426	505677	52,3	26447
785 Vaala	88493	64,0	5661	18862	13,3	251	107355	55,1	5912	117016	50,5	5909
940 Vuolijoki	52272	74,6	3900	8344	10,2	85	60616	65,7	3985	63536	62,7	3984
Total, MS-NFI	1681876	71,1	119507	224477	11,5	2589	1906353	64,0	122097	2036410	60,0	122153
Total, NFI	1659701	70,8	117000	222675	12,6	2800	1882376	63,9	120000			
Standard error of NFI	13895	1,4	2494	8969	0,7	198	11165	1,3	2502			

Table 1c. Total volume of growing stock by timber assortment classes on combined forest and scrub land.

		Pine			Spruce			Birch			Other broad leaved tree species		
		Total	Saw timber	Pulp wood	Total	Saw timber	Pulp wood	Total	Saw timber	Pulp wood	Total	Saw timber	Pulp wood	Total
105	Hyrynsalmi	4602	1578	2702	2132	735	1255	961	15	677	117	2	78	7812
205	Kajaani	3755	1033	2441	1527	545	867	1048	17	715	143	2	93	6473
290	Kuhmo	18163	6835	10143	7877	2727	4593	3263	138	2270	345	8	246	29648
578	Paltamo	3199	999	1987	1858	706	1040	1000	20	712	157	3	102	6215
620	Puolanko	7374	2341	4470	4410	1503	2646	1718	26	1226	238	3	169	13741
697	Ristijärvi	2549	824	1539	1446	539	815	732	14	509	94	1	63	4822
765	Sotkamo	8743	2815	5308	5115	1997	2781	2825	92	1951	380	3	266	17063
777	Suomussalmi	16264	6247	9070	6957	2252	4275	2901	71	2265	304	3	243	26426
785	Vaala	4075	1160	2541	732	222	446	984	10	657	121	4	72	5912
940	Vuolijoki	2250	554	1503	751	265	424	852	13	593	133	4	82	3985
Total, MS-NFI		70974	24386	41704	32805	11491	19142	16284	416	11575	2032	33	1414	122097

Predictions of some (optional) forest variables are written in the form of a digital map during the procedure. The land use classes outside forestry land are transferred to map form predictions directly from the digital map file. Within forestry land, the variables are predicted by the weighted averages of the *k* nearest neighbours (see Tomppo, 1991, 1996)

A pixel-level prediction $\hat{m}_p$, of variable *M* for pixel *p* is defined as

$$\hat{m}_p = \sum_{i \in F} w_{i,p} m_i , \tag{12}$$

where m_i is the value of the variable *M* on plot *i*. Mode or median value is used instead of the weighted average for categorical variables. The predicted variables are usually, land use class, site fertility class, stand age, mean diameter of stand, mean height of stand, and volumes by tree species (pine, spruce, birch, other broad leaved trees) and by timber assortment class. The total amount of the maps is thus somewhat over 20. An example of an output map from MS-NFI8 is shown in Figure 1.

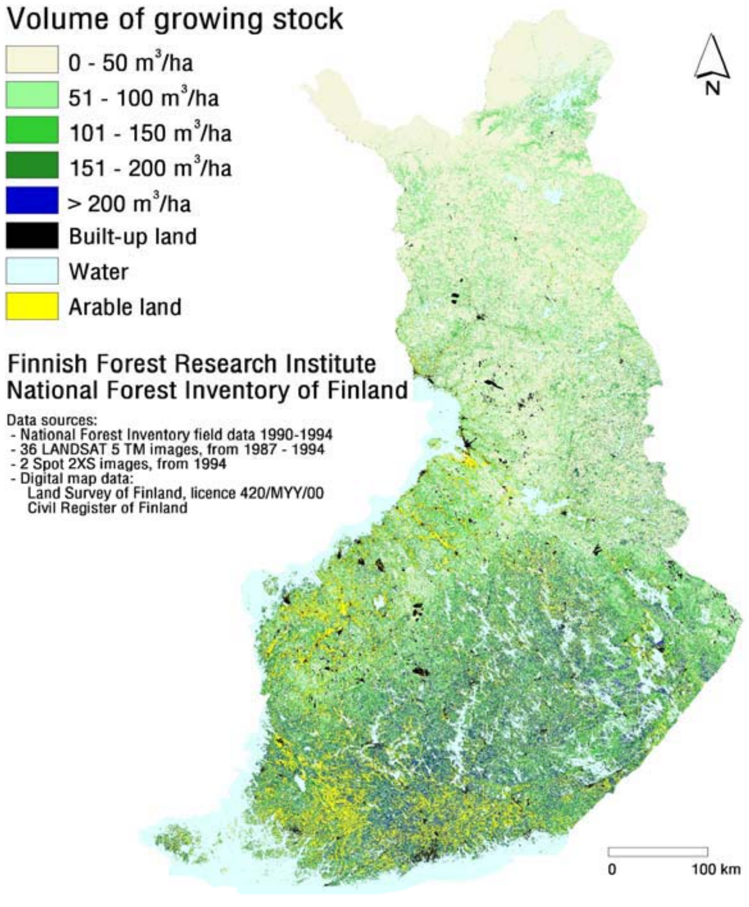

Figure 1. An example of a wall-to-wall output map of the Finnish multi-source national forest inventory, the volume of growing stock. Note that the classification has been done for colouring. The unit in the original data is 1 m^3/ha.

5. Improved k-nn, ik-nn, method

As given earlier, one of the main problem in practical application of k-nn method is how to select the sub-area and sub-set of the field plots from which the potential nearest neighbours are sought for each pixel. An other problem is the selection of the spectral features in the applied distance metric (7) in order to get as small as possible errors.

These problems were studied in Tomppo, & Halme (2004). In that paper, a method called ik-nn, an improved k-nn method, was introduced. A summary of the method is presented here.

The overall aim of the improved method is to minimize the errors of the predictions of the multi-source inventory. The goal was to reduce the errors both at the pixel level, and particularly, at the larger area level (from several tens of thousands of hectares up to several millions of hectares).

Two modifications of the k-nn estimation method were introduced:
1) the use of supplementary ancillary variables in addition to spectral data in selecting neighbours,
2) the use of 'optimal' weights for both the image features and ancillary information. A vector consisting of these elements is called a vector of explanatory variable weights and denoted by ω. A method was developed to utilise ancillary data and to find the optimal explanatory variable weights.

As for the first modification, to restrict the complexity of the problem, a few core variables were selected and the estimates of these variables were studied. The volumes by tree species were selected as the variables. Tests with age class distributions and also earlier experiments showed that the errors of the predictions of other variables are reduced when the errors of the predictions of volumes by tree species are reduced (Tomppo, Katila, Moilanen, Mäkelä, & Peräsaari, 1998).

The optimization was carried out solely at the pixel level. It was hoped, and later checked, that larger area errors decreased with the optimized weights. This was considered to be the ultimate check of goodness of the procedure.

A weighted sum of pixel level biases and RMSE's of the predictions was selected as the objective function. The weights are called fitness function weights and denoted by γ (13). The variables employed were: 1) total volume, 2) volume of pine, 3) volume of spruce, 4) volume of birch and 5) volume of other broad leaved tree species. These 10 variables have been used also in the operative applications of the method. The fitness (objective) function to be minimized with respect to ω is:

$$f(\omega,\gamma,\hat{\delta},\hat{\hat{e}}) = \sum_{j=1}^{n_e} \gamma_j \hat{\sigma}_j(\omega) + \sum_{j=1}^{n_e} \gamma_{j+n_e} \hat{\hat{e}}_j(\omega) \tag{13}$$

where $\gamma > 0$ are user defined coefficients for pixel level standard errors $\hat{\sigma}_j$ and biases $\hat{\hat{e}}_j$ for forest variable j (applied in genetic algorithm) and ω is the weight vector to be estimated (formula 13). Denote the feasible set of weight vectors by $\boldsymbol{W}$.

The pixel-level biases and errors of multi-source inventory (k-nn) estimates are

$$\hat{\sigma}_m = \sqrt{\frac{\sum_{i \in F} (\hat{m}_i - m_i)^2}{n_F}} \text{ and bias } \hat{\hat{e}} = \frac{\sum_{i \in F} (\hat{m}_i - m_i)}{n_F}$$

where m_i is the observed value of the variable to be estimated (e.g. total volume), $\hat{m}_i$ its estimate on the plot i and n_F the number of the field plots.

The fitness function weights, bias weights and RMSE weights, were experimentally given values and then fixed. This weighted sum was the criterion in the search for good weight vectors for image features and ancillary information.

The computation of the large-area predictions of the forest variables for even one weight vector is an extremely computer intensive task. The pixel-level objective function (formula 13) have to be considered as a proxy of the real objective. This is a major source of imprecision in the process. Other sources of imprecision in the procedure are the choices of variables and fitness function weights and the non-optimality of the optimization result.

Note that the explanatory variable weights (ω) are sought in such a way that the prediction of the selected variables, in this case volumes, is optimized. Note also that the Landsat pixel measures information from an area larger than what is the size of a field plot (e.g., Halme, & Tomppo, 2001). This discrepancy is interpreted as a measurement error: a large one in the case of satellite images. It was decided to seek the weight vector using only field plots sufficiently far from the nearest stand boundary or land use class boundary to reduce this error. A minimum distance of 20 metres was used. A source of error is the location of a field plot with respect to the satellite image pixel, which also motivates this decision. It is important to note that the final large-area and municipality-group level estimates and error validation are calculated in operative applications using *all NFI field plots* and weights obtained from optimization with plots with at least 20 metres apart from the nearest stand boundary.

The predictions and their standard errors computed from field data only are employed in validating all multi-source predictions in areas ranging from several hundreds of thousand hectares to several million hectares. This is due to the fact that multi-source error estimation for areas larger than a pixel (field plot) is complicated and the solution is yet to be found. Satisfactory predictions for groups of municipalities (at the level of several hundreds of thousand hectares) and at a pixel level are assumed to be satisfactory also at the level of a few thousand and some tens of thousands of hectares.

A new distance metric was proposed in Tomppo, & Halme (2004). Two types of new elements of the distance vector were introduced 1) the transformations of the spectral bands, 2) the coarse scale forest variable predictions of some key forest variables (formula 14), called also the ancillary variables. All possible ratios of spectral bands were used. It was hoped that band ratios better distinguish different tree species, e.g., pine and spruce, than the original bands. The use of large area forest variables as additional elements direct the selection of the nearest neighbours to forests similar to the target pixel (cf. Figures 2, 3, 4, and 5). All elements were finally weighted. The applied distance metric was thus, and has also been in the operative MS-NFI

$$d^2_{p_j,p} = \sum_{l=1}^{n_f} \omega_{l,f}{}^2 (f_{l,p_j} - f_{l,p})^2 + \sum_{l=1}^{n_g} \omega_{l,g}{}^2 (g_{l,p_j} - g_{l,p})^2 \qquad (14)$$

where $f_{l,p}$ is the *lth* image variable, $g_{l,p}$ the large area prediction of the *lth* applied forest variable*,* n_f the number of image variables (or features) and n_g the number of coarse scale forest variables and $\boldsymbol{\omega}_\mathbf{f}$ and $\boldsymbol{\omega}_\mathbf{g}$ the weight vectors for image features and coarse scale forest variables respectively. A pixel size of 1 km × 1 km is used in the coarse scale forest variable predictions $g_{l,p}$. (Note the different pixel size for large area forest variables and satellite image data.) The values of the elements of the weight vector to be estimated are derived from optimization employing a genetic algorithm as given below. The first phase of ik-nn is to run the optimization algorithm, in the applications possibly by strata, e.g., mineral soil stratum and mire and bog stratum. The estimation after that returns to the basic k-nn estimation.

5.1 Simplified sketch of the genetic algorithm

A genetic type algorithm was selected due to the complexity of the optimization problem and because the optimization problem may have several local optima. The method noticeably reduces the errors both at the pixel level and over areas of some thousand square kilometres, as well as in larger areas.

Genetic algorithms that imitate the behaviour of genes are currently used to solve difficult optimization problems such as combinatorial problems, but they are also popular for modelling economic and ecologic phenomena and machine learning (see e.g. Mitchell, 1996). Genetic algorithms often produce good results for problems that are hard to solve. Normally, they also require a considerable amount of adjustment to fit the algorithm in the problem.

The following outline of the algorithm serves two purposes: it illustrates the principles of a genetic algorithm in general and, moreover, the version presented is similar to the genetic algorithm application in this paper. For more information about the genetic algorithm schemes (see e.g., Mitchell, 1996, see also Tomppo, & Halme 2004).

The elements and operators of genetic algorithms originate from biology. The candidate solution vector is called a chromosome and its goodness is called its fitness. A group of chromosomes is called a population. One population is one generation. The operators are: selection of chromosomes (the criterion being their fitness), the crossover of chromosomes producing new offspring and the random mutation of new offspring.

The next presentation does not include all features of the algorithm employed in this paper. A more detailed version is presented in Tomppo, & Halme (2004). In a genetic algorithm, the value of the objective function for a trial solution is called the solution's fitness value.

The key parameters of the algorithm are:

n_{gen} = number of generations
n_{pop} = number of weight vectors in one population and number of vectors in the medipopulation (does not have to be the same)
p_u = probability used in uniform crossover
p_c = probability of accepting an inferior solution created by mutation
p_m = mutation probability
p_{rm} = radical mutation probability
p_{t1} = probability 1 in selection
p_{t2} = probability 2 in selection

The definitions of the parameters are given in the following simplified sketch, borrowed from Tomppo, & Halme (2004).

1. Initialisation
Generate the initial population with n_{pop} random weight vectors. Calculate their fitness values (13). Set the generation count to 1.

2. Selection
In this step a medipopulation (an intermediate group of weight vectors between two populations) is formed. Choose in the population two weight vectors (e.g., randomly or successive at some points) the fitness values of which are compared. Only the more fit one is chosen to member of the medipopulation with probability p_{t1}. Only the less fit one is chosen to be member with probability 1-p_{t1}- p_{t2}. They both are members with probability p_{t2}. Repeat until the medipopulation consists of n_{pop} vectors. Note that several copies of vectors may occur.

3. Crossover
In this step a new population is formed. With two successive vectors of the medipopulation ***a*** and ***b*** (parent vectors) carry out uniform crossover to produce two offspring ***c*** and ***d***. That means with probability p_u the *kth* element (k = 1, …, n) of ***c*** (***d***) comes from ***a*** (***b***) and $(1- p_u)$ from ***b*** (***a***); Pick the vector having the best fitness in the set, consisting of both offspring and parents, to be member of the next population. Repeat until the population consists of n_{pop} vectors. Increase the generation count by 1. If the count is equal to n_{gen} stop.

4. Mutation
In this step, the weight vectors in the new population are possibly mutated.
In each vector of the population each element is mutated with a probability p_m. Two kinds of mutations can occur: radical (probability p_{rm}) (the element is subtracted from 1) or nonradical (the element is changed by +-20 per cent). The mutated vector replaces the original vector as a member of the population if its fitness is better than the original vector's. If its fitness is less than that of the original vector, it replaces the original vector as a member of the next population with probability p_c and with probability $1- p_c$ the original vector remains a member of the population. Go to 2.

An element changes by -+20 per cent if nonradical mutation takes place. This percentage was observed to perform well.

5.2 The application of the algorithm

The practical solutions in applying the genetic algorithm are described in this section. The optimization problem to be solved is, which distance metric gives the lowest value for a linear combination of the RMSEs and biases. An 'optimal' weight vector for the elements of the distance metric has to be sought.

Let us fix in the following the vector $\gamma > 0$ (formula 13). The objective function can therefore be denoted $f(\omega, \hat{\sigma}, \hat{\hat{e}})$. The objective as a function of ω is not continuous.

After numerous experimental runs in developing the method, upper bounds were introduced for the elements of the weight vector. This was because the objective seemed to be unexpectedly flat, providing a huge number of "equally good or almost equally good" solutions. No meaningful losses in the objective function optimal values were observed due to the bounds (Tomppo, & Halme, 2004, see Tables 2 and 3). Thus the set of feasible weight vectors W fulfils the condition

$$W = \left\{ \omega \in R_n^+,\ 0 \le \omega_k \le uppe_k,\ k = 1,\dots,n,\ \sum_{k=1}^{n} \omega_k = 1 \right\}$$

where
$uppe_j$ = upper bound for variable j
n_g = number of large area forest variable estimates employed
n_f = number of image spectral variables employed
n = $n_g + n_f$ sum of the number of spectral image and ancillary variables.

The variables employed in the fitness function (formula 13) were 1) mean volume (m^3/ha) of all tree species on the field plot, 2) mean volume of pine, 3) mean volume of spruce, 4) mean volume of birch (two species) and 5) mean volume of other broad-leaved tree species. The values of the vector γ (formula 13) were sought at the beginning and finally fixed to be γ=(0.3, 0.6, 0.6, 0.2, 0.1, 0.5, 1, 1, 0.2, 0.1). The first five elements are the coefficients of the estimates of the standard errors $\hat{\sigma}_j$ and the rest those of the estimates of the biases $\hat{\hat{e}}_j$, cf. formula (13). In the fitness function, the biases were given weights larger than the standard errors and the biases of pine and spruce were given especially large weights. The aim was to reduce the biases of the corresponding estimates both at pixel level and for large areas because of the problems in distinguishing between pine and spruce volumes in some areas.

The values of parameters that worked successfully, were:

n_{pop} = 50
n_{gen} = 30 - 80
p_u = 0.75
p_m = 0.05
p_{rm} = 0.35
p_c = 0.5
p_{t1} = 0.95
p_{t2} = 0.03.

These values seem to work well for all multi-source data sets and have been applied also in the operative MS-NFI since the implementation of the method.

5.3 Reductions of the bias and standard error of the estimates at pixel level and region level

To demonstrate the performance of ik-nn method and to show the difference of the errors of the estimates obtained with ik-nn to those obtained with k-nn method, some results are shown from an area in East-Finland. These results are part of the operative MS-NFI and were obtained when ik-nn method was developed.

The area covers the most parts of Forestry board Centres East Savo and North Karelia, whose total land area is 3.222 million hectares and forestry land area 2.861 million hectares. The NFI9 was conducted in the area in 1999 and 2000. The total number of the field plots was 11 415. In here, some results from a sub-area of are shown. Its land area (not covered by clouds or cloud shadows of the applied satellite image) is 2.22 million hectares with 1.97 million hectares of forestry land. The remaining area was arable land and built-up areas. The area was covered with two Landsat 7 ETM+ images, 186-16 and 186-17 from June 10, 2000 (Figure 2).

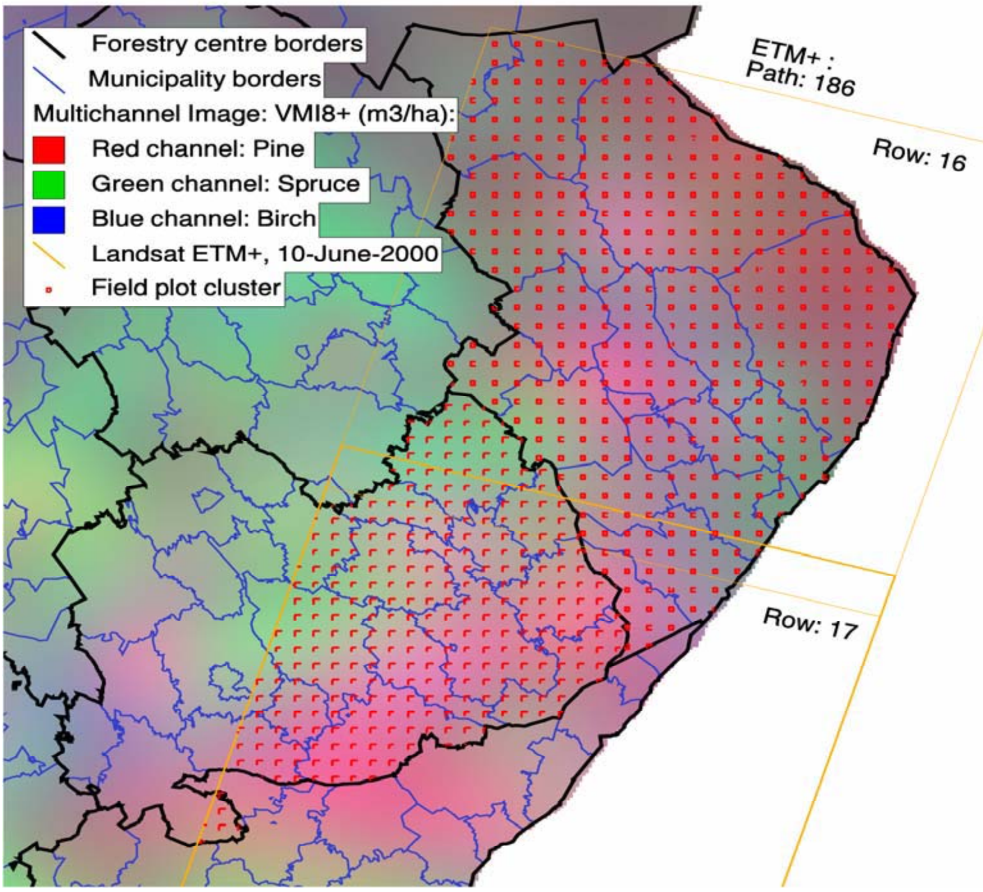

Figure 2. An example of large scale variation of mean volumes of main tree species with boundaries of municipalities and forestry centres as well as with field plot clusters and Landsat ETM+ image boundaries.

The first phase in applying ik-nn method is to compute the weights (ω) (formula 1.11). The weights are computed using only field plots far enough from the nearest stand boundary or land use class boundary (20 metres). The goal is to try to avoid the effect of mixed pixel on the weights. Recall that all field plots are used in the estimation phase with the computed weights.

The main objective in introducing ik-nn method was to decrease the bias of the predictions both at pixel level and, particularly, over larger areas. An ultimate goal was to improve the estimation of pine and spruce volumes. Table 2 shows an example of the pixel level (field plot level) biases for the predictions of volumes by tree species for k-nn estimates (k-nn), for k-nn predictions using large area variables (k-nn la) and for ik-nn methods using leave-one-out cross-validation and field data based volume predictions $\hat{V}_F$ as a reference (Efron, & Tibshirani, 1993). A total of 1953 field plots with at least 20 *m* to the nearest stand boundary were employed. Spruce volume was underestimated significantly. Adding large area variables to k-nn did not alone decrease the biases. The reduction in biases with ik-nn was noticeable for all predictions, although they were somewhat lower for birch and other broad-leaved tree species than for pine and spruce. (Column a/b in Tables 2 and 3 indicates the relative decrease of the absolute value of the bias. Use columns a) and b) for comparison.) This results from the selection of the weights fixed in the fitness function rather than, for instance, from the capability of remote sensing data to distinguish broad-leaved tree species. The biases are much less than one standard error for all of the variables.

Table 2. Bias examples of k-nn predictions, k-nn predictions with large-area variables (k-nn, la) and ik-nn predictions at pixel level (field plot level) on mineral soil stratum, leave-one-out cross-validation. Field data based volume predictions $\hat{V}_F$ as reference. 1953 field plots, k=5, upper bounds employed.

	$\hat{V}_F$	Bias	Stand err. of bias	Bias a)	Stand. err. of bias	Bias b)	Stand. err. of bias	Reduction
		k-nn	k-nn	k-nn, la	k-nn, la	ik-nn	ik-nn	a) / b)
Volume	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	%
Pine	63.750	2.430	1.648	2.230	1.570	-0.002	1.539	99.925
Spruce	38.883	-3.167	1.304	-4.725	1.293	-0.005	1.260	99.891
Birch	15.903	-0.961	0.684	-1.571	0.696	-0.199	0.701	87.346
O. br. l.	3.874	-0.382	0.376	-0.430	0.383	-0.133	0.389	69.057
Total	122.303	-2.021	1.827	-4.432	1.764	-0.259	1.800	94.152

Table 3 shows an example of the bias reductions for peatland soil stratum. Here, 638 field plots with at least 20 *m* to the nearest stand boundary were employed. The relative bias reductions for pine and spruce volumes are about as high as for mineral soil stratum, for birch a little less and for other broad-leaved tree species much less. The original absolute biases for broad leaved trees were small. The biases divided by the predictions were nevertheless high due to the low value of the predictions. All the pixel level biases for volume predictions were satisfactory.

Table 3. An example of biases of the k-nn predictions, k-nn predictions with large-area variables (k-nn, la) and ik-nn predictions at pixel level (field plot level) on peatland soil stratum using leave-one-out cross-validation and field data based volume predictions V_F in comparison, 638 field plots, k=5, tolerance = 5 × correlation coefficient with ik-nn has been employed.

	$\hat{V}_F$	Bias k-nn	Stand err. of bias k-nn	Bias a) k-nn, la	Stand. err. of bias k-nn, la	Bias b) ik-nn	Stand. err. of bias ik-nn	Reduction a) / b)
Volume	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	*m³/ha*	*%*
Pine	50.101	1.735	1.888	1.610	1.813	0.012	1.924	99.255
Spruce	10.498	-1.482	1.268	-2.694	1.214	-0.019	1.738	99.295
Birch	7.633	-0.454	0.760	-1.092	0.762	-0.303	1.151	72.253
O. br. l.	0.305	-0.029	0.128	-0.069	0.125	-0.062	0.757	10.145
Total	68.525	-0.231	2.058	-2.241	1.975	-0.367	0.123	83.623

When applying the method, in addition to pixel level errors and biases, region level errors are also controlled. The predictions are validated at the level of groups of municipalities as follows. The area in question is divided into sub-areas with forest and other wooded land areas ranging typically between 150 000 ha and 300 000 ha. The objective in the division is to create sub-areas that are as homogenous as possible with respect to mean volumes by tree species, with their forest and other wooded land area being at least 150 000 ha (Figure 3). The evaluation is carefully designed to identify possible confusions in mean volume predictions by tree species. This is possible if the within group variation is as small as possible and between groups sub-area variation is as high as possible. The field data based estimates of areas and volumes by tree species and their standard errors are computed for these areas. All field plots on forestry land (forestry road plots excluded) were employed both in the field data based estimation and in the multi-source estimation.

Examples of the predictions for mean volumes by tree species (m^3/ha) are given for two municipality groups in Table 4. The table also gives standard errors for the field data based predictions. The table enables multi-source predictions to be compared with the field data estimates and assessed in terms of the field data based standard errors.

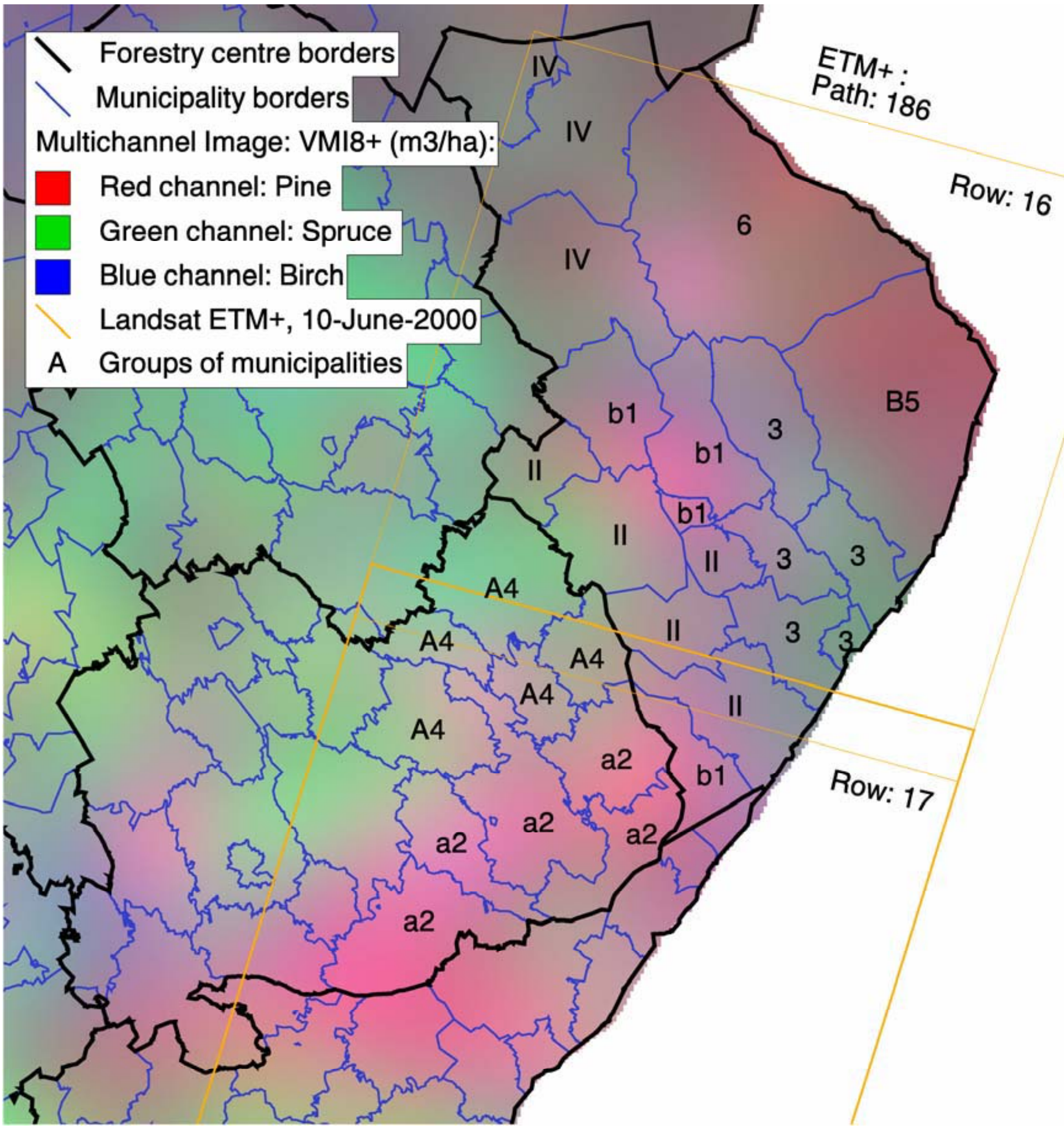

Figure 3. Result computation units of Table 3 together with municipalities and forestry centre boundaries displayed on large scale volume maps.

The distinction between pine and spruce is often not good enough (Table 4). In both areas, pine mean volume was originally over-estimated and spruce mean volume under-estimated. The mean volumes of pine in these areas are lower than in the neighbouring areas and also lower than the averages for the entire area in question.

Table 4. The estimate of the volume of growing stock (m^3/ha) on forest and other wooded land (a) and its standard error (a_{er}) by tree species based on field data, and based on the k-nn method (b), ik-nn method (c) and on ik-nn method when the obtained large-area weights have been multiplied by 10 (d) given for two municipality groups. The estimate of the area forest land and other wooded land is 241 200 ha for group 1 and 234 700 ha for group 2. The multi-source estimates are compared to the field data based estimates.

	a	a_{er}	b	b-a	c	c-a	d	d-a
Group 1								
Pine	48.6	2.9	53.8	5.2	47.5	-1.1	49.7	1.1
Spruce	38.5	2.5	35.6	-2.9	41.9	3.4	40.3	1.8
Birch	15.7	1.2	15.7	-0.0	15.8	0.1	15.9	0.2
Other br. 1.	4.3	0.6	3.7	-0.6	3.6	-0.7	3.1	-1.2
Total	107.2	3.3	108.8	1.6	109.0	1.8	108.9	1.7
Group 2								
Pine	47.9	3.2	56.3	8.4	49.1	1.2	51.0	3.1
Spruce	53.7	2.8	49.6	-4.1	56.9	3.2	55.8	2.1
Birch	18.1	1.2	18.5	0.4	17.5	-0.6	18.0	-0.1
Other br. 1.	8.1	0.9	5.4	-2.7	6.0	-2.1	5.7	-2.4
Total	127.9	4.2	129.7	1.8	129.4	1.5	130.6	2.7

In both sub-areas, ik-nn gave lower deviations from the field data based predictions and thus more accurate predictions. The predictions of the mean volumes of birch and other broad-leaved trees using the ik-nn method were also nearer to field data based predictions than for the k-nn method; or at least they did not deviate more than the predictions based on k-nn. (Note that more weight is often given to pine and spruce volumes in formula (13) than for birch and other broad-leaved tree volumes.)

The ik-nn method using information from large area variation of forest variables, noticeably reduces the problem of distinguishing, e.g., pine dominant stands from spruce dominant stands and of estimating the volumes by tree species. The effect on the weights of the field plots, i.e. on the quantities $c_{i,u}$, formula (10), is demonstrated in Figures 4) and 5). The weights are given for the northern most municipality in sub-area 2 (indicated by number 309). The weights were more evenly spread over the entire area covered by field plots with the k-nn method than with ik-nn. On the other hand, the field plots on forests with tree species composition similar to that of municipality 309 obtained higher weights with ik-nn than with k-nn. Note that field plots were employed only from two forestry centres.

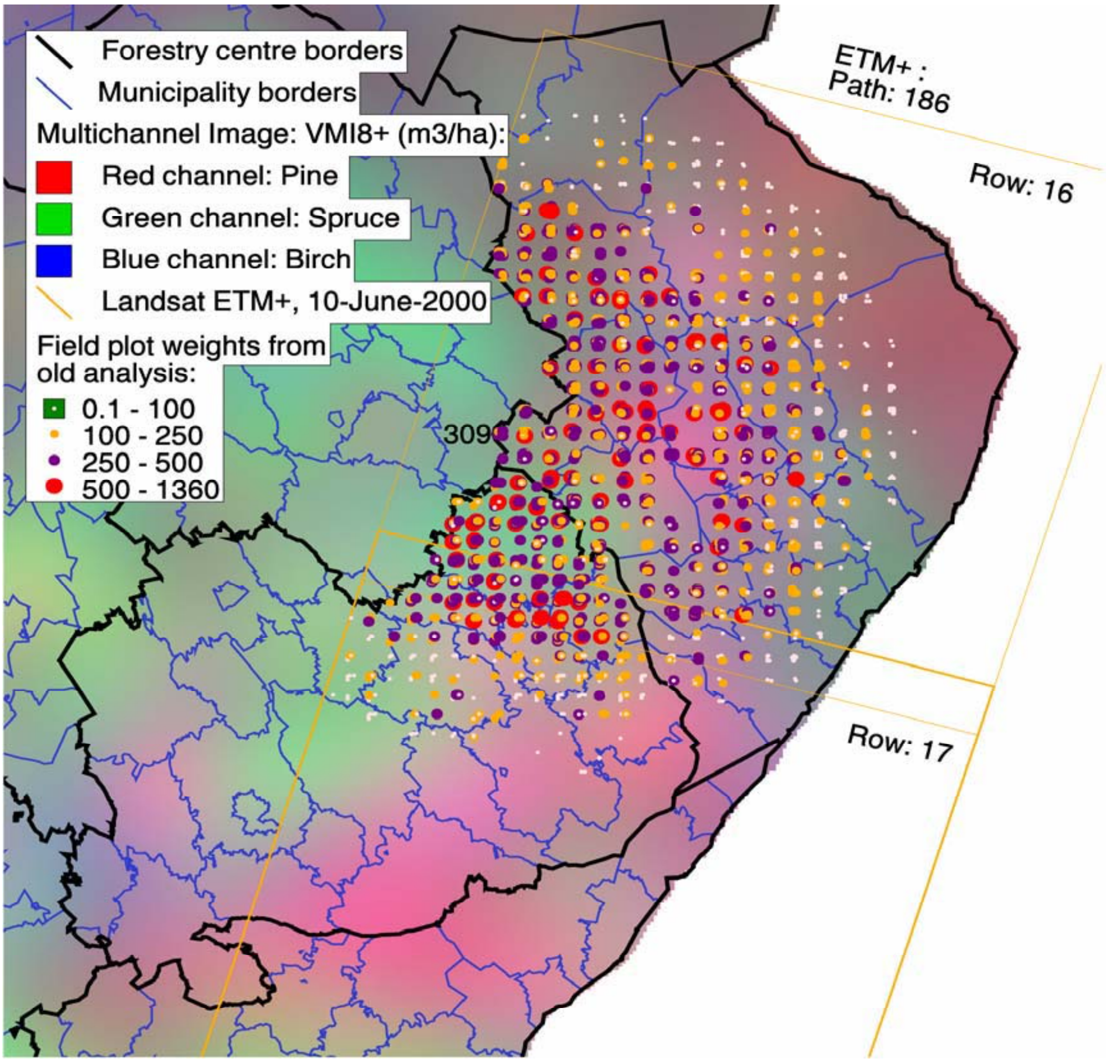

Figure 4. The distribution of the weights for one municipality with the old k-nn method: large-area information is not used, only the original bands with even weights are employed.

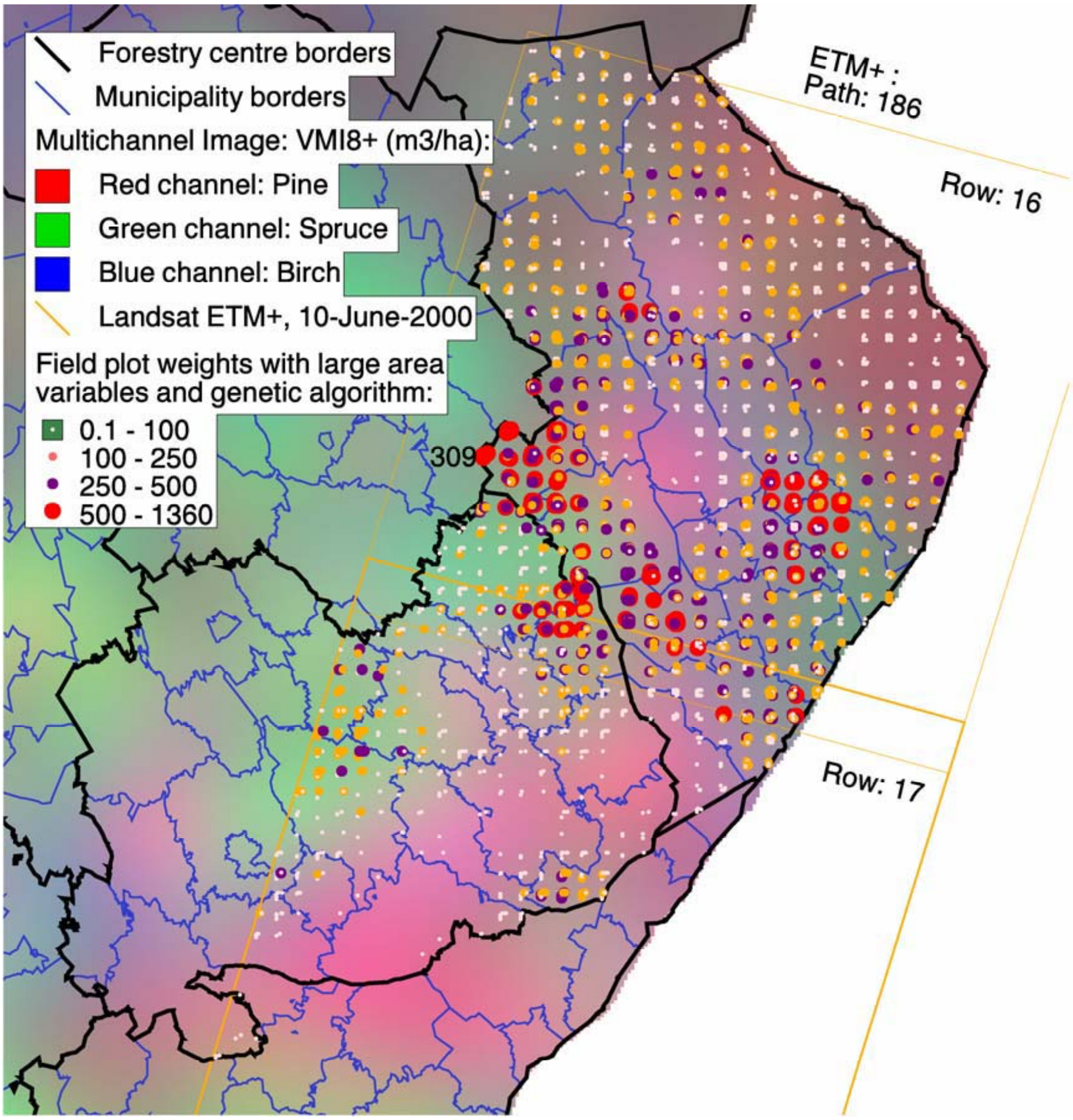

Figure 5. The distribution of the weights for one municipality with the ik-nn method: large area information, the original bands and band ratios with optimised weights are employed.

6. Conclusion

The Finnish National Forest Inventory has utilised satellite image aided multi-source method since 1990 in order to be able to compute results for areas smaller than what is possible using field data only. The entire country has been covered twice with this method. The method is under continuous refinement. During the ninth inventory (1996-2003), the method was enhanced introducing a couple of new features: 1) the use of large-area forest variables for directing the selection of the nearest neighbours, 2) the use of an optimization method based on genetic algorithm to weight both large-area forest variables and satellite image variables, and further, 3) two optional methods were developed to remove the effect of the map errors on the estimates. The new ik-nn method performs noticeably better than the original k-nn method. The use of the information from large area forest variables reduces noticeably the problem of distinguishing stands with different tree species, or tree species composition, and reduces the errors of the estimates of volumes by tree species. This problem has been severe in areas where large-area tree species dominance changes, for instance, where spruce dominated forests change into pine dominated forests or vice versa: a common occurrence in the Boreal region. Note that any relevant data, like soil data or vegetation zone data, can be employed as ancillary data. The method, which is already in operative use in the Finnish multi-source forest inventory, reduces the biases and standard errors both at pixel level and in larger areas. Comparisons with the k-nn method have been made with tens of Landsat TM and ETM+ images. The method seems to perform well, and in practice gives predictions with smaller errors than the old k-nn method. Validation has been carried out, and is always done in operative applications, at the pixel level and at the level of municipality groups for which the predictions and standard errors can be computed by means of field data only.

Two methods for reducing the errors of predictions caused by the possible errors in digital base maps are in use in the operative MS-NFI, a calibration method (Katila, Heikkinen, & Tomppo 2000) and a stratification method (Katila, & Tomppo 2002). The new ik-nn method is applicable with both map correction methods. When using the stratification method, field plots outside of forestry land can be employed. Different weights can be computed for different strata, as is done within forestry land for the mineral soil stratum and peatland soil stratum.

The pixel level and stand level errors of the estimates are rather high with current satellite images. There are several reasons for this. The error sources in pixel level predictions of forest variables have been listed in many articles (e.g. Katila 2004, and Tomppo, Katila, Moilanen, Mäkelä, & Peräsaari, 1998). Examples are, 1) possible errors in field data measurements and applied models in estimating tree and plot variables, 2) errors in the geographic location of a field plot and the corresponding pixel, 3) field measurements are done from an area which does not correspond the area of a satellite image pixel, 4) very seldom all factors affecting spectral response of satellite image are measured, sometimes not all trees, and seldom ground vegetation, 5) radiometric resolution of the sensors (the sensors are not able the recognize all variation the target area, i.e., two different targets in the field may give same spectral response), 6) scattering of radiance in the atmosphere, 7) within image variation in imaging condition (different parts of an image are in different sun illumination and atmospheric conditions), 8) a possible fact that the variation of the field plots does not cover all the variation in the field, and 9) possible timing difference in field data and image data. 10) Furthermore, soil moisture variation in the target area affects the spectral properties wherefore two areas with same growing stock may have different spectral properties, or vice versa, two areas with different growing stock may have same spectral properties.

There are several methods to assess the pixel level errors. Leave-one-out cross validation has been applied in many studies. Kim, & Tomppo (2004) applied variogram modelling in the spectral space. A generally applicable error estimation method for areas larger than a pixel is a challenging task. The error of the predictor of a variable depends on the true value of the variable wherefore the errors are spatially correlated. The spatial dependencies on the image itself make the error structure even more complex. Lappi (2001) presented a different, calibration type of approach to multi-source estimation, together with variance estimator based on variogram. Some other interesting variogram based approaches are currently under development.

The practical application of multi-source inventory is facing currently also other problems. One of the most severe one, related to optical area images in certain regions of the globe, is the availability of images, obtained in cloud-free imaging conditions. The most applicable satellite sensor, Landsat 7 ETM+, has suffered a failure of scan line corrector since 2003. Several correction methods have been introduced but the quality of the product is not the same as without the failure (see, e.g., USGS, 2005). One advantage of k-nn method is that it is applicable with all image material. The precision of the estimates depends, however, on the spectral, spatial and radiometric resolution of the sensor. Some image material may presume the use of another image material as an intermediate step between field data and and the final image data (Tomppo, Nilsson, Rosengren, Aalto, & Kennedy, 2002). Furthermore, the precision of the estimation depends on how k-nn method is applied, as it has been seen above. Lot of research work has been carried out and are going on to analyse the errors and to improve the precision of the estimates.

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The Performance of a Local Maxima Method in Detecting Individual Trees in Medium-scale Colour-infrared Aerial Photographs

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Introduction

Forest planning needs accurate and up-to-date information on growing stock. Aerial photographs provide an affordable alternative to update a stand database, e.g. after a thinning cutting. One cannot detect suppressed trees from above, but the fact that the dominant trees make up a vast majority of the commercial stem volume justifies the individual-tree based approach (Talts 1977). In this study, a local maxima (LM) based method for detecting individual tree crown and tree top image positions was chosen. The method has been tested by several researchers (e.g. Dralle and Rudemo 1996, Bolduc et al. 1999, Wulder et al. 2000, Pitkänen 2001), but only Dralle (1997) and Dralle and Rudemo (1997) have considered varying camera-object-Sun geometry. The objectives of this study were 1) to develop a method for linking the tree candidate positions obtained by a LM method from 2D images to the 3D field data for reliable detection testing at the single tree level, also in off-nadir views, and 2) to test the performance of the LM method for tree and tree top detection.

Materials and Methods

The field data consisted of seven recently thinned field plots in Southern Finland. The size of the plots was 40 x 40 m^2 or 50 x 50 m^2. Each tree base was accurately positioned, and tree species, diameter at breast height, and height determined. Altogether 12 colour-infrared aerial photographs at a scale of 1:12 000 formed the image data. The forward overlap of the photography was 70% and side overlap 60%. Photographs were scanned at a resolution of 14 μm, which yielded 16.8 cm nominal pixel size. The red band of the scanned image, corresponding to the infrared sensitivity of the aerial film, was used in the analyses.

In tree detection, the positions of LM on the bright areas of an aerial image were considered as tree locations. The image was first smoothed for noise elimination and image binarization was then used to obtain a mask of bright areas, assumed to be tree crowns, to restrict the search for LM. The idea of smoothing is to obtain only one local maximum in each crown and the aim of background masking is to reduce the number of nontree maxima. This method has been presented in detail by Pitkänen (2001).

To match the LM and field measured tree tops, the following procedure was developed. First, one fixed-size model-polygon per plot-image combination was digitised to capture the photo-visible tree crown. Second, the polygon was positioned on each tree in the plot and re-sized based on the relative height of the tree. Third, each candidate point was defined as either a miss or a hit by using an inclusion test. Fourth, if a candidate point had hit more than one polygon, the tree visible in that image position was determined by ray-tracing. In it, the crown envelopes were modeled by parabolic, fixed-sized (per plot) synthetic crowns, which were positioned in the known 3D tree top locations. The camera-crown distances were computed analytically by ray-intersection, and the tree closest to the camera was defined as the visible tree in that image point.

Results and Conclusions

The preliminary results indicate that the LM method works best in the central parts of the aerial images, where the commission and omission errors are the smallest. Illumination conditions were not found to affect accuracy. The LM method was able to detect the dominant and co-dominant trees with a high probability, but the intermediate and suppressed trees were primarily overlooked. This results in biased stem number estimates. However, a large portion of volume in each plot was found. With the best parameter combinations, the volume of uniquely detected trees consisted 78-92% of total volume. The tree positions in the images were systematically displaced from the true tree top positions down the trunk and towards the direction of the incoming sun rays. On average, LM lay 2.8m below tree tops. A displacement model was applied, which considerably reduced the systematic positioning inaccuracy.

The tested method was found simple with only two parameters. Price of methods based on aerial photographs is still much lower than price of methods that rely on laser scanning. Tree positioning and stem number estimation are reliable near nadir, but also there, omitted trees, non-tree maxima and multiple hits need to be edited manually. Another downside of the method is that the (near) optimal parameter values have to be determined before tree detection. We propose further work that will assess the applicability of the LM method as a feature detector in connection with stereo image matching for canopy elevation modelling.

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A Multi-scale Method for Segmentation of Trees in Aerial Images

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Abstract

Scale-space related image processing methods have been shown to work in blob detection with automatic scale selection. Because tree crowns in aerial images can be often seen as bright blobs, these methods are interesting also in individual tree detection. However, trees in aerial images are not ideal bright blob targets, because large parts of tree crowns are shaded, crowns have overlap and background intensity varies a lot. In detection and scale selection of blob-like features, normalised Laplacian convolved images are formed for a range of scales based on possible object sizes. Blob locations are then points where the normalised Laplacian operators achieve a local maximum with respect to both space and scale. In this study, a Laplacian image, combined across scales, was used in segmentation of tree crowns as well. Accuracy of tree detection and possibilities for tree size estimation were studied using a digitised 1:20 000 aerial photograph from a spruce dominated field plot in southern Finland.

Introduction

Aerial photographs have been used in forest inventories and management planning for decades. Today, photographs are increasingly more often delivered in digital form to be included as layers in geographical information systems. This makes photo based updating of existing forest databases more tempting. The actual image interpretation, however, is still mostly done visually, although there are pressures to gain more from the digital images by computer based automatic interpretation. Yet, trees and background in aerial images form complex systems that are affected by imaging and illumination geometry and conditions and further complicated by shading and occlusion by trees. Hence, deriving forest stand or tree information from aerial images automatically is not an easy task.

In recent years, individual tree based approach for the characterisation of forests has been widely studied. Methods have been proposed for detection of trees (e.g., Dralle and Rudemo 1996, Lowell 1998, Wulder et al. 2000) or apexes of crowns (e.g., Pollock 1994, Larsen 1997, Korpela 2004) and for delineation of tree crowns. Getting crown delineations instead of only single pixels, e.g., from local maxima methods, is useful in determination of further characteristics, like tree species (see e.g. Gougeon 1995b, Haara and Haarala 2002) and tree size (e.g. Brandtberg 1999, Maltamo et al. 2003). A variety of approaches has been proposed for crown delineation or crown circle estimation: for example, valley following (Gougeon 1995a) and region growing segmentation (Culvenor

2002, Haara and Haarala 2002) and edge curvature based methods (Brandtberg and Walter 1998, Brandtberg 1999).

One problem of individual tree detection on aerial images is handling of tree crowns of different sizes. When a crown of specific size is processed, the image should be on appropriate scale for the interpretation of crowns of that size. In tree detection, adaptation to the local scale has been tried at least by adjusting the window size used for finding local maxima according to the semivariance range or slope breaks (Wulder et al. 2000) and with multi-scale analysis (Brandtberg and Walter 1998, Brandtberg 1999). Of course, automatic scale selection for feature detection has been a subject of interest in computer vision as well. A widely used method for blob detection with automatic scale selection is based on scale-space representation and Laplacian filtering (Lindeberg 1998).

The aim of this study was to try automatic scale selection in tree detection and to develop a scale adaptive segmentation method for delineation of tree crowns, which are further used in tree size estimation. Accuracy of tree detection and possibilities for tree crown width and trunk diameter estimation were studied using a digitised 1:20 000 aerial photograph from a spruce dominated field plot in southern Finland.

Material and methods

The test site was near the Hyytiälä Forestry Field Station (61º50'N, 24º18') in the municipality of Juupajoki in southern Finland. Field data used consisted of individual tree measurements made in one stand on a sample plot that was established on the test area in summer 1995. All trees having a diameter at breast height (DBH) of more than five cm were mapped using a tacheometer to get tree co-ordinates (x, y and z). Tree species, DBH and tree height were registered. In addition, the maximum crown width of trees was measured at 8 m wide strip around the centre line of the 40 m wide plot. The field plot used was part of larger data set whose collection is described in more detail in Pitkänen (2001). The total number of mapped trees in the 0.65 ha plot was 318, of which 80 % were Norway spruces (*Picea abies* (L.) Karst.), 13 % Scots pines (*Pinus sylvestris* L.) and 6 % birches (*Betula pendula* Roth, *Betula pubescens* Ehrh.). The mean and standard deviation of dbh were 27.5 cm and 8.3 cm, respectively.

The field plot located near nadir in the aerial photograph used that was exposed on 24th June 1995 at scale 1:20 000 on a colour infrared film. The photograph was scanned as a raster image with resolution of 14 µm and the image was ortho-rectified and resampled to the pixel size of 40 cm. The DEM used in the ortho-rectification was calculated to the level of highest tree tops based on the co-ordinates and heights of the tallest trees. Tree detection and segmentation was done on single-band images. Tentative results of tree detection were similar for all bands of the RGB image. Band 2, corresponding mainly to red radiation, was selected to be used in further processing (Figure 1).

Tree locations were detected using a method proposed for blob detection with automatic scale selection (Lindeberg 1998). The method is based on scale-space approach (Koenderink 1984, Lindeberg 1994), in which the image is convolved with Gaussian filters of increasing scale to get a multi-scale image description with two spatial dimensions and a scale dimension. In feature detection and scale selection, scale-space representations are formed with suitable normalised differential operators. Features are then detected as local scale-space extrema, i.e. as points where the differential operator achieves a local extremum with respect to both spatial dimensions and scale.

The differential operator used in detection of blob-like features is Laplacian (Lindeberg 1998). Because the magnitude of the Laplacian filter response changes with scale, normalising is needed. In this study, Laplacian was calculated from the trace of the second derivative matrix of Gaussian function. The normalised response at scale σ was obtained from $\sigma^2(L_{xx}+L_{yy})$. A series of normalised Laplacian bands were calculated for σ values 0.5 – 5 pixels with stepsize of 0.25 (Figure 1). A combined Laplacian image (Figure 2) was then formed by taking for each pixel the value of that scale band whose absolute value was largest over the scales. In a Laplacian image, the bright blobs of the original image are seen as local minima. Watershed regions associated with the local minima in the combined Laplacian image were identified using a drainage direction following algorithm (Gauch 1999, see also Narendra and Goldberg 1980). In this variant of watershed segmentation, each local minimum is first labeled with unique region identifier. For each of the remaining pixels, the eight neighbours of a pixel are searched to link the pixel to the most steeply downhill direction. The links are then followed to some minimum to get a region label for each pixel.

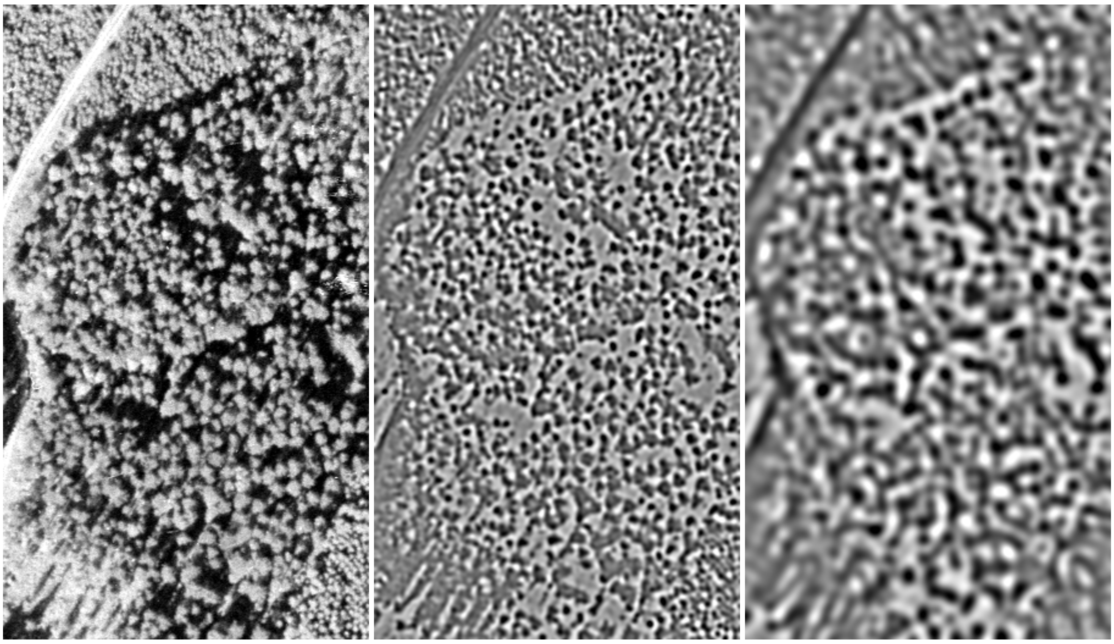

Figure 1. Band 2 of the aerial image (left) and normalized Laplacians at scale σ = 2 pixels (centre) and σ = 5 pixels (right) from the field plot area.

The watershed segmentation divided the whole image area to segments. To get the extent of tree crowns, a canopy mask of bright areas in the original image was formed from the combined Laplacian image by thresholding (Figure 2). In the mask, pixels with the Laplacian value less or equal to 0 were labelled as canopy and others as background. The segmented image was then masked to get final segments (Figure 2), whose location, area and diameter in the image were calculated. The centre of gravity was used as location and the maximum of four diameters through the centre of gravity in horizontal, vertical and two diagonal directions was taken for diameter. Only segments that were at least six pixels in size (0.96 m^2) were considered as trees. Further, diameters over 8 m were set to 8 m to not to get too large tree crown segments. The described method is later referred as blob segmentation.

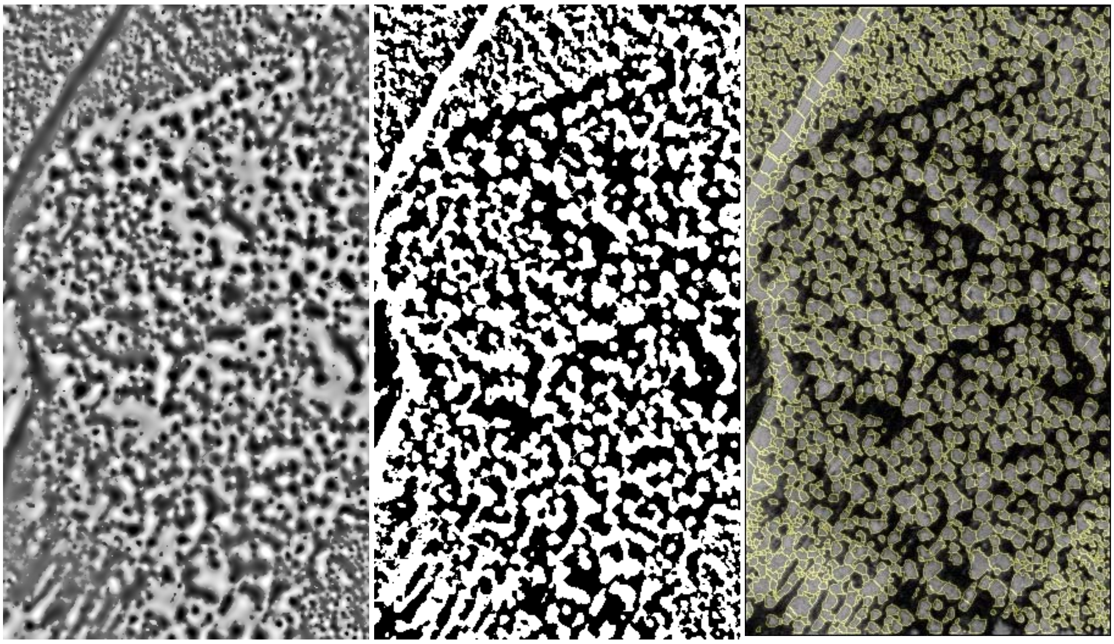

Figure 2. Combined Laplacian image (left), canopy mask (centre) and final segment boundaries overlaid on the band 2 image (right).

Models by Kalliovirta and Tokola (2004), of the form

$$\sqrt{DBH} = f(d_c) + \varepsilon$$

where d_c is maximum crown diameter, were used to estimate a DBH for each tree segment within the field plot. Because there was no tree species recognition from the image, the DBH estimate was calculated as an average of the estimates given by pine, spruce and birch models.

The original band 2 image was pre-smoothed with Gaussian filter at scale σ = 0.5 pixels before inputting the image to the described blob detection method. This was found necessary to keep the number of non-tree segments at reasonable level. In the results, the accuracy of tree detection and crown width and DBH estimation are presented. To get results on individual tree basis, an estimated set of candidate tree locations was matched to a set of tree locations so that first 50 largest trees and tree candidates, based on the field measured and estimated DBHs, were searched for matches using a distance limit of 3 m and a DBH difference limit of 30 cm. The found matches were used to calculate average translations in x- and y-co-ordinates, translations were added to all tree candidate locations and the full sets were searched for matches. The matches were used to get second translations that were applied and full sets were searched for final matches. A program, originally made for matching start lists (Richmond 2002), was modified to do the matching as described. For comparison, tree detection results are presented for local maxima finding on three Gaussian filtered images at the scales of σ 1.1, 1.2 and 1.3 pixels as well. To get DBH estimates for tree location matching, watershed segmentation was run on the negative of the Gaussian filtered image and the canopy mask was obtained using Otsu's thresholding (Otsu 1979) in local, 47 pixels wide square windows (see Pitkänen 2001).

Results

About 85 % of trees were detected with blob segmentation method. With Gaussian filtering and local maxima method (GF&LM), about four per cent less trees were detected when the filtering scale was $\sigma = 1.1$ pixels, which gave the same percentage of false positives as blob segmentation (Table 1). However, the number of false positives was then quite high, about 20 % of the total tree count. If the Gaussian filtering scale was increased, the percentage of false positives decreased faster than the percentage of found trees. If the filtering scale was $\sigma = 1.3$ pixels, GF&LM method produced 7 % less detected trees and 10 % less false positives than blob segmentation (Table 1).

Table 1. Accuracy of tree detection using blob segmentation and Gaussian filtering and local maxima finding methods.

Method	Sigma	Percentage of all trees		Basal area of found trees (%)
		Found trees	Non-tree candidates	
Blob segmentation	-	85.2	19.2	91.4
Gauss. filt. and LM	1.1	81.1	20.1	88.1
Gauss. filt. and LM	1.2	80.2	14.2	87.2
Gauss. filt. and LM	1.3	78.6	9.7	85.8

In the set of trees detected with blob segmentation, 48 trees had crown width measured in the field. The mean of these crown widths was 4.32 m, whereas the mean of corresponding segment diameters was 4.55 m. Between segment diameter and crown width, the Pearson's correlation coefficient was .35 ($p < .05$) and the RMSE was 1.50 m (Figure 3, left). However, if four largest estimate errors were left out, the correlation was .59 ($p < .01$) and the RMSE was 1.11 m. The DBH estimates of detected trees were clearly biased towards underestimation (Figure 3, right): the average underestimation was

11 cm on spruce and on all tree species and 15 cm on pine. On birch, the underestimation was only 1 cm. However, the number of found birches was low and there was no statistically significant correlation between DBH and DBH estimates (Figure 4). The correlation coefficient was .41 on all tree species ($p < .001$), .30 on pine ($p < .1$) and .48 on spruce ($p < .001$). Visually, the correlation on pine seemed to be quite strong but it was reduced by the tree divergent cases that were below the 1:1 line (Figure 4). If these were omitted, the correlation was .63 ($p < 0.01$).

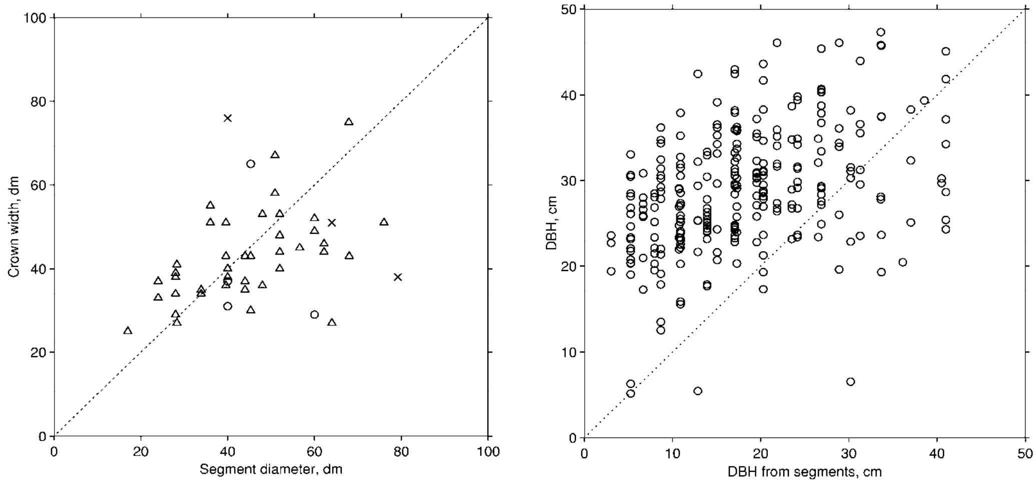

Figure 3. Estimates from blob segmentation plotted against field measured values. Left: Crown width vs. segment diameter for pine (circle), spruce (triangle) and birch (x symbol). Right: DBH vs. DBH estimates.

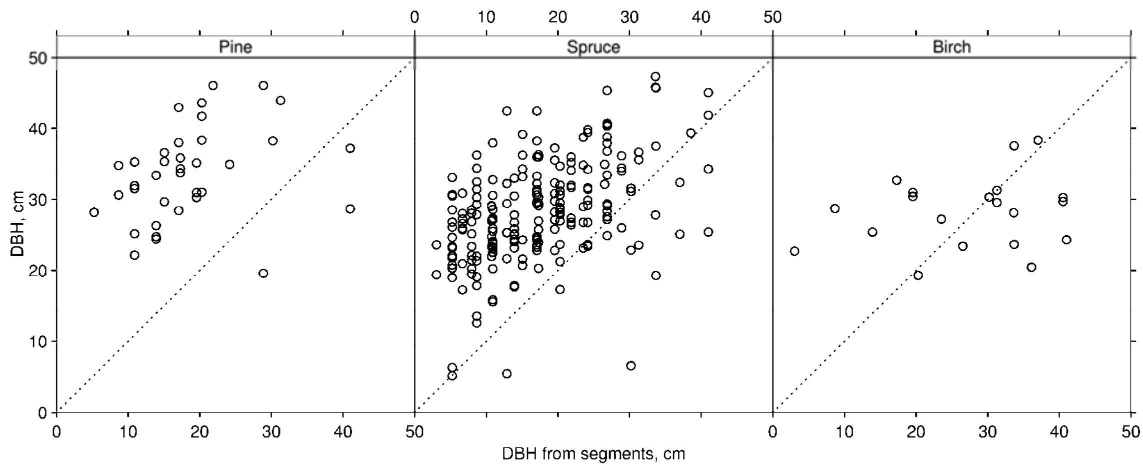

Figure 4. DBH vs. DBH estimates from blob segmentation by tree species.

Discussion

In this study, it was assumed that trees in an aerial image are seen as bright blob-like structures. Therefore, a blob detection method (Lindeberg 1998) was tried for finding possible tree locations. In the method, blobs are detected and scale is selected simultaneously from a multi-scale Laplacian image, calculated from the original image. The selected scale in a blob location is related to the size of the blob. The assumption of trees showing as bright blobs generally holds true in near-nadir areas of an aerial image of boreal closed forest. However, often trees are not ideal bright blob targets, because crowns are next to each other or even over-lapping, large parts of tree crowns or whole crowns are shaded and background intensity varies a lot. Hence, the scale of found blobs did not seem to be directly proportional to the size of the blobs. Therefore, tree crown size was not estimated from the blob scale but tree crowns were further delineated by thresholding and watershed segmentation from a combined image of Laplacians at different scales.

The proposed blob segmentation method performed fairly well in tree detection: about 85 % of all trees were found, which was a few per cent more than what was found by the GF&LM method. The main problem of the multi-scale blob method was over-segmentation that resulted in the relatively large number of non-tree segments. To reduce the number of these, pre-smoothing and minimum segment size were included in the image interpretation chain. Still, the number of false positives remained in almost 20 % of the total tree count. Clearly lower amount of false positives could be obtained with the GF&LM method by setting the scale of Gaussian filtering to $\sigma = 1.3$ pixels. However, the rapid decrease in the number of non-tree segments when the scale was only slightly increased (Table 1) shows that the GF&LM method may be sensitive to the selection of appropriate filtering scale.

Comparison of segment diameters and crown widths indicated, a bit contrary to expectation, that segment diameters were not clear underestimates for crown widths, as they were in an earlier study (Brandtberg 1999). The mean segment diameter was even larger than the mean crown width but this was caused by a few large segments that probably contained two or more trees or a tree and some bright background area. Otherwise the segment diameters were at the same level as crown widths (Figure 3 left). Because there was only a limited number of crown width measurements from one stand of the study, it is difficult to say whether the lack of underestimation was caused by the material or the segmentation method used or some particular characteristics of the study stand. In contrast to crown width, DBH estimates from segmentation were clear underestimates. This was partly caused by equal weighting of tree specieswise DBH models, of which model for birch gives clearly smaller DBHs from same crown diameters than models for pine or spruce. However, as the underestimation was so large, it is apparent that the large area models underestimated DBH in the study stand.

Automatic scale selection would be very desirable feature in the interpretation chain for individual tree detection and crown delineation from aerial photographs. With the tested blob detection method, the scale is in best case selected at an individual tree level. The original aerial image had to be pre-smoothed before blob detection, so the scale selection did not quite directly work. However, tentative tree detection and segmentation results were promising, so that further work to overcome over-segmentation problem and testing with larger material is justified.

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Landsat TM Imagery and High Altitude Aerial Photographs in Estimation of Forest Characteristics

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Abstract

Satellite images have been commonly used in multi-source forest inventory for estimating the forest characteristics of large areas. Their advantages generally are large geographic coverage and large spectral range. Another remote sensing data source for forest inventories offering a large geographic coverage is the high-altitude aerial photography. In high-altitude aerial photographs the spectral range is very narrow but the spatial resolution is high. This allows the extraction of texture features for forest inventory purposes. In this study Landsat TM satellite image, photo mosaic composed of high-altitude panchromatic aerial photographs and a combination of the aforementioned have been utilized in estimating forest attributes for an area covering approximately 280 000 ha in Forestry centre Uusimaa-Häme in Southern Finland. NFI9 sample plots were used as field data. In the estimation 9 Landsat TM image channels were used, and for aerial photographs, 4 image channels were composed from the spectral averages and texture features. In their combination 6 Landsat channels and 3 aerial image texture channels were used. The accuracy of the Landsat image based forest estimates was better than estimates based on high-altitude aerial photographs. On the other hand, using a combination of Landsat TM spectral features and textural features of high-altitude aerial photographs improved the estimation accuracy of most forest attributes.

Timber Volume Mapping from Atmospherically Corrected Landsat TM Mosaic

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Abstract

Monitoring large forest areas using remote sensing usually require large field data sets. By interpreting several images simultaneously, the need for intensive data collection can be reduced. The study concentrated on evaluating the accuracy and functionality of stand volume models on overlapping, multitemporal images. 6S atmospheric correction algorithm was tested in order to develop methods for generalizing field information outside the coverage of one image. Two Landsat ETM+ images from different dates were used to compare atmospherically corrected data with uncorrected data. MODIS weather satellite data was used in retrieving meteorological data for 6S algorithm. Classification accuracy using atmospherically corrected data inceased on average 41%.

1. Introduction

The accuracy of satellite image-based forest inventories are highly dependent on the quality of the satellite data being interpreted. The possible season for acquiring Landsat-images for forest inventory purposes in Finland is in average under four months. Because of the relatively long repeat time for Landsat satellite (16 days), cloud-free images for creating multi-image mosaics are frequently not available. When such data exists, it usually consists of images from many different parts of the growing period of forests. Since the cost of Landsat images has recently decreased there has been growing interest in the use of multitemporal Landsat imagery and previously it has been studied in several publications (Helmer et al. 2000, Lefsky et al. 2001, Oetter et al. 2001, Song & Woodcock 2002, 2003; Hadjimitsis et al. 2004). There are many factors that cause uncertainty in using multitemporal satellite data: Aging of the instrument, atmosphere, topography, phenology, distance of the target to the sun, and sun and view angles. In optical remote sensing, atmosphere is the primary source of noise to measure surface reflectance accurately (Song & Woodcock 2003). Important atmosphere related factor that reduces the radiometric accuracy is the proportion of aerosols and gases in the atmosphere. This has a direct affect on the amount of scattering and absorption registered by the instrument. Different types of algorithms are proposed for removing the atmospheric effect from the satellite data: image-based algorithms (Chavez 1988, 1989, 1996; Song et al. 2001, Song & Woodcock 2003) and a number of methods that use radiative transfer codes (RTC), which require in situ measurements of atmospheric conditions (Kneizys et al. 1988, De Haan et al. 1991, Rahman & Dedieu 1994, Vermote et al. 1997). Also combination methods, that utilize time-dependent meteorological measurements and image-based information, have been developed (Liang et al. 1997, Ouaidrari & Vermote 1999, Wen et al. 1999).

In Finland, environmental authorities, paper companies and teleoperators utilise regional forest maps in the scale of 1:50 000-1:100 000 for different planning tasks as well as for timber procurement. Large-area forest inventory based on Landsat image interpretation is often suitable method for producing such maps. Normally interpretation of multiple imageries require large field data sets which makes interpretation costly. In this study 6S correction method is tested in order to generalize field information outside the coverage of one image. Mainly the study is concentrated on evaluating the accuracy and functionality of the stand volume models on overlapping, multitemporal images.

2. Material

The tests for the atmospheric correction were made using two multitemporal overlapping Landsat ETM+ images (table 1) in the region of Kainuu in northern Finland (figure 1). The field data consisted of 444 sample plots which were placed using advance information so that the data set would include as much variation in height, basal area and tree species composition as possible. MODIS weather satellite data was used to derive some of the input parameters for the 6S atmospheric code.

Table 2. Landsat ETM+ images used in the study

Path	Row	Acquisition date
188	15	29052002
188	15	17082002

Out of the 444 sample plots 315 were placed on mineral soils and 129 on peatlands. Average volume for the sample plots on mineral soils was 130 m^3/ha and 104 m^3/ha on peatlands. Data was distributed in two data sets, which located about 150 kilometers apart from each other (figure 1). First of the datasets was measured during summer 2002 and included 277 sample plots. The rest of the sample plots (167) were measured during summer 2003.

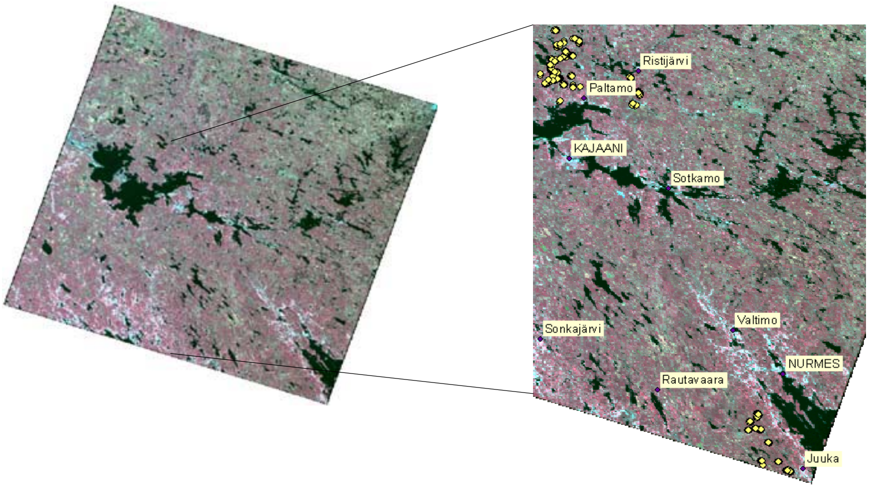

Figure 1. Study area and coverage of the Landsat images used

3. Methods

3.1 Atmospheric correction

6S -model (Second Simulation of the Satellite Signal in the Solar Spectrum) predicts the effect of the atmosphere to the radiance registered by the satellite and it is based on the radiative transfer theory developed by Chandsarekhar (1950). The model takes into account the main atmospheric effects; the gaseous absorption by water vapour, oxygen, ozone and carbon dioxide and the scattering caused by aerosols and molecules. The input parameters for the model are the sun-sensor geometry, atmospheric model for gaseous components, aerosol model (type and concentration), aerosol optical depth, ground reflectance and spectral band. 6S model requires several measurements of atmospheric optical properties at the time of image acquisition, which often limits the use of the model. Unavailability of accurate atmospheric data is one of the main reasons why in many applications only such correction algorithms that utilize the information derived from the image itself are being used operationally. By using the data from MODIS satellite it is possible to derive many of the parameters used in 6S model (e.g. Kaufman et al. 1997). In this study, the parameters derived from the MODIS data were the altitude, pressure, temperature, H_2O and O_3 density, which were computed from the MOD07 dataset (Menzel et al. 2002). The aerosol optical depth at 550 nm was computed from MOD04 dataset (Kaufman & Tanré 1998).. Parameters were calculated as an average from cloud free pixels in a window of 100x100 km. Within the study the aerosol model was kept constant. Before running the code, the sensor signal was converted to at-satellite radiance using relation, $L_{sat} = G(DN)+B$, where G is the sensor gain and B the bias.

3.2 The estimation method for stand volume

The study was based on multitemporal Landsat images and field data that was used to supervise the estimation. Separate stand volume equations based on the field data and spectral values were created for uncorrected images, as well as for atmospherically corrected images (*reference models)*. The quality of the reference models was tested by comparison with an overlapping image from different date. Different statistics (RMSE, bias, classification accuracy) were computed to evaluate the effect of atmospheric correction on timber volume accuracy. The form of the stand volume models was the following:

Growing stock: $y = e^{\eta}$

η = *linear combination of radiances registered by ETM+ bands 2, 3, 4 and 5*

4. Results

4.1 Atmospheric correction

Since the image acquired on August was relatively cloudy (14 %), its' atmosphere optical properties differed quite a lot from the image acquired on May. This increased the uncertainty of image correction. Most significant differences were in aerosol optical depth value and water vapour content. The MODIS derived AOD value was 0.08 for the reference image (29.5.2002) and 0.16 for the image compared (17.8.2002). There was also quite a lot of variation in aerosol optical depth within the coverage of the images used (figure 2). Effect of within image AOD variation was however ignored.

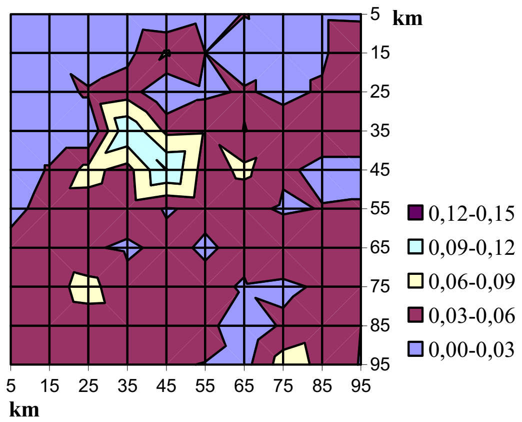

Figure 2. AOD surface (29.5.2002) within the study area (100km x 100km) at 550 nm (MODIS retrieval)

6S corrected the satellite measurements into surface reflectances (figure 3) with relatively good accuracy. After correction, there was on average about 1 % difference in reflectance values on band four, whereas on band five there was still 10-15 % differences in corrected values. This was due to the different conditions of humidity.

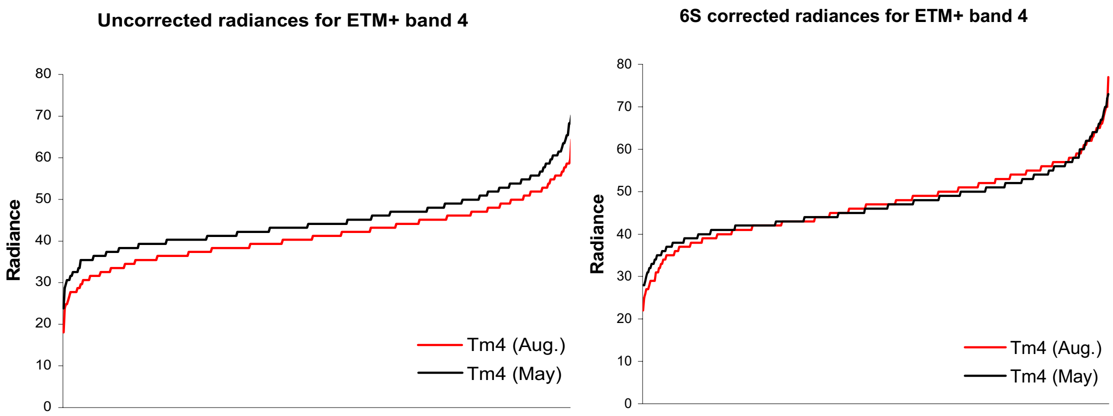

Figure 3. Uncorrected and 6S corrected radiances for ETM+ band 4

4.2 Timber volume estimation

The standard deviation value for uncorrected reference model (May) was 63.14 m^3/ha and 62.32 m^3/ha for the 6S corrected model (table 2). Biases for the models were -1.24 m^3/ha and -1.80 m^3/ha respectively.

Table 2. Key statistics for the reference models

Reference image	Calibration method	s (m^3/ha)	r^2	bias (m^3/ha)	sdb	n
31052002	Uncorrected	63.14	0.494	-1.24	3.00	444
31052002	6S	62.32	0.473	-1.80	2.96	444

The reference model was applied to a similarly processed overlapping image and the statistics were calculated. The classification result was evaluated by classifying the estimates into classes of 50 m^3/ha. The proportion of estimates falling into the correct class and neighbouring classes were calculated. In general the neighbouring image standard deviation values increased to some extent but most significant was the increment of bias. When applying the raw reference models to neighbouring images, the relative RMSE value increased by over 25 % (table 3). Also the classification results became poor. When atmospheric correction was applied to the images, the relative RMSE increased only 5 % on overlapping image. Also the classification accuracy increased noticeably.

Table 3. Effect of atmospheric correction on key statistics

Correction method	Reference image	compared image	RMSE (%)	correct class (%)	class ±1 (%)
Uncorrected	31052002		52.2	36.26	79.50
		17082002	77.4	13.51	45.27
6S	31052002		51.5	32.35	77.60
		17082002	56.4	25.00	71.59

Atmospherically corrected Landsat data is suitable for producing coarse scale timber volume maps from extensive areas (figure 4). When combined with different digital datasets, these maps can be used for multiple purposes such as timber procurement, radio network planning and environmental planning operations.

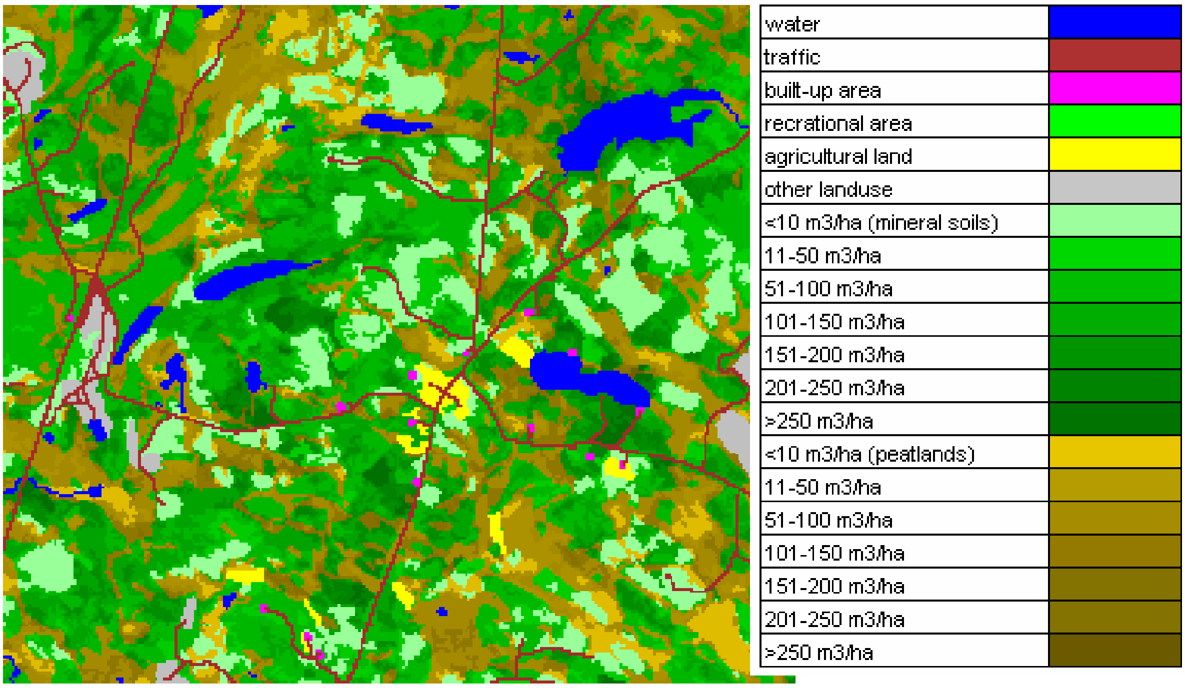

Figure 4. Example of a timber volume map, generated with the proposed method

5. Discussion

6S algorithm can convert the satellite measurements accurately into surface reflectances (Holm et al. 1989; Moran et al. 1992) and this leads to improved classification results when multitemporal satellite images are used. 6S requires many time-dependent input parameters which makes its' use more complicated than purely image-based algorithms. At present there are sources such as MODIS where many of these parameters can be obtained with sufficient accuracy. Cloudiness and haze (scene includes semitransparent cloud and aerosol layers) though can dilute the quality of MODIS data. As was the case in this study, atmospherically clear scenes are seldom available in Finland. Haze can arise from a variety of atmospheric elements, such as water droplets, ice crystals or fog/smog particles (Kaufman, 1989). Influence of haze on measured radiance is most significant on the visible spectral region (Zhang et al. 2002). For hazy scenes ancillary data upon which to base an absolute atmospheric correction is often missing. MODIS data used in this study was imperfect for the image acquired in August, which evidently increases the uncertainty of the 6S correction. In this study, there was after correction at most 10-15% differences in forest area reflectances between the images used. This was mainly due to phenology and to the differences in water vapour and AOD values of the images. Eventhough 6S worked well in correcting the images to same radiometric scale, it must be taken into consideration that not always it is possible to assume that empirical models from one date would seamlessly apply to another image.

There are also several factors in Finnish forests which could lead to bias when a large area field sample is used in a small area estimation. One significant factor that can lead to bias in estimates is the variability of surface reflectance due to phenology (Song & Woodcock 2003). Even if the leaf spectral properties and amount of leaves in the canopy could be assumed to be the same between images used, the observed reflectance may vary within season. This is due to the changing sun angle which causes variability in the amount of shadows casting in the canopy. The images used in the study were acquired in different sections of the growing period. Especially in the beginning of the growing period there is always local variation in the development of different plants.

Differences in the forest stand structure between forest ownership groups are another reason for local variation in forested areas. Also soil fertility factors vary locally within the vegetation zones. Eventhough the sample plots used in the study (figure 1) located within the same plant ecological zone, there is variability in soil factors. In the conditions prevailing in Finland, soil type affects the spectral responses received from forested areas. Different objects, e.g. a dense spruce stand and open swamp areas, can have similar reflectance properties (Saukkola 1982). If digital ancillary data, e.g. forest or soil type maps concerning the target area, are available, the reliability of sub area estimation can be improved and more representative field samples can be chosen on the basis of a prior information.

Also geographic distance between sample areas can cause bias to estimates. It has been stated that the best interpretation results using satellite images is achieved when the field data is collected within 20-km search radius (Tokola 2000, Katila & Tomppo 2001). The results presented by Lappi (2001), confirms this: Estimation errors were smallest, when plots between a 20-50 km search radius were used. Even though the distance between the remotest plots used in this study was more than 100 km, the distribution of the error terms of the models didn't seem to have geographic dependency. The reliability of estimates depends also on the size of the forest stand (Poso et al. 1987). Laasasenaho and Päivinen (1986) calculated 11% relative error in a survey by stands. For small stands and areas the mean estimates can be significantly poorer (Poso et al. 1987, Muinonen and Tokola 1990, Holopainen and Lukkarinen 1994).

Using regression analysis and relatively small amount of field data, coarse scale timber volume maps can be produced cost-efficiently. Generated with the classification method proposed, the total volume of growing stock in municipal level seems to be mainly an overestimate when compared with national forest inventory (NFI) statistics (Tomppo et al. 1998). However, for the practical users of data, the relative differences between growing stock volume estimates might be sufficient enough, since the cost of the data can be kept low.

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Forest Planning

Photo: John Y. Larsson
Picture of clear cutting. Grong, Nord-Trøndelag.

A Selective Cutting Index for Application in Forest Management Planning

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1. Background

There has been an increased attention drawn to uneven-aged forests, selective cutting regimes and natural regeneration in Norway over the past few years. This interest is partly due to expected enhancements for landscape aesthetics and biodiversity, and partly to expected benefits for regeneration costs, timber quality and profits. Selective cutting can be defined as *cutting based on defined criteria for choice of trees that maintains or develops an uneven-aged stand structure*. Selective cutting is characterized by i) only parts of the standing volume is harvested, ii) conditions for recruitment are favoured in order to maintain or develop an uneven-aged stand structure, iii) each individual tree, or small groups of trees, are decision units and iv) the decision of which trees to be harvested are based on some specified criterion (e.g. size, quality, volume increment, financial maturity).

One of the basic questions in forest management planning is the choice of cutting-method, which is dependent of economically as well as biological factors. Long-term field experiments have revealed that selective cutting should be restricted to stands were the biological conditions are considered to be suitable, since inappropriate conditions with respect to stand structure and natural regeneration may cause low volume production, and hence low profitability (Lundqvist, 1989, Andreassen, 1994). It is therefore important for the forest manager to be able to decide whether a particular stand is suitable for selective cutting or not. It is preferable that this decision is based on objectively measured variables.

Several factors affect whether a stand has suitable biological conditions for selective cutting. Diameter diversity, growth potential, stability and conditions for natural regeneration are considered to be among the most important characteristics. Other factors mainly connected to the location of the stand (e.g. climate, topography, surrounding stands, harvesting conditions and probability of browsing) are also expected to affect the suitability. Such factors are, however, more difficult to assess objectively than stand variables.

An index describing the biological conditions for selective cutting based on the criteria diameter diversity, growth potential, stability and conditions for natural regeneration is presented. The index is based on objectively measured variables, and has primarily been developed for application in practical forest management planning.

2. The Selective Cutting Index (SCI)

The biological conditions for selective cutting can be estimated with the following index

$$SCI = I_1^{\beta_1} \times I_2^{\beta_2} \times I_3^{\beta_3} \times I_4^{\beta_4} \times 10 \tag{1}$$

where I_1, I_2, I_3 and I_4 are sub-indices describing diameter diversity, growth potential, stability and conditions for natural regeneration, respectively. β_1 - β_4 are parameters that weights the influence of the different sub-indices. All sub-indices are standardized to values between 0 and 1. Values close to 1 indicate suitable conditions, while values close to 0 indicate unsuitable conditions for selective cutting with respect to that particular criterion. Selective cutting is considered to be more suitable in stands with high values for SCI than in stands with low index values. The smallest possible value for SCI is 0, while the theoretical maximum is 10.

2.1 Diameter diversity

Lexerød and Eid (2005) found the Gini coefficient (Gini, 1912) superior among eight different diameter diversity indices evaluated. Sub-index I_1 was therefore expressed as:

$$I_1 = \frac{\sum_{j=1}^{n} (2j - N - 1) ba_j}{\sum_{j=1}^{n} ba_j (N - 1)} \tag{2}$$

where j = the rank of each tree in ascending order from 1…*N*.
ba_j = basal area of a tree with rank j
N = total number of trees

Basal area is used as a measure of tree size instead of diameter in order to increase the influence of larger trees (as suggested by Solomon and Grove (1999)). The index has a minimum value of 0 when all trees are equally sized, and a theoretical maximum of 1. The Gini coefficient provides a logical ranking of different diameter distributions, and it discriminates well between them. In addition, the Gini coefficient is independent of stand density. This means that two different stands with equally shaped diameter distributions get the same index value irrespective of stand density. Finally, the Gini coefficient is relatively independent of sample size. This is an important characteristic since SCI usually has to be calculated from a sample distribution representing the true diameter distribution. The main drawback of the Gini coefficient is the relatively complex calculation process compared to other indices of diameter diversity (Lexerød and Eid, 2005).

2.2 Growth potential

The growth potential of the remaining trees depends on the actual growth of the trees and the expected growth response after cutting. The size of the tree crown affects the actual growth, and different measures of crown size have frequently been used in growth models for individual trees (e.g. Wykoff (1990), Monserud and Sterba (1996), Wimberly and Bare (1996)). It is also reasonable to assume that released trees with large crowns will have a larger growth response to cutting than trees with small crowns. The growth potential (I_2) of the remaining trees was therefore assumed to rely on the crown ratio expressed as:

$$I_2 = \left[\left(1 - \left(\frac{CH_{pine}}{H_L} \right)^2 \right) \times \frac{Prop_{pine}}{100} + \alpha \left(1 - \left(\frac{CH_{spruce}}{H_L} \right)^2 \right) \times \frac{Prop_{spruce}}{100} \right] \quad (3)$$

where CH = mean crown height[1] by basal area.
H_L = mean height by basal area (m)
Prop = proportion of standing volume (%)
α = parameter defining the effect of species

The index value increases as the ratio between the crown height and the mean height weighted by basal area decreases. This means that the growth potential is high when the crown height is small. The index accounts for differences in crown morphology between Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). The crown ratio for Norway spruce is usually larger than the crown ratio for Scots pine under similar conditions (Petersson, 1997). Hence, Norway spruce has a lower growth potential at the same crown ratio. In order to express this the crown ratio for Norway spruce was multiplied by a constant (α), which was estimated to 0.81 based on growth models by Øyen (2003).

2.3 Stability

Stability *after* selective cutting depends on individual tree stability and the tree height diversity of the stand. Individual tree stability can be estimated by the height/diameter ratio or the crown ratio (Nielsen, 2001b). Hence, sub-index I_2 estimates the individual tree stability. In addition, height structure affects stand stability since dominating trees, with high individual tree stability, provide shelter for suppressed and codominating trees (Nielsen, 2001a, Mason, 2002). The positive effect on stand stability of increased height diversity can be expressed with sub-index I_3 as;

$$I_3 = \left(1 - \frac{H_L}{H_D} \right) \quad (4)$$

where H_L = mean height by basal area (m)
H_D = dominant height (m) (i.e. arithmetic mean height of 100 thickest trees per hectare)

The mean height compared to the dominant height is low in stands with large tree height diversity, something that gives a high index value, while even-aged stands with trees of almost the same height have a mean height close to the dominant height and thus a low index value.

2.4 Conditions for natural regeneration

Conditions for natural regeneration are mainly determined by the amount of seeds and suitable seedbeds (Hansen, 2002). The amount of suitable seedbeds can be indirectly described by vegetation type, while the amount of mature seeds is strongly correlated

[1] Crown height is defined as the vertical distance (m) to the first living branch.

with geographical location (Sarvas, 1957). Hence, conditions for natural regeneration in different geographical regions can be determined by ranking vegetation types with respect to their suitability for natural regeneration (see e.g. Larsson and Aalde (1996)). Sub-index I_4 determines the conditions for natural regeneration as;

$$I_4 = C_k \tag{5}$$

where $k = 1 \ldots n$ are clusters of vegetation types and regions with almost similar conditions for natural regeneration, and C is the relative value of cluster *k*. The cluster with the most suitable conditions for natural regeneration has a value of 1.0.

Sub-index I_4 was calculated from the amount of advanced regeneration (1-30 dm) of Norway spruce and Scots pine registered by the National Forest Inventory on the eight main vegetation types associated with coniferous forests in three different geographical regions, Table 1.

Table 1. Description of geographical regions and number of sample plots in each region.

Region	No. of plots	Description
1	137	Southern and Eastern Norway below 300 m a.s.l.
2	441	Southern and Eastern Norway above 300 m a.s.l.
3	95	Central Norway
Total	673	

Combinations of geographical regions and vegetation types were clustered into six different clusters, which are presented in Table 2 together with their corresponding values for C_k. A stand with vegetation type *Eu-Piceetum myrtillitosum* located in Region 2 will, for example, get an index value (I_4) of 0.31.

Table 2. Clusters of geographical regions and vegetation types, mean number of seedlings in each cluster and corresponding values for C_k

	Region				
Cluster	1	2	3	Seedlings/ha	C_k
1	*Eu-Piceetum athyrietosum* *Melico-Piceetum typicum* *Aconito-Piceetum*	*Melico-Piceetum typicum*		2321	1
2	*Cladonio-Pinetum boreale* *Eu-Piceetum myrtillitosum*			1944	0.84
3	*Barbilophozio-Pinetum* *Eu-Piceetum dryopteridetosum*			1588	0.68
4		*Eu-Piceetum dryopteridetosum* *Cladonio-Pinetum boreale*	*Eu-Piceetum athyrietosum* *Melico-Piceetum typicum* *Aconito-Piceetum* *Eu-Piceetum dryopteridetosum*	1070	0.46
5	*Calamagrostio lapponicae-Pinetum*	*Eu-Piceetum athyrietosum* *Aconito-Piceetum* *Eu-Piceetum myrtillitosum* *Barbilophozio-Pinetum*	*Calamagrostio lapponicae-Pinetum* *Eu-Piceetum myrtillitosum* *Barbilophozio-Pinetum*	728	0.31
6		*Calamagrostio lapponicae-Pinetum*		338	0.16
Seedlings /ha	1715	792	794	980	

2.5 Standardization of index values

Although all sub-indices are theoretically restricted between 0 and 1 they have different range of values, and will therefore have different impact on the final value if multiplied directly. Sub-indices I_1, I_2 and I_3 have therefore been standardized in order to ensure equal impact on the final index value. Standardized sub-indices are calculated as;

$$\hat{I}_j = \frac{I_j - Min(I_j)}{Max(I_j) - Min(I_j)} \tag{6}$$

where $\hat{I}_j$ is the standardized value of sub-index *j*, I_j is the original value of sub-index *j*, while $Min(I_j)$ and Max (I_j) are estimated minimum and maximum values for index *j*, Table 3.

Table 3. Minimum and maximum values for sub-indices I_1, I_2 and I_3.

Sub-index	Mean	Minimum	Maximum
I_1	0.45	0.16	0.68
I_2	0.80	0.59	0.96
I_3	0.12	0.02	0.36

3. Application of SCI in forest management planning

SCI was mainly developed in order to help forest managers to decide whether a particular stand is suitable for selective cutting or not based on objectively measured variables. SCI can, however, also be used to quantify potential areas suitable for selective cutting at the national, regional or forest estate level (Lexerød and Eid, 2004), to study changes in stand structure over time with respect to the suitability for selective cutting and as an integrated part of growth simulators in order to control silvicultural treatments in projections.

Several simplifications and assumptions were made in order to make the index applicable for practical managerial decision-making. First of all, only variables that can be registered directly or derived from inventories for practical forest management planning is needed in order to calculate SCI. Secondly, factors affecting the suitability for selective cutting, but which are difficult to measure objectively, are not included (e.g. climate, topography, surrounding stands, harvesting conditions and probability of browsing). These factors have to be considered subjectively before the final decision is made. It can also be necessary to adjust the sub-indices for stability and regeneration with respect to local variations.

A decision regarding which cutting method that is appropriate in a particular stand has to be based on the state of the stand prior to harvesting. Hence, SCI must be calculated from variables describing the state of the stand *before* harvesting. This is straightforward with respect to diameter distribution (I_1) and conditions for natural regeneration (I_4). It is, however, more complicated when regarding growth potential (I_2) and stability (I_3) since these factors are dependent of the stand structure *after* harvesting, which is unknown at the time of decision. Sub-indices I_2 and I_3 are based on the relative relationships between different variables, and calculation of SCI therefore assumes that these relationships are not altered considerably by the harvest (i.e. when the dominant height is reduced because of the harvest it is assumed that the mean height is reduced in the same proportion making the relative relationship between these two variables to remain the same).

SCI does not consider at which point in time selective cutting should take place. A stand may get a high index value even though standing volume, and hence the volume of financially mature trees, is low. Usually, a minimum amount of financially mature trees are required before harvesting is performed. The amount of financially mature trees at a specific point in time depends on the value growth of each individual tree, timber prices and the costs of harvesting, administration and capital (Duerr, 1993). The amount of volume to be harvested is thus dependent of changes in these factors, and should be compared, in each particular stand, to the minimum amount of financially mature trees required in order to perform selective cutting.

SCI gives a relative ranking of different stands and not an absolute measure of the profitability of selective cutting compared to other silvicultural alternatives. The profitability of different cutting regimes depends, in addition to the forest conditions, on timber prices, costs and the rate of interest (e.g. Andreassen and Øyen (2002)). These factors are dependent of time and ownership, and it is therefore not possible to assess an absolute and general threshold value for which selective cutting is the most profitable treatment. SCI may, however, indicate the relative profitability of selective cutting compared to other treatments. A low index value generally indicates low profitability of selective cutting, while a high index value indicates that selective cutting is relatively more profitable compared to other silvicultural alternatives.

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The Risk of Decision Making with Incomplete Criteria Weight Information

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Aiding decision making with multiple criteria is typically based on utility or value function with explicit weights given to the different criteria. In many cases, it may be difficult to obtain accurate or any information of criteria weights for decision analysis. This is typically the situation in public participation. The preferences of layman are not known, and even if they were, aggregation of those preferences to a social welfare function may be impossible. Often, however, the relevant criteria can be found, perhaps their importance order or even more accurate information.

In many MCDA tools, it is possible to utilise such incomplete information. One example of such methods is Stochastic Multi-criteria Acceptability Analysis (SMAA, Lahdelma & Salminen 1998, 2001; Lahdelma et al. 2003). In SMAA analysis, the weight information may be nonexistent, complete or somewhere in the middle of these extremes. For instance, it could be that the most important criterion or the importance order of all the criteria is known. It means that all the information available on the value function can be used in the SMAA analysis. Consequently, recommendations for choosing the best alternative can be given with very scanty information. Evidently, however, the recommendation is risky when the information concerning the criteria weights is incomplete.

The main results of SMAA are the so-called rank acceptability indices, providing the probability of a certain alternative obtaining a given rank, using all the information available. These indices can be used for choosing the most recommendable alternative, for instance by calculating a weighted sum of the probabilities, a so-called holistic acceptability index. The meta-weights used for weighting the probabilities are chosen with a simple, but somewhat arbitrary rule, so that probabilities for the best ranks are given large weights and those for worst ranks are given small weights (e.g. Lahdelma & Salminen 2001).

The risks involved in those recommendations 1) the probability that the best alternative is chosen and 2) the expected losses due to choosing the wrong alternative were analysed through a simulation study based on two old forestry decision problems with multiple criteria. In the simulations, it was assumed that the true value function exists and that it is a linear additive utility function. All the relevant criteria were assumed to be included in the analysis.

For each simulated case, a different "true" value function was generated. In the first analyses, it was assumed that no information about the criteria importance was available. For these reference analyses, 500 different cases were generated from both data sets. In each case, a normal SMAA analysis war carried out. In the first analysis from case study data 1 (see Kangas et al. 2000, 2003), all the 500 cases were obtained using the original data set, i.e. only the true value function was assumed to change between realizations. In the case study data 2 (Laukkanen et al. 2002, Kangas & Kangas 2003), also the decision problem changed in the realization, the original case being the first. The different cases were obtained by permuting the existing data. This was done in order to be able to analyze the effect of the characteristics of the problem to the risks involved. The probability of choosing the correct recommendation and the expected loss, among all the realizations where wrong recommendation was given, were modelled as a function of the true weights and the performance of the truly best alternative.

The results show that the quality of recommendations improves very fast with improving information of weights. In the analysis assuming no information was available concerning the value function, the correct decision alternative was found in 32% of the cases in data set 1 and in 45.8% of cases with data set 2 using the holistic acceptability index. The mean loss as per cents of the utility function value was 6.8% for the data set 1. In the data 2 the mean loss was 7.1%. In data 1, the probability to make a correct recommendation was fairly small. This is probably due to the fact that there were ten alternatives in data 1 compared to 20 alternatives in data 2. Furthermore, the alternatives in data 1 were clearly distinct and performed well with respect to different criteria (see Kangas et al. 2003). In data 2 the probability was greater, as permutation introduced also problems where certain alternatives performed well with respect to many criteria.

The maximum losses were considerable, in data 1 54.9% and in data 2 66.4% of the value of the utility function, which indicates that recommendations based on no preference information may be highly misleading. However, maximum value of losses depends on the amount of simulated cases: the more simulations, the larger the maximum loss is likely to be. Therefore, the maximum loss figure mainly serves as qualitative information about the risks.

The probability of choosing the correct alternative was modelled in data 2 as a function of the characteristics of the problem, assuming no information of the value function. In 85% of all cases, it was possible to predict with a logistic model, whether the correct alternative can be found or not. The two most important predictors were the performance of the correct alternative with equal weights, and the importance of the least important criteria. The first term indicates whether the correct recommendation is a good compromise, i.e. alternative that performs well with respect to all criteria, it is fairly easily found with SMAA. The next term implies that the closer the minimum weight is to the others, the more likely the correct alternative is found. The probability of finding the correct alternative was negligible unless its performance under equal weights was over 0.7.

The expected loss in this case depended on the importance of the most important criteria: the larger this importance, the larger the losses based on a compromise solution could be. However, only 7.7% of the variation in the logarithm of losses could be explained by the characteristics considered.

The probability of finding the true alternative was clearly enhanced with additional information. For instance, when the most important criteria was known, the mean probability to find the correct alternative increased from 45.8% to 63.8%, and the mean loss decreased from 7.1% to 2.6%. Assuming the total importance order known improved the results further. The probability of finding the correct alternative increased from 63.8% to 71.2%, when the total order was known instead of just most important variable, and the mean loss decreased from 2.6% to 1.9%. Even then, the maximum loss observed in the simulation was 19.9%.

It can be concluded that with no information at all, the correct recommendation could be found in less than half of the cases. It was found, if the correct alternative was a good compromise solution, i.e. it performed well with respect to all criteria. If, on the other hand, it was not a compromise solution, i.e. it performed well with some criteria but not all, it was not found but occasionally. Also, the nearer the true weights were to the equal weights, the more probably the correct alternative was found. Both these characteristics imply that the recommendations based on SMAA analysis with no information of the weights correspond to the decision making with equal weights. The more information is available, the better decisions can be made: the probability of finding the correct recommendation increases and both the mean and maximum losses due to the wrong decisions decrease. However, even with complete importance order the probability of choosing a correct recommendation was only 71%, i.e. quite low for real decision making.

Therefore, the clear conclusion is that it makes sense to invest to acquiring at the minimum the complete importance order, and if possible, also numerical weight information. Fortunately, it can be assumed that in those cases where the risk of poor recommendations is highest, i.e. when the compromise solutions are not strived for and the weights of the criteria differ markedly from the equal weights, it is also most likely that the importance order and weight of the most and least important criteria are easiest to find. It is not likely that when one criterion is highly important, this remains unnoticed in the process.

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A Growth Simulator Based on Models for Individual Trees

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Introduction

Even-aged forest management with clear cutting and artificial regeneration have been the dominating silvicultural regime in Norway for 50-60 years. Although such a management regime is expected to dominate also in future, the past few years has seen an increased attention drawn to uneven-aged forests, selective cutting regimes and natural regeneration. This increased interest is partly due to expected enhancements for landscape aesthetics and biodiversity, and partly to expected benefits for regeneration costs, timber quality and profits.

Ecological and economical consequences of different management regimes can be analysed with growth simulators. In Norway, several growth simulators have been developed based on stand models (e.g. Hoen and Eid 1990, Hoen and Gobakken 1997, Eid and Hobbelstad 2000), and over the last 20 to 30 years they have frequently been used to analyse different even-aged forest management regimes. Stand models are, however, not well suited for analyses of uneven-aged forest management. The main reason is that growth simulators based on stand models use the stand as simulation and decision unit, while uneven-aged forest management requires each individual tree or size class to be the simulation and decision unit. Single tree forest growth models represent a stand as a mosaic of single trees and simulate individual growth and interactions with or without consideration of tree positions (Munro 1974).

The first single tree growth simulator was developed for pure Douglas fir stands (Newnham 1964) and was followed by models for other species (e.g. Mitchell 1969, Bella 1970, Arney 1972, Mitchell 1975). In the mid-1970s, the first single tree growth simulators were developed for uneven-aged pure and mixed stands (Ek and Monserud 1974, Monserud 1975). During recent year's biological growth models, mortality models etc. for single trees in even-aged and uneven-aged pure and mixed stands have been developed also in Norway. A growth simulator based on these models for individual trees have been developed in order to analyse different consequences of even-aged as well as uneven-aged forest management.

Main features of the growth simulator

The growth simulator predicts growth and mortality for each individual tree or size class for four different groups of tree species (Norway spruce, Scots pine, birch and other broadleaves). The main data source for the parameterization of the model functions is the entire population of permanent sample plots from the National Forest Inventory in Norway (NFI). The NFI permanent plots were established from 1986 and we only have a limited number of growth periods. However, the data used for the model development reflect the full range of variability with respect to silvicultural treatments, sites, forest structures and tree species of the country. The models should be evaluated and, if necessary, revised or calibrated when data from new rotations of the NFI permanent sample plots measurements are available.

A simulation run is initialized with information about management, site conditions, and tree key variables. Especially, the latter is often incomplete and default values or generated values must be used.

The growth simulator projects the attributes of individual trees or size classes on a five-year cycle for a specified number of periods. The time interval corresponds with the standard time interval between two measurements on the NFI sample plots. The simulator is implemented using an object-oriented programming approach and the C++ computer programming language.

An overview of the simulation and analysis of the growth simulator is illustrated in figure 1. Projections of the stand development require an initial stand inventory, including diameter distribution or a tree list and site conditions. Numerous treatment schedules with different thinning programmes, rotation periods, etc. might be simulated for each stand. The simulations produce all feasible combinations of pre-defined treatment and regeneration options as pre-commercial thinning, thinning, regeneration cutting, and final felling. Different kinds of alternative thinning treatments, regeneration options etc. might easily be defined. Feasibility requirements must be defined for each of the defined treatment and regeneration options in order to prevent the calculation of totally unrealistic treatment schedules.

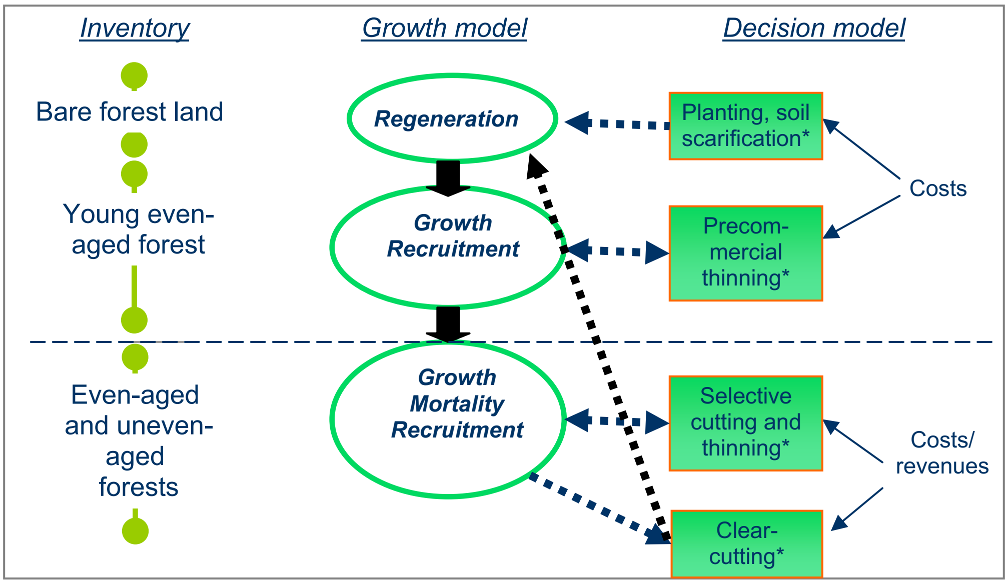

Figure 1. Overview of the simulation and analysis of the growth simulator.

Biological and economical models

Number of trees recruited to the smallest size class is predicted with a two-stage recruitment model (Lexerød 2005, Lexerød and Eid 2005a). The growth simulator projects the future development of trees or size classes based on single tree distance independent diameter growth functions (Bollandsås 2004) and mortality functions

(Eid and Tuhus 2001). The height of a single tree is described by the models developed by Øyen and Andreassen (2002).

Expected revenues from timber production are calculated with gross value functions (Blingsmo and Veidahl 1992, Lexerød and Gobakken 2002) while harvesting and forwarding costs are calculated with cost functions (Dale et al. 1993, Dale and Stamm 1994, Anon. 1996).

All models included in the growth simulator are based on variables directly or indirectly available from practical forest inventories. The growth simulator offers great potential for risk analyses, since both the mortality and the recruitment models can be used stochastically.

Output

From the simulated alternative treatment schedules, various aspects of the stand development can be visualized and analyzed. A large set of numerical information is available which can be viewed as diameter distribution diagrams, for living or dead trees, or as text files that are similar to standard yield tables. Examples of diameter distribution diagrams are shown in figure 2.

Different kinds of output can be distinguished: Firstly, classical growth and yield data are provided at the stand and tree species level, e.g. stem number, basal area, timber volume, increment, mean height, and number of recruited trees etc. Secondly, monetary values can be calculated based on timber prices, harvesting and regeneration costs, and interest rate specified by the user. The net present value including the value of the ending inventory is calculated for all treatment schedules. In addition, a Selective Cutting Index (Lexerød and Eid 2005b) is calculated describing the stand structure and the biological conditions for selective cutting.

The simulator can be used for evaluation of different management regimes at the stand level. In analysis, choice of regeneration and silvicultural treatments can be based on profitability criteria, maximum net present value with different forest management constraints. An example of the objective functions might be maximizing net present value of the stand with different constraints regarding standing volume, Selective Cutting Index etc.

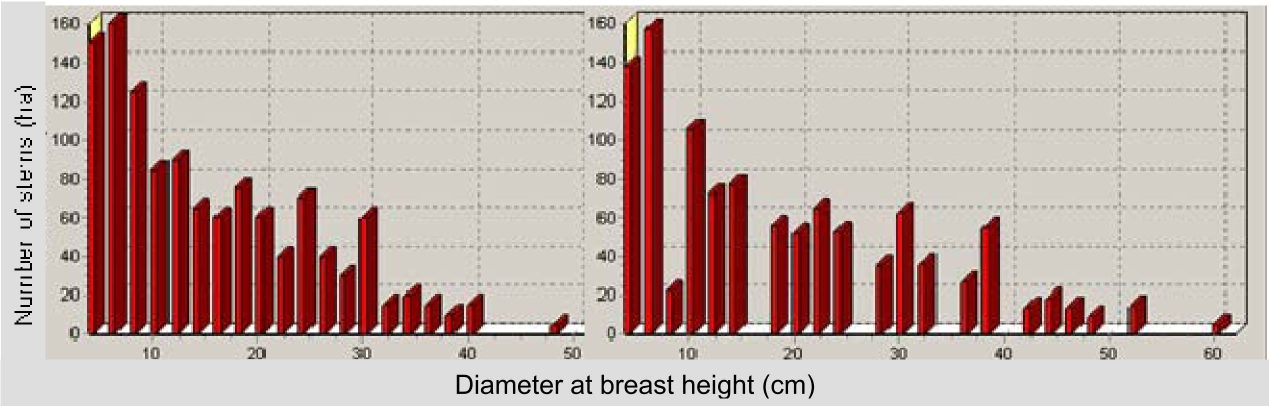

Figure 1. Diameter distribution in a stand registered in the field (left) and projected 20 year (right) with undisturbed growth and no active treatments.

Discussion

The simulator is still under development and the current implementation is a modeller's workbench as a test device for evaluation of models. It greatly facilitates study of the interaction between different model components when applied as a part of a large simulation system. Thus, it helps us to evaluate and improve the reliability and behaviour of models. It also reveals possible gaps in knowledge, and needs for future research. Future development and enhancement of the simulator might by integration of new biological models, implementation of forest management optimization features or strategic decision support features.

Evaluation is a very important recurring feature in the continues process of developing a simulation tool (Vanclay and Skovsgaard 1997). However, we believe that this growth simulator will improve forest management analyses of forests in Norway, and hence be a valuable tool for development of practical management prescriptions for both even-aged and uneven-aged forests.

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Current Topics in Forest Modelling

Photo: Karine Bogsti.

Forest stand. Nordmarka, Oslo.

Non-parametric Prediction of Stand Characteristics using Harvester Collected Stem Database

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Introduction

Nordic wood-procurement with the cut-to-length method has been based on distributing the procurement amounts among districts, ensuring that the wood supply fulfills the minimum quality requirements and minimizing costs, or at least keeping the costs at a reasonable level (Harstela 1993). However, increased competition and awareness of customer needs has forced wood-procurement enterprises and research organizations to develop customer-oriented wood-procurement (Asikainen 1995, Imponen & Lampén 1995, Metsäteho 1997, Kärhä 1998, Palander 1998, Sikanen 1999).

According to the philosophy of customer-oriented wood-procurement, the users of wood raw material should be served with the right kind of timber at the right time, which involves real-time steering of procurement according to the market situation (Fig. 1). The principles of logistics and management philosophies, such as Just-In-Time philosophy and Lean Management, have been applied to design customer-oriented management from markets to forest (Harstela 1999).

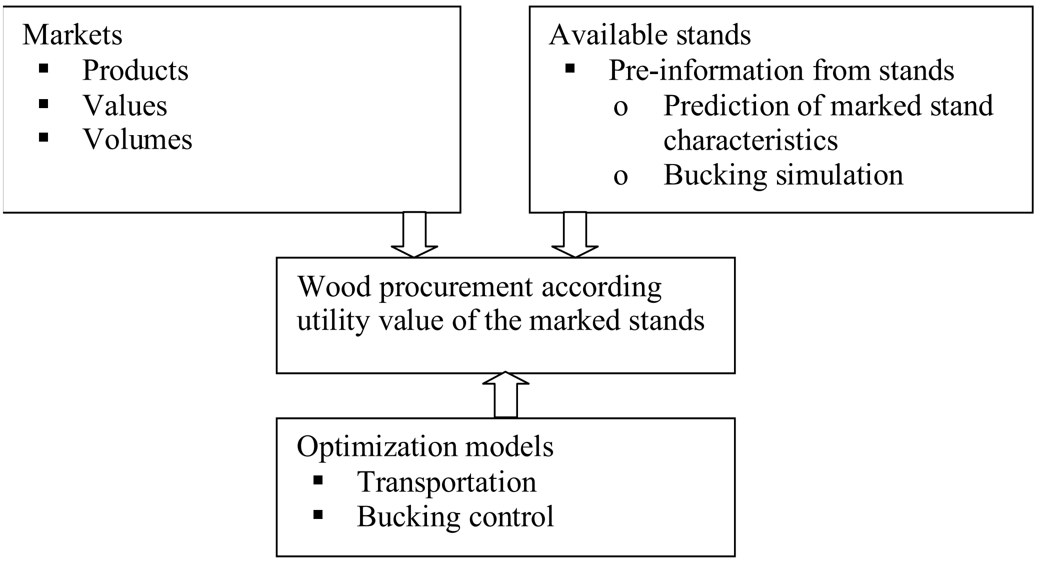

Fig. 1. Timber flow management according the philosophy of customer oriented wood procurement

For wood-procurement operators, allocation of timber from available timber stock to the different mills includes stand selection, scheduling of harvesting, cutting stems to specific dimensions and hauling timber to the different mills. The prerequisite for management and optimization of wood-procurement is availability of adequate information on marked stands. However, in Nordic wood-procurement, most of the wood raw material is purchased from small, non-industrial private forest estates, and this limits the data available for planning of wood-procurement (Harstela 1999).

Proper prediction of the quality would be helpful in analyzing the potential of raw material for different end uses. At the beginning of the 1990’s, the Nordic forest industry was interested in developing some method of pre-harvest measurement that could provide more accurate planning information about marked stands than traditional forest systems of planning do (e.g. Lemmetty 1991, Lemmetty & Mäkelä 1992, Uusitalo 1995, Hansson 1999). However, these methods are seen to be too laborious and time consuming to be used widely in practical operations. In Finland, the charactreristics of the qrowing stock can be described reasonable well in the new Solmu forestry plans of the private forests. The problems are, however, that the coverage of the plans is not yet, and probably will never be, as good as would be desired, the plans are not kept up-to-date continuously and, in practice, the areas of the logging sites very often differ from the forest stands of the plans (Räsänen 2000).

In order to develop a method capable of producing accurate enough estimates without expensive pre-measurements, Tommola et al. (1999) used data, that were measured by log-measurement instruments installed at sawmills and a non-parametric k-nearest-neighbor (k-nn) regression to estimate the characteristics of a marked stand. The results were encouraging, although the method was incapable of producing estimates for new log length-diameter constraints and demands.

An interesting option for producing data for non-parametric methods is to use harvesters that are capable of measuring stems while bucking. The measurements made by harvesters are accurate enough to be used as information for payment of stumpage sales. In the studies of Ahonen & Marjomaa (1994) and Möller (1999), it was noted that all the harvester measurements were accurate to ± 4 % of the volume measurements made by the measurement society.

Although non-parametric regression methods are among the most successful for many applications, there are some situations where their performance is unsatisfactory. The most discussed problem (e.g. Friedman 1994, Hastie & Tibshirani 1996, Schaal et al. 1998, Vijayakumar & Schaal 1998) in nearest neighbor methods is curse-of-dimensionality, which means rapid increase in the complexity of solution as dimensions, i.e. number of independent variables, increase (e.g. Friedman 1994). However, the problem of the curse-of-dimensionality can be reduced by a priori information, careful selection of the independent variables and weighting of the inputs.

The other main problem with non-parametric nearest neighbor methods concerns the size and shape of the neighborhood used, i.e. the number of the most similar observations and their weights used in calculation of weighted averages, and is called the bias/variance dilemma. The variance reflects the sensitivity of the methods to changes (sampling variations) in the data, while the bias reflects how closely, on average, the estimate is able to approximate the target (Friedman 1997). While it is desirable to have both low bias and low variance, there is, however, a tension between these goals. When the number of the nearest neighbors increases, the variance decreases; but the bias increases. Hence, there is a natural bias – variance trade-off associated with the size of the neighborhood.

The main hypothesis of this study was that, based on the harvester-collected databases of wood-procurement enterprises, the stand- and tree-stock variables can be predicted with adequate accuracy for operational purposes by using non-parametric regression methods.

Study material

This study used harvester collected stem data. It was measured and stored by Finnish forest enterprises in order to be used as the stem database prototype (Table 1). Due to different measurements and data collection in enterprises the data also includes information which was not usable as actual study material. The uniform study data consist of 209 stands located in central Finland. 151 stands were dominated by Norway spruce and 58 by Scots pine. Due to the small amount of Scots pine and birch data only the Norway spruce data was used in the study.

Table 1. Mean stand characteristics in study data.

	Min	Mean	Max
Stand area	0.3	2.3	20
Stand age	58	93	160
Basal area	0.1	14.2	47.4
Basal area mean diameter	12.9	25.8	35.0
Height of basal area median tree	11.38	21.1	28.2

Stand variables of this material were calculated as means and sums of standwise measurements. Other variables such as forest site, location and stand development class were registered when these stands were originally pre-measured.

Methods

MSN Distance function

Moeur and Stage (1995) developed a nearest-neighbor method called Most Similar Neighbor (MSN) Inference, which is a special case of k-nn methods and uses only one neighbor. In their MSN method, the similarity function used is generalized Mahalanobis (1936) distance, for witch the weighting matrix is produced by canonical correlations analysis. By using canonical correlations, it is possible to find linear transformations U_k and V_k for the set of independent variables (Y) and dependent variables (X) which maximizes the correlation between them:

$$U_k = \alpha_k Y \text{, and } V_k = \gamma_k X \text{,} \tag{1}$$

where α_k is canonical coefficients of the independent variables and γ_k is canonical coefficients of the dependent variables.

The MSN distance metric derived from canonical correlation analysis is:

$$D_{uj}^2 = \underset{1\times p}{(X_u - X_j)} \; \underset{p\times p}{\Gamma\Lambda^2\Gamma'} \; \underset{p\times 1}{(X_u - X_j)'} \tag{2}$$

where X_u is the vector of the known search variables from the target observation, X_j is the vector of the search variables from the reference observation, Γ is the matrix of canonical coefficients of the predictor variables and Λ is the diagonal matrix of squared canonical correlations.

The main advantage of the MSN distance is the fast computational method to produce weights for distance metric with a multivariate approach. This enables updated weighting for independent variables with continuously updating databases. In addition, it provides transformability of the application without extensive knowledge about the correlation structure of the data.

Neighborhood selection

K-nn method

Despite the method chosen for distance function, the question of bandwidths remains, i.e. the span in the kernel method and the number of neighbors used in the k-nn method. The size of the neighborhood used is usually determined by minimizing or maximizing some chosen criterion by cross-validation. In the study, the relative root mean squared error (RMSE %) was used.

$$\mathrm{RMSE\%} = 100 * \frac{\sqrt{\dfrac{\sum_{j=1}^{n}(y_{ij} - \hat{y}_{ij})^2}{n-1}}}{\bar{\hat{y}}_i} \tag{3}$$

where n is the number of observations, y_{ij} is the real value of variable i in stand j, $\hat{y}_{ij}$ is the estimated value of variable i in stand j and $\bar{\hat{y}}_i$ is the mean of the estimates of variable i.

Locally Adaptable Neighborhood method

In addition to selection of global bandwidth, bandwidth can also be set locally (Atkeson et al. 1997), typically by an optimization process that minimizes the cross validation error or a related criterion. Using the same bandwidth at the boundary as at the interior point clearly results high variability (Cleveland & Loader 1996).

With the optimization process it is possible to select the number of neighbors needed to symmetrize the neighborhood. Moreover, it is possible to omit unfavorable neighbors to produce an even more symmetrical combination of neighbors. Local adaptation of neighborhood selection was tested in study by using the Locally Adaptable Neighborhood (LAN) method developed.

In the LAN-method, every possible combination of neighborhood is examined in turn, and the averages of the predictor variables of the neighborhood combinations are calculated. Every vector of the average predictor variables of all possible neighborhood combinations is compared to a vector of the predictor variables of the target stand using MSN metrics; and the combination of neighbors that most closely resembles the target stand, i.e. minimizing the MSN distance between the target stand and average for the neighborhood combination, is chosen for use in calculation of estimates.

Forming stand characteristics

The stand characteristics of a target stand were formed according the estimated diameter distribution by selecting actual stems from the stem database using selected neighbour stands. In the selection the probability to pick actual stem from database was weighted according similarity of the chosen neighbour stands and the target stand. The estimated stem population was bucked with the bucking simulator to obtain an estimation of the log length-diameter distribution of the target stand. The log length-diameter distribution was also estimated from the corresponding characteristics of the reference stand by using weighted averages of each log length-diameter class. The estimated diameter distributions were scaled to the measured basal area of each target stand, which were assumed to be known.

In the bucking simulator the stem was divided into 10-cm sections. For each section the thin-end diameter was obtained from the taper curve. Optimal bucking was performed by using dynamic programming (Bellman 1954) and bucking to demand.

Comparison of results

The method used to estimate the accuracy of estimates was cross-validation. The search variables (Table 2) were chosen from among commonly measured stand characteristics. According Malinen et al. (2001) the mean tree variables are the most important search variables, while the significance of the other variables is small. The design attributes used were obtained diameters in percentages of 0% (the smallest diameter), 20%, 40%, 60%, 80% and 100% (the largest diameter) of accumulated basal area, a and b of Näslund's height parameters (Näslund 1937) and volume of tree species.

Table 2. Variables used in selection of the nearest neighbours.

Variables describing site:	Variables describing growing stock:
Location	Number of tree storeys
Temperature sum	Relative proportion of spruce
Stand area	Basal area per hectare
Stand age	Basal area mean diameter
Forest site type	Height of basal area median tree
Logging method	Volume of basal area median tree
Dominant species	

The weights for the reference stands were calculated inversely according to similarity distance:

$$W_{ij} = \frac{1}{1 + d_{ij}} \tag{4}$$

where d_{ij} is the distance between target stand and reference stand.

The estimations of length-diameter class distribution achieved through bucking simulation were compared to the length-diameter class distribution achieved through bucking simulation of actual stand values. These two distributions were compared using a distribution level (Dl):

$$Dl = 100 * (1 - \frac{\sum_{i=1}^{n} \left| D_{rj} - D_{ej} \right|}{2}) \tag{6}$$

where D_{rj} is the length-diameter class distribution of actual output in stand j and D_{ej} is the length-diameter class distribution of estimated output in stand j.

Distribution level is a simple and illustrative variable, which has been used in comparisons between demand and actual output distributions (Lukkarinen & Vuorenpää 1997). Distribution level indicates the similarity of two distributions. Identical distributions get a value of 100 (%) and the smaller the value is the more different the distributions are. It is also suitable for comparisons between predicted and actual output distributions. In addition, the accuracy of the methods was measured by using relative root mean square error (RMSE%).

Results

The k-nn method yields more information when the number of reference stands is increased. However, if the number of reference stands is too large, the averaging effect of the method is also increased. In several studies where the k-nn method has been used in forestry the suitable number of reference stands has been set between 3 and 10. In this study the size of the neighbourhood in the k-nn MSN method was set to 5 neighbours to give the best performance within the RMSE criteria (Malinen et al. 2001). A smaller neighbourhood would reduce the bias, but the RMSE would indicate weaker local validity of estimates.

The accuracy of the volume and sawtimber ratio was clearly better when using the LAN MSN method than with the k-nn MSN method (Table 3). However, the LAN MSN method did not yield a better accuracy of the sawtimber sized stems ratio and mean height. While relative errors of volume are displayed as a function of volume, it can be seen that the LAN MSN method outperforms the k-nn methods on the edges of the study data (Fig. 2).

Table 3. Relative RMSE (%) of the k-nearest neighbour MSN method and locally adaptable MSN method.

	Volume	Sawtimber ratio	Sawtimber sized stem ratio	Mean height
K-nn MSN	5,41	7,10	24,09	2,27
LAN MSN	4,03	5,51	24,36	2,28

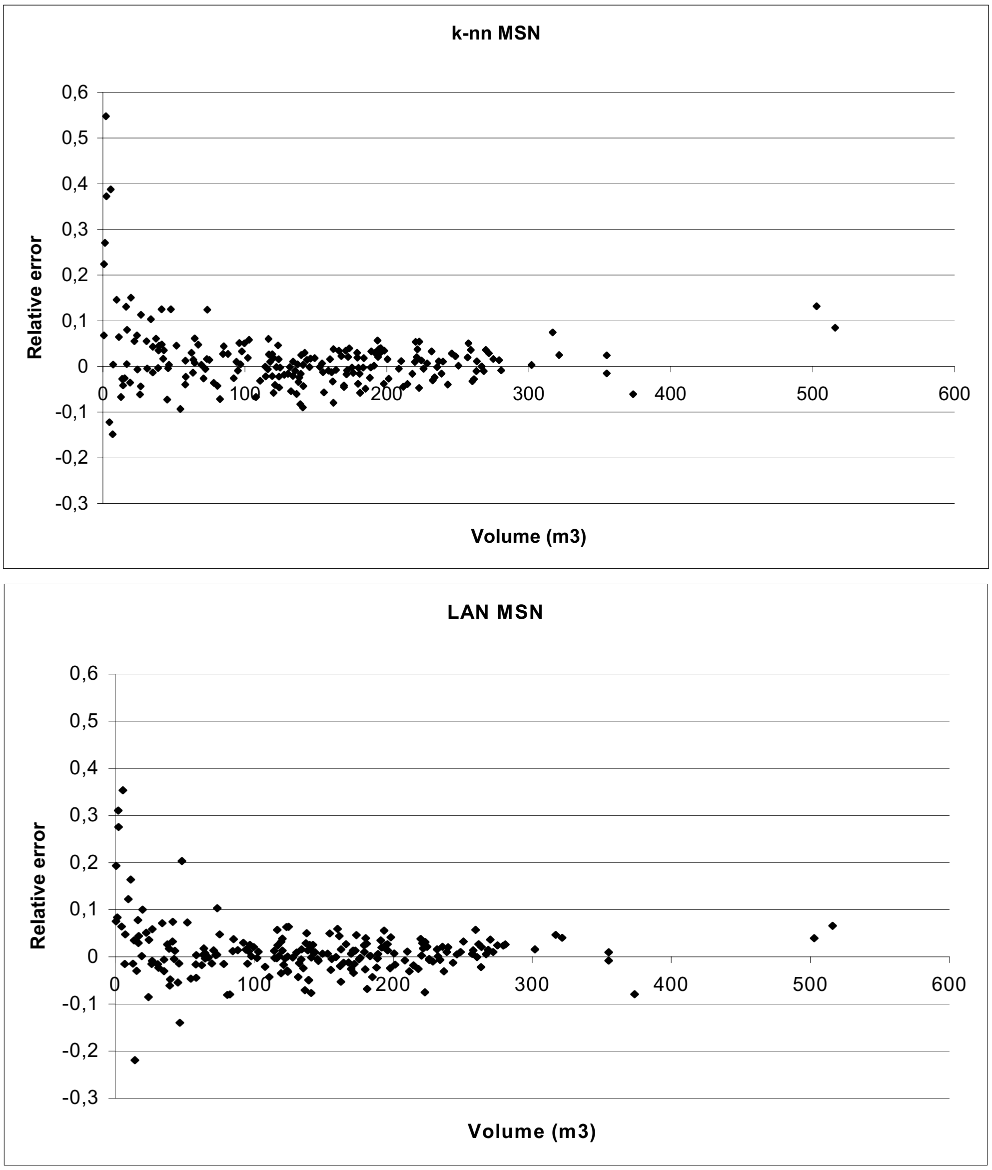

Fig 2. Relative error of volume for the k-nn MSN method and LAN MSN method.

Although distribution level is a simple and illustrative parameter when comparing two different log length-diameter distributions, it does not work well if the number of logs is too small compared to the number of different classes (Fig. 3). However, it can be clearly seen than distribution level emphasise more average goodness of estimates than RMSE. At the distribution level errors are weighted equally, independent of the error level, while RMSE is more sensitive to some large errors.

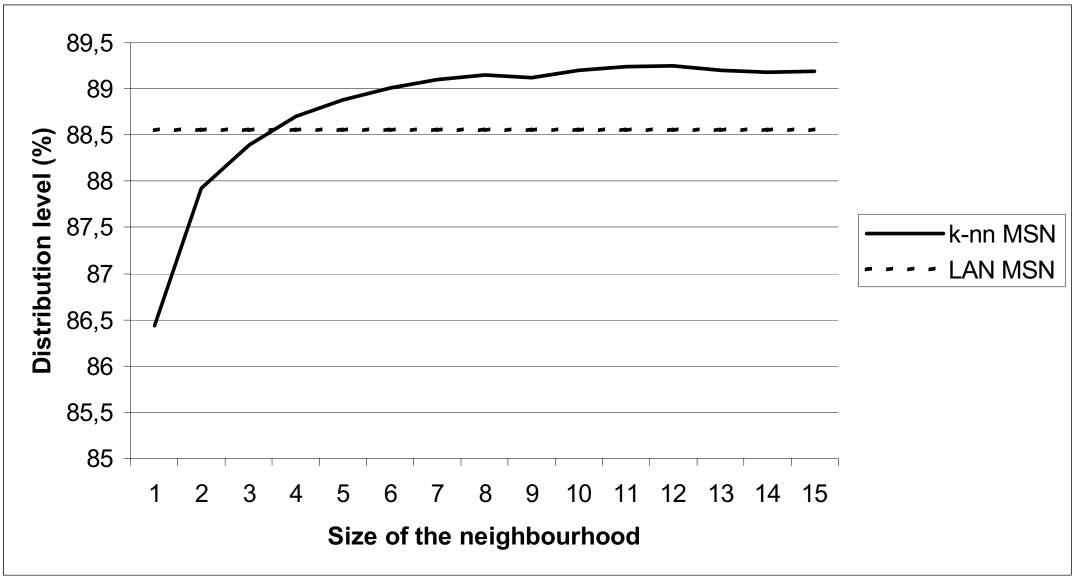

Fig 3. Distribution levels from the k-nn MSN method and LAN MSN method.

Discussion

In the study, for planning wood-procurement the non-parametric MSN method was tested and further developed for predicting stand and stem characteristics. According to the results, the method was flexible and reasonably accurate for predicting the external characteristics of a marked stand.

While the idea behind non-parametric estimation is to associate previously collected measured information with the target of estimation, the performance of the non-parametric methods is greatly dependent on the data used. If these data do not include suitable neighboring observations, the predictions will be biased. Modern harvesters are able to collect huge amounts of data without much additional expense, and therefore the use of non-parametric methods with the harvester-collected data is an inexpensive technique for producing pre-information from the available stands.

The most important advantage of the MSN method is its ability to produce weighting for neighbor selection analytically. With this property, the application based on the MSN method is flexible for different prediction situations and databases. However, in the MSN distance, the weighting matrix weights the independent variables according to their power to predict dependent variables (Moeur & Stage 1995). The nearest neighbors are defined according to correlations between independent and dependent variables, which does not necessarily guarantee optimal neighborhood according to the objectives of the user. If the user can define an objective that can be optimized the iteration process will produce better weights for independent variables.

The local adaptability of the non-parametric methods has been studied in many non-forestry applications. The results of this study showed the potential of LAN, as a method for overcoming problems concerning the definition of k and for improving the performance of the MSN method.

Acknowledgements

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The use of Quantile Trees in the Prediction of Diameter Distribution

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Abstract

A usual approach for prediction of the diameter distribution of a stand is to utilize relationships between some stand variables and parameters of the diameter distribution, either by parameter recovery method (PRM) or by parameter prediction method (PPM). In PPM, the diameter distribution is predicted using the estimated (fixed) coefficients and measured stand variables. This means that (assuming that the model is right and parameters are correct) one predicts the conditional expectations of the parameters given the values of stand variables. The residual errors of the model are the deviations of the true parameter values from their conditional expectations, i.e. stand effects. Thus, the residual variance-covariance-matrix is the between-stand variance-covariance matrix of the stand effects. This study utilizes also this information, which traditionally has not been utilized.

This study utilizes a recently developed method (Mehtätalo Forthcoming, Mehtätalo 2004, Mehtätalo and Kangas 2005), which utilizes PPM with percentile-based diameter distribution and, in addition, predicts the stand effects of the parameters using information from a diameter sample. The parameters of the percentile-based distribution are the percentiles corresponding to predefined fixed values of the cumulative distribution function. The sample measurements utilized are order statistics of a diameter sample, which are interpreted as observed percentiles of the diameter distribution and called quantile trees. The standard linear prediction theory can be utilized in prediction of the stand effects of the distribution parameters (i.e. predicted percentiles) using the measured quantile trees (i.e. observed percentiles).

In this presentation, I first explain the general idea of the new method. Secondly, I show examples of predictions with varying number of quantile trees. Finally, I show how correct measurements of quantile trees affect the Reynolds' error index and RMSE of volume and stem number.

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