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Nordic Trends in Forest Inventory, Management Planning and Modelling

Proceedings of SNS Meeting in Solvalla, Finland April 17–19, 2001

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Nordic Trends in Forest Inventory, Management Planning and Modelling

Proceedings of SNS Meeting in Solvalla, Finland April 17–19, 2001

Juha Heikkinen, Kari T. Korhonen, Markku Siitonen, Mikael Strandström and Erkki Tomppo (editors)

Helsinki 2002

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This proceedings includes papers and abstracts presented in the 2001 meeting of "Nordiska Samarbetsgruppen för Skogsinventeringsfrågor" (Nordic work group of forest inventory specialists), sponsored by SNS (SamNordisk Skogforskning – Nordic Co-operative Research Group on Forest Inventory Questions). Recent achievements of the research teams represented in the meeting are reported in team and country reports. These reports include lists of recent publications (up to April 2001 at least) produced by the teams. The other four parts of the proceedings contain both original research reports and more general presentations of, e.g., modelling and planning systems organised according to the main themes of the meeting: multisource inventory, other inventory topics, forest management planning and forest modelling.

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E-mail to editors: juha.heikkinen@metla.fi; kari.t.korhonen@metla.fi;
markku.siitonen@metla.fi; mikael.strandstrom@metla.fi;
erkki.tomppo@metla.fi

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Preface

The origin of the Nordic Co-operative Research Group on Forest Inventory Questions dates back to the beginning of 1970's when the first attempt was made to get funding for a common research project focusing on forest inventory questions. The first fund was granted, however, not until the end of 1970's. The first meeting ('Nordiskt Inventerarmöte') was held in August 27–30, 1979 in Torpshammar, near Sundsvall, Sweden. The inventory situations in different countries and activities of the responsible institutes and universities were the topics of the meeting, as well as demonstration of practical inventory work. The meetings were biennial until 1991. The tenth meeting was in held in Solvalla, Espoo, Finland in April 17–19, 2001.

A tight co-operation in forest inventories has even longer traditions than the Co-operative Research Group in Nordic countries. The first national forest inventories were developed simultaneously with a constructive interaction more than 80 years ago. Same co-operation was prevailing in the earlier county level and municipality level inventories preceding the national inventories.

The aim of the Nordic Inventory co-operation and meetings have been to bring together persons and groups working in practical forest inventories and in forest inventory research for changing ideas and to discuss ongoing and future research and to create atmosphere for future co-operation.

Most of the presentations given in the Solvalla meeting are collected to this volume. English language has been selected in order that the articles could reach the audience outside the Nordic region. The content of the volume has been organised into topical chapters: country and team report, remote sensing aided multi-source inventory methods, special inventory topics focusing in different sampling and estimation questions, forest management planning, as well as modelling of volume, growth and natural losses. These topics have been the traditional subjects of the forest inventory meetings. However, the method development in inventory has greatly affected the presentations and the contents of the papers.

The type of the presentations ranged from case studies to wide reviews, some specifically prepared for the meeting, others intended for publication in peer-reviewed journals. As a result, the articles in this collection are quite heterogeneous in length and style, and attempts to harmonise them were considered impossible and unnecessary. However, this collection undoubtedly serves as a largely comprehensive documentation of the state-of-art in Nordic forest inventories and management planning, with at least references to practically all relevant recent activities of the participating research groups.

This inventory meeting, tenth in its series, serves the overall goal to strengthen and harmonise the Nordic forest inventories and forest inventory research and maintain the high level standard of Nordic inventories. These are again topical issues when discussing how the European level and global level forest resource information should be collected for different types of decision making. The success of the meeting was a result of many individual persons, not least the participants of the meeting. On the behalf of the local organisers, I have the pleasure to thank all the persons and groups contributing to the meeting, as well as the Nordic Forest Research Co-operation Committee (SNS) and the Finnish Ministry of Agriculture and Forestry for financial and institutional support.

Helsinki December 18, 2002

Erkki Tomppo

Team and Country Reports

Team report from Finnish Forest Research Institute, National Forest Inventory

Erkki Tomppo, Kari T. Korhonen and Jari Varjo

Finnish Forest Research Institute
Unioninkatu 40 A, 00170 Helsinki, Finland
e-mail erkki.tomppo@metla.fi, kari.t.korhonen@metla.fi and jari.varjo@metla.fi

1 General

This paper describes the main renewals and news from the Finnish National Forest Inventory (NFI) since 1996. NFI was organised into a Research Programme at Finnish Forest Research Institute (Metla) in the beginning of 1998. NFI is thus one of the main research areas at Metla. This reflects the importance of the inventory in the changing forestry and forest industry environment. The forest and nature laws have been renewed in Finland in the end of 1990s. These implicate new tasks for the inventory, e.g. measuring of characteristics describing forest biodiversity.

The NFI programme consists of the coordination (Erkki Tomppo, vice coordinator Helena Henttonen) and three main research projects, operative inventory (Kari T. Korhonen 1998–2001, Tarja Tuomainen 2002–), method development (E. Tomppo) and customer service (Jari Varjo 1998–5.2001, Matti Katila and Antti Ihalainen 6.2001–6.2002, Anssi Pekkarinen 7.2002–). In addition, a number of temporary projects belong to the NFI. The operative NFI is financed through Metla's budget (comes from the Ministry of Agriculture and Forestry). Temporary projects, such as research and marketing, are often financed by sources outside of Metla, e.g. European Comission, Academy of Finland and Technology Development Centre of Finland (Tekes).

The staff of the Finnish NFI is: 1 professor[1], 20 other researchers[1], 5 permanent forest engineers (crew leaders), 2 other forest engineers, (data handling) and 3 other persons (secretaries and research assisting persons). During the field season, in addition to permanent crew leaders, 5–7 temporary crew leaders and 20–24 measurement assistant have been employed. The number of field crews have thus been 10–12 during the past years.

2 Measurements and results of the National Forest Inventory

2.1 Current status of the 9th NFI

The 9th NFI round began in 1996. By 2000, the inventory had covered the South Finland, 51 % of the land area of the country. The field work has proceeded district wise, in the same manner as in the previous inventories.

During the field season 2001, field work began in North Finland. This caused some changes in the measuring procedures because permanent plots were established in the 8th NFI in North Finland. These plots are remeasured now for the first time.

[1] Erkki Tomppo, Arto Ahola, Markus Haakana, Reija Haapanen, Juha Heikkinen, Istvan Heiler, Helena Henttonen, Anneli Jalkanen, Matti Katila, Kari T. Korhonen, Helena Mäkelä, Raisa Mäkipää, Kai Mäkisara, Anssi Pekkarinen, Juho Pitkänen, Sirpa Rajaniemi, Mikael Strandström, Tiina Tonteri, Tarja Tuomainen, Sakari Tuominen and Jari Varjo

2.2 Latest changes in the field work

New field equipment were tested during the field seasons 1999 and 2000 and taken in full use in the field season 2001. Husky FSIII field computers, Vertex Forestor height and distance measuring instrument and GPS equipment were introduced.

The use of the Husky field computer has made it possible to increase the number of data checking procedures in the field. Field teams have also laptop computers with them. Laptops are used as temporary data stores before transferring the data through cellular phones to main frame computer in Helsinki.

Garmin GPS equipment were used in the field work already in 1996. Experiences were so poor (see Rouvinen et al. 1999) that traditional tape and map measurements were applied in 1997–2000. The new GPS equipment has proved to be much more applicable.

A half-automatic ring analysis tool, WinDendro software with a scanner, has been used in measuring diameter increment cores since 1999. A traditional microscope (with video camera) for tree ring measurements and WinDendro were compared in a study before taking the WinDenrdo in use (Tuomainen 2000).

Vertex Forestor height and distance measuring instrument has been tested in field during the field season 2000 and replaced the traditional Suunto hypsometer during the field season 2001.

2.3 Data processing

During the past few years, SAS statistical software has been applied in tabulation of inventory results. SAS macros have been programmed also for estimating sampling errors.

Main frame computers and workstations with VAX/VMS operating system have been replaced with workstations and servers with Compaq Unix operating system. NFI data processing procedures have been transferred to the Unix environment.

2.4 Publication of results

The inventory results of the 9th NFI are published for each Forest Centre a refereed research article in the Folia Forestalia (Metsätieteen Aikakauskirja, in Finnish) series (see references in Section 5A). These articles have a fixed format including

- the latest inventory results with 49 tables
- development of the forest resources since the 5th NFI (in the mid 1960's) presented with tables and graphs
- interpretation of the results by researches.

The municipality level results were published for the entire country first time in the inventory's history (Tomppo et al. 1998). These are based on the satellite image aided multi-source inventory.

The vegetation maps and species description, together with environmental articles, e.g. forest resource article, were compiled into a Vegetation Atlas book. It describes the abundance and distribution changes in the 100 most common forest and mire species since the beginning of 1950s (Reinikainen et al. 2000).

The MELA research team of Metla estimates the cutting possibilities for each Forest Center. These results are published by the MELA team as a separate article in the same volume of Folia Forestalia as the actual NFI results. For each Forest Centre the articles are published as soon as possible after the field work and data processing, lately this has taken about 1 year. The published articles are listed in the list of literature later in this report.

Other main sources of NFI results are the Finnish Statistical Yearbook of Forestry series and Metla's Metinfo web sites (see http://www.metla.fi/metinfo/index-en.htm).

A separate network of 3009 permanent sample plots was established in the beginning of the 8th NFI (in 1985–86). These plots have been remeasured twice, in 1990–91 and 1995. These data have been used for estimating the annual natural losses. The preliminary results have shown that the not harvested annual natural losses are about 2.5 mill. m^3, i.e., about double to the earlier estimate.

2.5 Future perspectives

In the 8th NFI, permanent sample plots were established in the Northern Finland. A part of these plots were remeasured for the first time during the field season 2001. The data from permanent plots will be used in estimating changes and removals. Also, the accuracy of the estimates for current state of forests can be improved with permanent plot data.

3 Method development and research in National Forest Inventory

Research has been carried out with the financing of Metla, European Comission, Academy of Finland and Technology Development Centre of Finland.

3.1 Research based on field data only

The research in analysing different *sampling designs* has been continued. Output maps of satellite image based multi-source inventory and simulation have been utilised. The method has been applied with 8th inventory in North Finland and with 9th inventory. The research is continuing and will be published (Henttonen).

A study was carried for analysing on *the effect of the measurement direction of the diameter* and *increment cores on the estimates of cross-sectional area* and *diameter increment of a tree stem*. Two different diameter increment and score analysing equipments were compared in this task (WinDendro and a traditional microscope). The cross-section disks of trees (at the height of 1.3 m) were used for assessing the goodness of the methods (Tuomainen 2000).

The estimating of taper curve by means of a digital camera and an a'priori taper curve model was studied in a co-operation project with Helsinki University of Technology (Henttonen, Lappi, Varjo).

Utilisation of remeasured relascope plots has been studied in the connection of evaluating update methods for volume estimates (Heikkinen and Henttonen, this volume). First remeasurements of permanent plots established as a subsample of the usual inventory plots was undertaken in summer 2001. Application of SPR in this context is currently under research.

Estimation of sample tree variables for tally trees using remeasured relascope sample plots is studied by Korhonen (this volume). Estimating of stem volume (or h and d_6) for tally trees is one of the main problems. Specific problems related to permanent relascope sample plots are going to be solved. Preliminary results obtained by applying local regression are presented.

An ecological vegetation Atlas was compiled within a Biodiversity Research Programme of Academy of Finland and published by Tammi publisher (Reinikainen, Mäkipää, Vanha-Majamaa, Hotanen, Eds., together with 10 other authors). The book is based on the data of NFIs since the third inventory (1951–53) when the first country wide vegetation information was collected. Two other country wide vegetation data of the NFI comes from the years 1985 and 1995. The multi-temporal abundance maps (kriging predictions) of the 100 most common forest and mire species, together with their ecological properties and frequency distributions by site fertility classes, are presented. The development of the stand structure, forest resources and changes in site conditions are presented. A review of the history of Finland's floristic mapping and the development of the pyhytogeography of the country are given. In the background chapters, post-glacial development of the vegetation of Finland and is presented and the regional variations of the physical environmemt of Finland reviewed. An English summary with the English titles of the figures and tables is given. The book was awarded with the *State Award for Public Information in 2001*.

In a project called '*Risk estimation and management in forest management planning*', logistic regression models were developed for predicting probabilities of forest damage on stand level based on the NFI8-data. The models are planned to be tested in the context of forest simulators. The consequences of forest damaging agents, especially in terms of wood quality should also be studied. More info: Dr. Anneli Jalkanen (Jalkanen and Mattila 2000, Jalkanen 2001).

3.2 Research in multi-source inventory

The *k-nn estimation method* used in multi-source forest inventory (MS-NFI) is under a continues development. Examples of current or ongoing studies are given.

The digital base maps are used in delineating forestry land from non-forestry land. *Two methods* have been developed for reducing the effect of map errors from the estimates: a statistical calibration method and a MS-NFI estimation by strata. The first method is based on large area estimates of map errors; confusion matrix between land use classes of the field sample plots and corresponding map information (Katila, Heikkinen and Tomppo 2000). In the second method, the k-NN estimation is done separately within each map strata applying all the field plots within each stratum (Katila and Tomppo 2001b, Katila, this volume).

The selection of parameters for the non-parametric k-NN estimation method applied in the MS-NFI has been studied in several test areas. The emphasis has been on the search for moving geographical horizontal and vertical reference areas (HRA and VRA), as well as in the stratification of the field plots and the satellite images on the basis of auxiliary data. With the current sampling intensity, a HRA with a radius of 40–50 km in the mineral land map stratum and 60–90 km the peatland stratum was found suitable for the total volume and volumes by tree species estimates. Stratification based on a digital site class map on reduces the bias of the estimates significantly within each strata (Katila and Tomppo 2001a).

A procedure is introduced to *reassign satellite image information to field plot data* of forest inventory by a multi-criteria approach. The method can be utilised in satellite image aided forest inventories, e.g. in the MS-NFI. This inventory method presumes that the field sample plots are geographically accurately located and each individual field plot can be identified with a specific picture element of the applied satellite image. Satellite image information is reassigned to the field plots within an image window around the assumed location. A weighted function of the correlation coefficients of the selected image and field variables is used as a scaling function in this multi-criteria optimisation approach. The root mean square errors of estimates, produced with a non-parametric k-nn estimation method, are applied as a criterion when judging the final goodness of the relocation. The relocation reduces the pixel-level root mean square error of total volume per ha by 36 % (Halme and Tomppo 2001, and this Volume).

The use of *SAR* instruments have been studied in a co-operation with the Helsinki University of Technology and other institutes, e.g. ITE, UK (Balzter et al. 2002).

The work on the *AISA airborne imaging spectrometer* has been continued. The preprocessing radiometric and geometric preprocessing software has been improved. Data has been collected during summers 1997, 1998, and 1999 for several research projects both for Metla and for other institutes in Finland (geological and water quality applications). *Methods for utilising the AISA data in forest applications* have been developed at Metla for NFI, (Mäkisara et al. 1997), *analysis of forest damages* (Tomppo et al. 1999) as well as *monitoring Heterobasidion annosum and Peridermium pini* in Norway spruce and Scots (Kankaanhuhta et al. 2000). The results have been better than with satellite data but no operational applications have been created so far.

A wide project for *updating multi-source based NFI estimates* by means of new satellite images and forest stand growth models is going on. The project is financed by Metla and Technology development Centre of Finland (Tekes). Big changes in forests are identified from images and growth models used in predicting other changes (Mäkisara, Tomppo, Henttonen, Heikkinen, Heiler, Pitkänen). The project was reported in 2001 and the articles were written in 2001 and 2002.

Currently, a new co-operation project with Helsinki University of Technology (HUT) and Rolf Nevanlinna Institute (RNI), University of Helsinki, department of mathematics, has been started. The project aims at *developing methods for multi-source forest inventory* (Tomppo, Heikkinen, Mäkisara from NFI, Holmström, Koistinen from RNI, Hallikainen, Praaks from HUT).

In the MARIE-F project (financed by EU, Lead by EARS Ltd -Delft) the Forest Light Interaction Model (FLIM) was used for modelling the

forest. Focus was laid on making the methodology operational and not on the search for the best model to describe forest. The model was tested in several case studies with test sites all over Europe (Varjo, Standstrom).

Output maps of the multi-source forest inventory, together with species data, are used in *forest fragmentation and landscape ecological* studies. Three toed woodpecker (*Picoides tridactylus*), pygmy owl (*Glaucidium passerinum)* and capercaillier (*Tetrao urogallus)* are examples of species used in the anlyses (Tomppo, Maria-Luisa Paracchini in a co-operation with Timo Pakkala, Ilkka Hanski and Harto Linden).

The project "*Developing multisource forest inventory methods and use of indicator species for surveying tropical rain forests*" is the co-operation project with the Amazon research team of University of Turku. At the moment, there is two different study under the work in the project. The first study surveys the vegetation of rain forests by means of the satellite image and the field data of understorey ferns and Melastomataceae species in the Western Amazonia, Ecuador. The k-nn-estimation method is used in the satellite image analyse and methods has been developed for correcting the brightness variation created by the atmosphere and for destriping. The another study focus on studying the successional stages of the tropical rain forests in the river meanders. The successional gradient is studied through the satellite images in Peruvian Amazon (Rajaniemi, Tomppo).

NFI is participating at the moment three projects financed by European Commssion, *MNTFR*, lead by prof. Michael Köhl, UT, Dresden, *DMMD*, lead by prof. Göran Ståhl, SLU, Umeå, and *Bioasses*, lead by Dr. Allan Watt, ITE, UK.

4 Forest Resources Information Service in National Forest Inventory

The Forest Resources Information Service was established as a project in the reorganisation of the whole NFI as a research programme in 1998. Main reason was the increased demand on the NFI multi-source inventory products. It was foreseen that the flexible and reliable customer service might require more resources and attention than before.

National Forest Inventory has traditionally been developed as a scientific exercise. However, the end user needs have been always been taken into the consideration as far as resources have allowed. Up to the beginning of 1990's most of the customer tailored products and services were produced under the normal budget line. However, the legislation was changed in early 1990's and after that commercial bases is applied in customer products. Thus at the moment, the forestry centre level statistics are kept free by publishing them as a scientific exercise. The estimates for areas smaller than forestry centre, or customer tailored products, are commercial on net budgeting basis.

The customer demanded applications on 1970's and 1980's were mostly special inventories for smaller areas that were possible with operative NFI. This included denser sampling in the field compared with NFI and was thus expensive. Typically the products were range statistics or ownership statistics for large institutional forest owners or special results for research purposes. Another important types of products were different models and system development, for example, for timber measurements systems and forest data systems of end users. The development of multi-source NFI methodology expanded the interest towards large-scale forest inventory results notably. The municipality level forest statistics were especially welcomed by the Forestry centres. These statistics became available also by ownership classes when wall-to-wall ownership information became available. The ownership information is traditionally applied in NFI at sample plot level but nowadays also as wall-to-wall maps for delineating the areas owned by forest industry and public forest owners. This information is used to differentiate the areas to major ownership category classes, and to calculate separate statistics for them via multi-source inventory. This information is widely used for example by forestry centres and forest industry for different strategic and operative planning purposes.

Soon after the introduction of multi-source NFI results, forest industries become interested in using the thematic map information for timber

procurement planning. First products were plotted total volume or tree species level volume maps on paper, together with borders of forest holdings and identification information. This material was applied also for calculating forest holding level statistics. The use of this material required the access to the contact information of the forest owners. At the same time, the forest industry was rapidly developing GIS capacities for operational use and the paper map and forest holding level statistics phase was relatively short. The demand moved to digital products. Options for visual applications or digital analyses have been built in the data systems of the customers. At the moment, the thematic forest maps produced in NFI form important part of timber procurement system in forest industry.

It seems to be a constant demand for improving the accuracy of the multi-source inventory products. The results should be accurate for as small areas as possible (forest holding, even forest stand) and they should be updated more often than the NFI proceeds normally. Different change detection methods have been developed and unsupervised approaches are also on commercial phase for detecting final cuttings. This kind of updating of final cuts is becoming operational at the moments. In addition, these applications have had commercial demand on different environmental monitoring purposes as well. More throughout updating system for whole multi-source information content is also under development.

The development of the accuracy and variety of the themes in NFI products seem to open possibilities for new markets. The increasing demand towards bio fuels in energy production creates demands for mapping the bio energy sources, for example. In addition, different recreational activities create demand for new kind of information about the recreational values or existence of berries or mushrooms. A good example of existing commercial product in this field are the potential cloud berry picking area maps produced via classifying peat lands based on multi-source information. In addition, many entities such as authorities and companies working with communication and power networks as well as nature monitoring authorities seems to be all the time more and more interested to have wall-to-wall thematic forest information in their GIS systems.

5 Some publications since 1997

A. Publications on Forest Resources

Korhonen, K.T. 1999. Pohjanmaan rannikon metsät: uusia tuloksia VMI:stä. In: Karlsson, K. (ed.). Metsät Pohjanmaan rannikolla. Kustskog i Österbotten. Metsäntutkimuslaitoksen tiedonantoja 723: 7–14.

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— , Tomppo, E., Henttonen, H., Ihalainen, A. & Tonteri, T. 2000. Hämeen-Uudenmaan metsäkeskuksen alueen metsävarat 1965–99. [Forest Resources of Häme-Uusimaa 1965–99. In Finnish.] Metsätieteen aikakauskirja 3B/2000: 489–566.

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Salminen, S. & Salminen, O. 1998. Metsävarat Keskisessä Suomessa 1988–92 sekä koko Etelä-Suomessa 1986–92. Summary: Forest resources in Middle Finland, 1988–92, and in South Finland, 1986–92. Metsäntutkimuslaitoksen tiedonantoja 710. 137 s.

Tomppo, E. 1998. Metsävarat vuosina 1989–1994 ja niiden muutokset vuodesta 1951 lähtien. [Forest resources 1989–1994 and their changes since 1951. In Finnish.] In: Mälkönen, E. (ed.). Ympäristömuutos ja metsien kunto. Metsien terveydentilan tutkimusohjelman loppuraportti. Metsäntutkimuslaitoksen tiedonantoja 691: 9–24.

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Team Report from Finnish Forest Research Institute, MELA Team

Tuula Nuutinen[1], Aimo Anola-Pukkila[1], Arto Haara[1], Leena Kärkkäinen[1], Reetta Lempinen[1], Eero Muinonen[1], Visa Redsven[1], Hannu Hirvelä[2], Kari Härkönen[2], Olli Salminen[2], Markku Siitonen[2], Maarit Teuri[2] and Juha Lappi[3]

[1]Finnish Forest Research Institute, Joensuu Research Centre
P.O. Box 68, FIN-80101 Joensuu, Finland
[2]Finnish Forest Research Institute, Vantaa Research Centre, Helsinki Research Unit
Unioninkatu 40 A, FIN-00170 Helsinki, Finland
[3] Finnish Forest Research Institute, Suonenjoki Research Station
Juntintie 40, FIN-77600 Suonenjoki, Finland
e-mail: firstname.lastname@metla.fi

1 Background

MELA is a forestry model and an operational decision support system designed in the 1970s for regional and national timber production analyses in Finland (Kilkki & Siitonen 1976, Siitonen 1983). MELA was used as an analysis tool for the Forest 2000 Programme in 1985 (The Forest 2000...1986) and its revision in 1990 (Siitonen 1990, Siitonen 1993, Komiteanmietintö 1995:5). Markku Siitonen, the main programmer of the software, made the analysis. The growth models applied are reported by Ojansuu et al. (1991).

In the 1980s forestry organisations got interested in applying MELA as a forest management planning module in their stand information systems. Several research teams got involved and interfaces between the stand information systems and those versions of MELA software the teams happened to have available, were built. The applications to update forest resource data, to predict stand development, and to solve planning problems were defined and tested (Kangas 1985, Vainio 1986, Mäkitalo 1986, Pihljerta 1987, Jääskeläinen 1987, Pesonen 1987, Muinonen 1988, Nuutinen 1989, Jämsä 1991, Kähkönen 1991, Jorri 1992, Kolström 1992, Nalli 1992, Pesonen et al. 1993, Nuutinen 1994, Anola-Pukkila 1995, Vauhkonen 1995, Oksanen-Peltola & Paananen 1995, Nalli et al. 1996, Nuutinen 1996, Soinne 1996). In strategic planning the stands were usually aggregated into calculation units.

In the 1990s, a new linear programming (LP) solver (JLP, Lappi 1992) was integrated into the MELA software. Because JLP has an outstanding capacity and speed in solving large scale multi-level LP problems it became possible to solve more complicated decision problems – without data aggregation.

Forestry organisations wanted to incorporate the new features into their applications. During the years, however, MELA versions in different organisations had been developed separately and the effort to merge new features with each different MELA version was more than the users could afford. Therefore a commercial project to develop a common MELA version for the practical forestry was initiated.

In addition, a 3-year project (1994–1996) "The production potential of the Finnish forests in 1996–2025" was launched. During the 3-year period some regional and national MELA-analyses were carried out (Nuutinen & Siitonen 1994, Mielikäinen et al. 1995, Malinen & Pesonen 1996, Kajala 1996, Nuutinen et al. 1996).

2 Results in 1996–2001

2.1 Forestry Analyses

In 1997 both a set of models for natural processes (Hynynen & Ojansuu 1996), developed in the project "Prediction of stand development" (1994–1996, project leader Jari Hynynen), and new economic models for logging operations were incorporated into the MELA software. Using the new models, the third round of national timber production analyses was carried out and reported (Nuutinen et al. 1998).

The analyses were based on the 8th national forest inventory (NFI8) data updated to year 1996 using MELA software, growth indices together with the statistics and remote sensing data on forest operations. The main results of the analyses were distributed also via the Internet.

The analyses were utilised in regional forest programmes prepared by regional forest centers in 1997–1998 as stated in the new Forest Law. The first National Forest Programme was prepared in 1998–1999. To assist the policy makers, the MELA team carried out a set of analyses for the whole country (Nuutinen & Salminen 1999). As a follow-up, the revision of regional forest programmes was required. For the revision, the Ministry of Agriculture and Forestry ordered a new set of regional MELA analyses based on the most up-to-date forest resource information.

During 1996–2000, the MELA Team carried out and reported analyses of the regional timber production possibilities based on both the 8th (Salminen & Salminen 1996, Jämsä & Hirvelä 1996) and the 9th national forest inventory data (Hirvelä et al. 1998, 1999, Hirvelä 1999, Hirvelä & Härkönen 1999, Hirvelä 2000, Nuutinen & Hirvelä 2000a, 2000b, 2000c, 2001a, 2001b). For the revision of regional forestry programmes, the NFI9 data were used for the regions, where the fieldwork had been finished. The analyses for the rest of the country were based on the NFI8 updated to year 1996. The results were published in the Internet (http://www.metla.fi/metinfo/mela), where the public had access to both tables and graphs illustrating the timber production possibilities.

Average annual cutting removal in 1994–1998 was 54 mill. m^3, approximately 80 percent of the estimate for maximum sustainable yield for the first ten year period of calculations (69 mill. m^3 per year). Regionally the level of utilisation varied from 57 to 92 percent. The proportion of spruce in the removals was larger than in the estimate of maximum sustainable yield – especially in the middle and eastern Finland.

2.2 MELA in Practice

In 1996 the MELA software and related information services and products were made commercial. An organised structure and routines for the maintenance and further development of the common MELA software were defined. The responsibilities for the products and services were allocated between the members of the MELA Team (Fig. 1). At the end of the process the MELA version 1996 (Siitonen et al. 1996) was published and made available for the Finnish clients.

Currently, MELA is used as the forest management planning module in the stand information systems (Fig. 2) of the Finnish forest industry companies, Forest and Park Service (Laamanen et al. 1997), regional forestry centers and Forestry Center Tapio, and Finnish Forest Research Institute. In addition, MELA is used for teaching at forestry schools and universities.

A new MELA version has been made commercially available each year since 1998. In the MELA version 1998, new models for natural

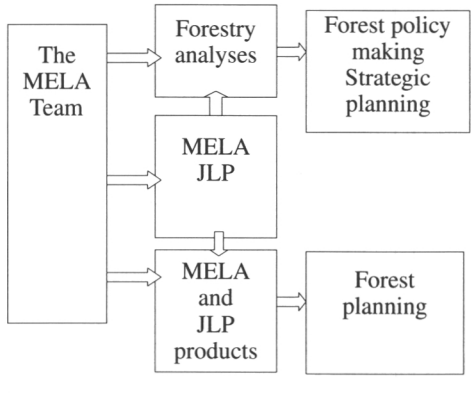


Fig. 1. The responsibilities of the MELA Team.

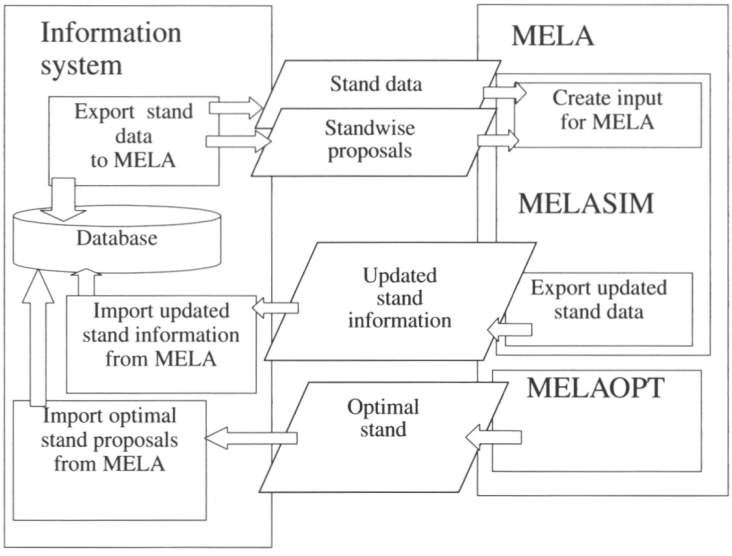


Fig. 2. The interface of MELA and stand information systems.

processes (Hynynen et al. 2002) and the first MELA extensions intended for the stand information system interface were presented (Nuutinen & Mäkkeli 1998). In the MELA version 1999 new economic models for logging and silvicultural operations were introduced (Siitonen et al. 1999, Nuutinen & Suokas 1999, Nuutinen et al. 2000). Features to incorporate retained trees in the analysis were added into the MELA version 2000 – together with some modifications for the MELA extensions (Siitonen et al. 2001, Nuutinen & Suokas 2001).

In practical applications, the models seem to give high estimates for spruce compared with other studies (Hyvönen 2000). The models do not cover the whole range of variation in young stands (especially damages and resulting decrease in timber quality or increasing mortality) and therefore the models are at their best in the areas, where the proportion of mature stands is high, and when the simulation horizon is short.

The development of MELA software and its commercial versions is organised into stages. In the first stage, new models and methods are developed and tested – sometimes separate from the MELA software. If the new feature is accepted to be part of the MELA software, it goes into the second phase, where the integration of the new feature into the MELA software is designed, prototyped, and tested. If the prototype is accepted, a product is made of the feature. This third stage starts by bringing together several features that have passed the second stage. From these, a combination of new features for the next release of the MELA software is selected. The integration of selected features into the MELA software is re-designed, implemented, and tested.

The features of the next release, the MELA version 2002, were developed and tested in the project "Description of commercial roundwood and its distribution in analysing future cutting possibilities" financed by Metla and National Technology Agency Tekes. In co-operation with Matti Maltamo and Annika Kangas a set of new models and methods (Kangas & Maltamo 2000a, Kangas & Maltamo 2000b, Kangas & Maltamo 2000c, Maltamo et al. 2000, Kärki et al. 2000, Muinonen et al. 2001) was produced and tested.

2.3 JLP

Since 1991, when JLP was adopted as an LP solver in the Norwegian GAYA-JLP planning system, several forestry organisations in Norway and Sweden have purchased the software.

3 On-going Research Projects

The MELA Team consists of researchers and system analysts interested in participating in the maintenance and development of MELA and JLP software for forestry modelling and analysis.

The work of the MELA Team is currently organised into four research projects: "Forestry modelling and analyses", "Forest simulator", "A forest management planning method based on integrated simulation and optimisation", and "Timber production possibilities on Finnish peatlands". The first three projects, together with projects "Participatory planning in state and private owned forests" (2000–2004, project leader Irja Löfström) and "Forest inventory and estimation methods for management planning" (2002–2005 project leader Kari T. Korhonen), form a research programme "Forest management planning" (1999–2005, co-ordinator Tuula Nuutinen).

The Ministry of Agriculture and Forestry has defined a new generation planning system as the goal of the research programme. The new planning system should effectively integrate data, methods, and tools in planning and decision making processes, and assist in the utilisation of analysis results by providing support for the visualisation and interpretation of the numerical results and their sensitivity. In addition, the system should serve the scientists within different disciplines as an open platform for incorporating new aspects in the analyses and exporting research results to practical forestry.

The duration of the programme is synchronised with the NFI9 round (1996–2004). The aim of the programme is to apply new models and methods for national forest production analyses based on NFI9 data for the whole country, when the data are available.

"Forestry modelling and analyses" (1985–, project leader Tuula Nuutinen) has two responsibilities

- to maintain and further develop the MELA software and its extensions, and
- to carry out and further develop regional and national timber production analyses, especially for the purposes of regional and national forestry programmes.

Current challenges include:

- integrating models for biomass, carbon, and climate change into the MELA system and analyses (co-operation with a project "Climate Change impacts on the Dynamics of Functioning and Structure of Boreal Forests with Implications for the Sustainability of Forest Production and Carbon Sequestration", co-ordinated by prof. Seppo Kellomäki, EcoTeam, and financed by the Academy of Finland), and evaluating the MELA information system (Nuutinen & Kellomäki 2001) as a carbon accounting tool,
- models and data structures for alternative timber assortments – including energy wood – and their pricing,
- modelling errors in data and models to search for the effective combinations of data and models in the updating and planning applications (co-operation with a project "Forest Information Assessment and Updating", co-ordinated by Jari Varjo and financed by the Ministry of Agriculture and Forestry),
- theories, methods and tools for system-user interaction,
- impact analysis for regional and national forestry programmes, and
- integrating GIS and remote sensing data (Lappi 2001) for impact analysis (a project " Methods for statistical integration of satellite imagery and GIS data for spatial analysis in forest planning", financed by the Ministry of Agriculture and Forestry).

The most important partner is "National Forest Inventory" (NFI, co-ordinator prof. Erkki Tomppo). Collaborative partners (Fig. 3) include research programmes "Alternatives of silvicultural practices in forest management and their effects on forest production" (co-ordinator prof. Jari Hynynen), "Forest regeneration in Southern Finland" (co-ordinator Taneli Kolström / Jaana Luoranen), and "Ecologically and economically sustainable forestry on drained peatlands" (co-ordinator prof. Seppo Kaunisto), which maintain and develop models of natural processes. The MELA information services and products are made commercial in a separate project financed by the customers.

"Forest simulator" (2000–2003, project leader Markku Siitonen) aims at building up a new forest simulator for superseding the MELASIM stand simulator in the MELA context. The primary

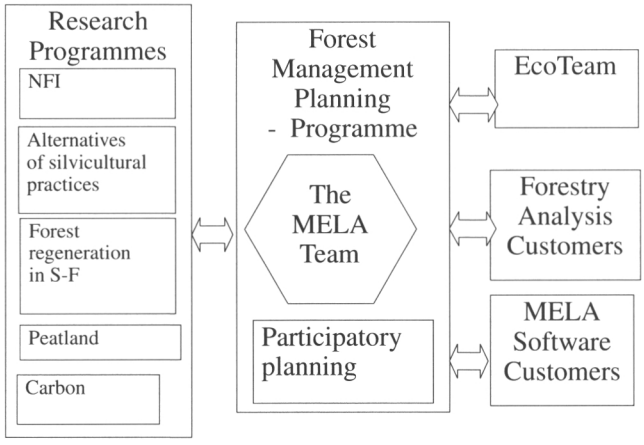


Fig. 3. The collaborative partners of the MELA Team.

task of the simulator is the automatic generation of alternative management schedules for stands over time. The new simulator should also provide an open platform for collaborative scientists to comply with the foreseeable simulator requirements of forestry analysis and forest management planning.

"A forest management planning method based on integrated simulation and optimisation" (2000–2003, project leader Juha Lappi) aims at developing a new software integrating stand simulation and forest level optimization. The main component of the simulation part is a simulator definition language by which the user can define the simulator using text files. The simulator can be defined using stand, plot and/or tree variables. The starting point for the optimization is the current JLP software. The new optimization software incorporates timber demand of factories, and transportations costs.

4 Some Publications in 1996–2001

4.1 Forestry Analyses

Hirvelä, H. 1999. Valtakunnan metsien 9. inventointiin perustuvat hakkuumahdollisuusarviot vuosille 1997–2026 Kymen metsäkeskuksen alueella. Metsätieteen aikakauskirja 1B/2000: 233–253. (In Finnish)

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Nuutinen, T. & Hirvelä, H. 2000a. Valtakunnan metsien 9. inventointiin perustuvat hakkuumahdollisuusarviot vuosille 1998–2027 Lounais-Suomen metsäkeskuksen alueella. Metsätieteen aikakauskirja 2B/2000: 413–428. (In Finnish)

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Nuutinen, T., Hirvelä, H., Hynynen, J., Härkönen, K., Hökkä, H., Korhonen, K.T. & Salminen, O. 2000. The role of peatlands in Finnish wood production – an analysis based on large-scale forest scenario modelling. Silva Fennica 34(2): 131–153.

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Team Report from Norwegian Institute of Land Inventory (NIJOS)

Stein M. Tomter

Norwegian Institute of Land Inventory
P.O. Box 115, 1431 Ås, Norway
e-mail: stein.tomter@nijos.no

1 Methods, Measurements and Equipment of the National Forest Inventory

About 10 500 permanent sample plots (on forest and other wooded land) were established between 1986 and 1993.

Re-measurement of all permanent plots was carried out in 1994–98. One fifth of the permanent sample plots is being measured each year (continuous forest inventory). The plots measured in 1998 will be measured again in 2003 etc.

In addition to the re-measurement of permanent plots, a number of temporary plots are being assessed according to a specific schedule. The aim is to be able to present reliable results for individual counties:

Østfold:	1995–99
Akershus/Oslo:	1995–99
Aust-Agder:	1995–99
Vest-Agder:	1995–99
Nord-Trøndelag:	1995–99
Hedmark:	1995–99
Buskerud:	2000–04
Oppland:	2000–04
Telemark:	2000–04
Sør-Trøndelag:	2000–04
Møre og Romsdal:	2000–04
Vestfold:	2000–04
Rogaland:	2005–09
Hordaland:	2005–09
Sogn og Fjordane:	2005–09
Nordland:	2005–09
Troms:	2005–09

For the National Monitoring of Forest Vitality, a 9 × 9 km subsample of the NFI permanent plots has previously been utilized. From this year on, the number of observation plots will be reduced to correspond with the international grid of 16 × 16 km. The reason for this is a 25% reduction of fundings for this programme.

At the national level, forest vitality data can also be provided on the basis of assessments from the ordinary NFI.

New attributes 1999

Included: Cause of stem breakage
Removed: Occurence of stumps

New attributes 2000

Included: New terrain descriptions; assessment of terrain surface obstacles harmonized with the Swedish system. Extraction distance has been divided into four new attributes: Winching distance, terrain transportation distance, distance for extraction on tractor road and on forest motor road. Some new attributes related to biodiversity, like remaining trees after harvesting ("eternity trees") and description of forest edge.

New attributes 2001

Included: International definition for minimum size and width of forest area.

Age assessment of all sample trees (necessary for reporting of forest vitality data).

New equipment of the NFI:

Fieldcomputers – PSION walk about
Vertex III digital instrument
GPS
Aluminum calipers
Magnifying glass for measuring annual ring width in the field (with a scale indicating tenths of millimetres).

2 Development of Forest Resources

Productive forest land is estimated at *7.5 million ha* according to the most recent inventory data (1995–99). In 1986–93 the corresponding figure was *7.2 million ha.* The development of growing stock is presented in Table 1.

Annual increment is estimated at *26.1 million* m^3 incl. bark.

Table 1. Growing stock on forest and other wooded land in Norway below the coniferous forest limit (million m^3 incl. bark)

	1986–93	1995–99
Spruce	318.5	343.2
Pine	216.8	253.0
Broadleaved	149.8	173.4
Total	685.1	769.6

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Country Report from Sweden

Göran Ståhl and Tomas Lämås

Swedish University of Agricultural Sciences,
Department of Forest Resource Management and Geomatics
S-901 83 Umeå, Sweden
e-mail: goran.stahl@resgeom.slu.se and tomas.lamas@resgeom.slu.se

1 Introduction

In this brief report, current Swedish research activities in the fields of forest inventory and forest management planning are summarized. The report is separated in two sections, one dealing with Forest Inventory, including the National Forest Inventory (NFI), the other with Forest Management Planning. The report is biased towards activities at the Swedish University of Agricultural Sciences. In the end, a list of recent literature references is given.

2 Forest Inventory

The Swedish University of Agricultural Sciences (SLU) is the major actor in the field of research in Forest Inventory. At the university, remote sensing is currently a very active field. Optical satellite data have been used for a long time, while recently promising results from using radar and laser data have also been obtained. Specifically, radar data from the CARABAS sensor have proved to be very useful for the estimation of stand volume. The k-NN method for combining remote sensing and field data has found many applications, e.g. as a tool for providing information for forestry and environmental planning.

One major remote sensing project in Sweden is the RESE project (Remote Sensing of the Environment). Examples of forestry applications in this project involve using time series satellite data for monitoring changes and improving state estimates, using satellite image data for assessing the forage conditions for moose, etc. The RESE project also includes the development of general statistical algorithms for assessing the quality of maps, etc.

The European Corine landcover vegetation map is currently being produced for Sweden. For forests, the method used is to combine satellite remote sensing with field plots from the NFI. In connection with the production of Corine landcover maps, more detailed information about the state of Swedish forests will be acquired as well.

Geostatistical modelling using remote sensing data has also been an area of activity. Kriging and co-kriging methods have been used for improving local estimates of variables such as timber volume.

In the area of field based surveys, quite some effort has been devoted to the development of methods for monitoring sparse populations. In particular, methods for inventorying dead wood have been developed and evaluated. An objective method, guided transect sampling, has been developed to mimic the way subjective surveys for sparse elements of importance for biodiversity are often carried out.

Development work is currently being conducted in connection with the Swedish NFI. The plan is that a revised NFI should be carried out for the first time in 2003. The basic design, a combination of permanent and temporary plots, will remain. Following the Finnish example, estimates of core

variables will be improved by combining the field plots with remote sensing. A new sub-programme related to biodiversity assessment will be linked to the NFI. In addition, a landscape monitoring programme, focussing on biodiversity, is currently being developed and will to some extent be coordinated with the NFI. On the international level, the development of the new ICP Forest and LUCAS programmes will be interesting to follow, especially regarding what roles these programmes will play in relation to the NFI.

At a more detailed level, GPS equipment is, from 2001 onwards, used not only for geo-referencing the field plots, but also for locating the field plots in the NFI. The procedure is to use the GPS for the orientation to a point in the close proximity of the plot location, from which standard procedures (compass and measuring tape) are used for the exact identification of the plot location. The reason for maintaining the old procedures for the last part in the location of plots is to avoid potential bias that might otherwise occur.

3 Forest Management Planning

Apart from SLU, the Forestry Research Institute of Sweden (SkogForsk) is performing research in forest management planning. SkogForsk, however, is mainly involved in short term planning such as operational planning and logistics concerning harvest activities and timber transportation.

At SLU, forest management planning is today to a large extent associated with two research programmes, Sustainable Forestry in Southern Sweden (SUFOR) and Heureka. SUFOR is a joint programme between SLU and a number of universities in southern Sweden. The main goal for the programme is to show how a high biodiversity, a better forest health and a sustainable production can be combined with an economic forestry. Projects concerning e.g., soil factors, risk of wind damages and root rot are included. A system for landscape level analyses has been constructed by which predictions of the forest state, the output of timber etc. can be performed.

The Heureka programme aims at the next generation of analyses and planning systems for a multi-resource and sustainable forestry. The programme is an attempt to gather research efforts in different areas into a common framework for the development of necessary models and methods. The new systems should be designed with

(i) a modular structure to allow for the development of different applications,
(ii) the landscape as the basic planning unit,
(iii) the tree as the basic unit of projection of the tree layer,
(iv) models for processes interacting with the management of the tree layer, and
(v) models for risk and uncertainty of data and of model projections.

Four systems aimed at different problem formulations and users are planned. The systems will to some extent use the same model base containing models for tree growth, timber yield etc. One system is intended for regional analyses and another for strategic and tactical planning at large forest companies. These systems will replace today's Hugin system and the Forest Management Planning Package (Indelningspaketet), respectively. The third system is intended for tactical and operational planning at large forest companies. SkogForsk is responsible for the development of this system. The last system will be designed for non-industrial private forest owners.

A number of projects have been started within Heureka programme, aiming at the construction of models needed for analyses and planning. One project concerns growth and yield models based on individual trees. Growth functions without tree age and site index as independent variables will be provided as well as new models for ingrowth, mortality, and the growth of young trees. Other projects concern, among other things, risk and uncertainty, root rot, biomass functions, carbon budgets, and the influence of climatic change on growth and yield. In the field of remote sensing, a project aiming at the automatic detection of individual trees in high resolution aerial photos, will be started.

Risk and uncertainty are inevitable elements of natural resource management. One research area within the Heureka programme is optimisation of decision under risk. This includes solution meth-

ods and definitions of problems and objectives. Within the research area we find, among others, methods to handle stochastic processes in forest management, optimisation methods for very large problems (number of decision variables and calculation units), and methods for optimisation of large problems with linked sub-problems.

Aiming at the integration of conservation with forest management planning, species dependent on dead wood are studied in a joint project between SLU (Dept of Forest Mgmt and Geomatics) and Umeå University. Probability functions for the occurrence of a number of species as well as (local) functions for dead wood decomposition have been constructed. These functions, together with a growth and yield model and a heuristic optimisation technique, have been used to study the probability of occurrence of species in relation to economic outcome on a stand management level. Using data on dispersal of species, the project will continue to study their probability of survival within landscapes. In a separate project at SLU, nation-wide functions for dead wood decomposition will be constructed.

A number or departments at the different locations of the Faculty of Forestry are involved in the Heureka programme. The only department participating in the SUFOR programme is, however, the Dept of Southern Swedish Research Centre in Alnarp. At that department, there is another project developing routines for identification of areas suitable for high yield forestry. At the Dept of Forest Mgmt and Products, there are projects concerning landscape level planning and regional adaptation of nature conservation issues, the spatial resolution of data used for management planning, and a social study concerning non-industrial forest owners' goals and objectives. At the Dept of Forest Mgmt and Geomatics, projects are, among other things, focusing on cost efficient data acquisition for management planning on small estates, spatial aspects in forest management planning, and the interaction between forestry and reindeer husbandry.

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Team Report from Agricultural University of Norway, Department of Forest Sciences

Tron Eid

Agricultural University of Norway, Department of Forest Sciences
P.O. Box 5044, NO-1432 Ås, Norway
e-mail: tron.eid@isf.nlh.no

1 Introduction

Department of Forest Sciences, Agricultural University of Norway (AUN) is engaged in education, research, and the dissemination of research results about forest ecology, silviculture and timber utilisation. AUN is the only academic institution in Norway that offers studies in these subjects at the university level. The department has 52 staff members (year 2000). Of these, 42 are either scientific or lecturing staff, including graduate students and project staff. The rest are technical or administrative personnel.

The department's annual budget is approximately 21 million Norwegian crowns (not including current expenses in buildings and common operations covered centrally by the university). Approximately two-thirds of this amount is granted directly from the central government, while the remaining is obtained from the Research Council of Norway or from other sources. About 40% of the activities conducted at the department are related to research.

Approximately 20 students are admitted annually to the 5-year program in forestry. In addition, approximately 20 students who have completed a 3-year program at regional colleges are admitted to a 2-year program of continued study. Within the students' major area of study, there are options for specialising in forest ecology, technology, or economics. At the completion of the 5-year program the degree of Cand. Agric. is awarded. It is similar to a M.Sc. degree in the educational system of the United States.

Post-graduate students admitted to the department generally complete a 4-year study for the degree of Dr. Scient. These students follow individual study plans and are advised by the scientific staff members.

The department is organised in an administrative section and 4 academic sections. The academic sections are:

- Silviculture
- Wood technology
- Forest operations
- Resource economics and planning

The academic field within the Section of Resource Economics and Planning is related to managing forest resources with the aim of obtaining the greatest possible contribution to people's welfare. This requires knowledge in two different academic fields: *biology* and *economics*. In order to understand forest biology it is also necessary to be able to document and *inventory* the conditions in the forest ecosystem. This is also an important academic field for this section. The academic fields may therefore be organised in the following way:

1) Resource inventories
- Inventory
- Sampling
- Mapping sciences, GIS, photogrammetry,
- Remote sensing

2) Economics and planning
- Business economics, finance and valuation
- Price setting, econometrics
- Forest politics, forestry policy instruments

- Valuation of environmental goods
- Large-scale forestry scenario modelling
- Long-term harvest- and investment analyses

3) Biology
- Tree growth models
- In-growth
- Natural mortality, dead wood

At present there are 14–15 persons at the section, and among these 7–8 work with subjects related to inventories, economics/planning and production/growth.

2 Research Findings

2.1 Resource Inventories

A relatively large number of different 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. Other projects have been concerned with evaluations of the existing practical inventory methods, where the cost efficiency has been focused.

2.1.1 Determination of Stand Parameters by Means of Airborne Laser Scanner

A practical two-stage procedure for determination of stand parameters of entire forest stands by means of field plots and airborne laser scanner data has been developed and tested. In the first stage, geo-referenced field sample plots are related to the corresponding laser data, and relationships (regressions) between field data and various canopy height and canopy density metrics that can be derived from laser data are estimated. In the second stage, the entire forest area in question is divided into a regular grid with cell size equal to the size of the field sample plots. Stand parameters of each grid cell are predicted by means of the estimated regressions and the laser data that correspond to each cell. Stand parameters of entire stands are finally computed from the individual cell predictions.

The procedure has been tested in a 1000 ha forest area. 173 systematically distributed sample plots in very young ($h < 10$ m) to mature forest were used to regress dominant height, mean height, mean diameter, stem number, basal area, and volume against the laser data. The regressions were used to predict corresponding parameters in 73 subjectively selected test stands. Verification of stand estimates revealed a negligible bias for most parameters. The precision was promising; 0.61–1.17 m, 0.57–1.33 m, 1.32–1.61 cm, 16.9–22.2% (128–400 ha^{-1}), 8.6–11.7% (2.33–2.54 m^2ha^{-1}), and 11.4–14.2% (18.3–31.9 m^3ha^{-1}) for mean height, dominant height, mean diameter, stem number, basal area, and volume, respectively. The proposed procedure will be applied in a 5000 ha practical stand inventory during summer 2001.

2.1.2 Cost Efficiency of Inventories

Several evaluations of Norwegian practical large-scale forest inventories have been done by the section over the last decade. Systematic and random errors at the stand level for parameters like volume, mean height, basal area, site quality and age have been quantified. Based on these results, the use of uncertain inventory data in long-term timber production analyses has been addressed.

Final harvest decisions, i.e. possible outcome intervals with respect to timing and expected net present value-losses due to incorrect timing, have for example been considered. A case study, where inventory data errors according to different error levels were generated randomly, was performed. Different variables and stands types were considered. The experiences from the case study, along with general considerations related to other sources of uncertainty, may help decisions-makers to get a more realistic attitude to the reliability of long-term timber production analyses. The results of the study may also serve as a starting point in a decision oriented inventory planning concept, in which alternatives for inventory design and intensity are based on considerations with respect to inventory costs as well as net present value-losses.

2.1.3 Stand Level Input for Large-Scale Forestry Scenario Models

A large part of the practical inventories for management planning in Norway are stand level inventories. Basal area mean diameter and number of trees in forest stand are compulsory variables for projections made with existing large-scale forestry scenario models in Norway. In the current practical inventories, however, these parameters are usually not determined. Models for estimation of these variables, adapted to different types of practical inventories (relascope, photo and visual inventories) have therefore been developed. Validations of the models provided few statistically significant differences between predicted and observed values, but the standard deviations for the differences were relatively large. There are in general numerous sources of uncertainty in large-scale forestry analyses, thus the developed models will probably not introduce any substantial change with respect to the final uncertainty at an aggregated level (forest). The large standard deviations, and large consequential losses in terms of net present value applying the models, however, indicated that one should avoid relying solely on the models with respect to decisions at the stand level.

2.2 Economics and Planning

Many of the activities within this field of the section have closely been connected to large-scale forestry scenario modelling and analyses. A continuous work with the purpose of enhancing the existing models is going on, along with large-scale scenario analyses at different geographical levels and for different purposes.

2.2.1 Large-Scale Forestry Scenario Models

There is a constant endeavour related to the large-scale forestry scenario models, where the basic models describing in-growth, growth and mortality, and timber value and harvest costs, are in focus. The main efforts during the last few years have been put on adapting the harvest cost calculations to mechanised harvesting systems, and on the development of models for birch, both with respect to growth projections and to price/gross value calculations.

There are two large-scale forestry scenario models developed at the section. One of these is GAYA-JLP. This model applies standard methodology of simulating treatment schedules for each management unit and solves the management problem at the forest level by linear programming (JLP). Projections of the forest development, and the corresponding economic calculations, are provided by using a stand growth model with the basal area mean diameter and mean height weighted by basal area as the basic entities, and number of stems ha^{-1} as a scaling factor. The projections are driven by diameter increment functions, height development models, and a mortality model. Timber values are estimated from gross price functions. An application with a spatial decision support system based on GAYA-JLP and a geographical information system has been developed (SGIS), and used, mainly for teaching purposes.

A major revision of a former developed model (AVVIRK3) has resulted in a new version now called AVVIRK-2000. The model provides for a range of possibilities with respect to long-term (100 years) analyses; possible management strategies, i.e., harvest strategies and silvicultural investment strategies, along with the corresponding income flow, development of forest state and profitability. The model might be operated with sample plots, stands or aggregates of sample plots as calculation units. The model is to a great extent based on the same basic models for projections and economic calculations as GAYA-JLP. A large number of control variables, i.e. parameters used for forest treatment manipulations, are provided both globally (forest level) and locally (plot/stand level). The model is a deterministic simulation model, and the decision making is based on a heuristic approach, with no optimising elements built in, where the user imitates the forest system through "intelligent" manipulation of data while searching for solutions. The net present value of a management strategy is calculated according to the net income flow over the planning period (100 years), the ending inventory, and a user defined real rate of discount.

2.2.2 Large-Scale Forestry Scenario Analyses

A public discussion on how to bring forest management practices in a more environmentally oriented direction has been going on in Norway over the last years. A report to the Parliament on the forest policy, prepared by the Ministry of Agriculture, has also been presented lately. In connection with these issues, the section has provided extensive analyses in order to map long-term consequences of different treatments options. The analyses have partly been related to more basic questions, e.g., "How intensively should a forest be grown?" In these analyses, the required real rate of return has been varied and used as the driving force to find the best (optimal) level of intensity in silvicultural management and thus optimal paths for harvesting and growing stocks. The regeneration strategy was a key factor for the long-term development of a forest and was thus given particular attention.

Environmentally oriented constraints have been the second main concern, when it comes to large-scale forestry analyses. Extensive analyses on national and regional, as well as on property level, have been performed in order to map the consequences of such constraints. In the analyses done at the national level, sample plots from the National Forest Inventory, covering the entire productive forest area in Norway, were used to describe the present forest state. The following environmentally oriented constraints were considered

(i) areas of current old forest set aside, either proportionally or cost-efficiently, for permanent preservation,
(ii) minimum target levels for area covered by old forest through time,
(iii) retention of trees at final felling, and
(iv) restricted management for border zone areas.

With a real rate of discount of 2.5%, and all the constraints imposed simultaneously, the annual harvest potential was reduced by 30% for the first 10-year period, while the net present value was reduced by 21.5%. The results of the analyses also demonstrated significant efficiency gains of letting the preservation of old forest be allocated cost-efficiently, compared with a strategy of setting aside an equal portion on all eligible areas.

Another project focused on broadleaves as a biodiversity indicator in long term forest management planning. A case study, where the economic value and harvest potential of adopting restricted timber management practices promoting the preservation of biodiversity in a 4260 ha boreal forest landscape in Southeast Norway, was performed. Silvicultural treatment options favouring broadleaves were specified to improve the living-conditions for a number of bird species, beetles, and wood-inhabiting fungi. Current timber management practices were also available as a reference alternative. The main conclusion from these analyses was that the reduction in net present value was relatively small when the treatments favouring broadleaves were compared to the reference alternative.

2.3 Biology

Although the section is mainly occupied with inventories, planning, economics and decisions-making problems, efforts have also been made to solve different biological questions and problems. The projects related to the biological part of the section's discipline have mainly been induced as a result of detecting obvious "biological knowledge gaps" when dealing with decision problems and economic analyses.

2.3.1 Growth in Mixed Birch/Spruce Forest

A stand-based model for predicting basal-area mean diameter growth for Norway spruce in young mixed stands of spruce and birch was developed and compared with two existing growth models developed for older stands (a Swedish one and a Norwegian one). The main data were from experiments with four different pre-commercial thinning regimes, and a multiplicative model with four independent variables was found suitable. The R^2 value was 0.59 and the coefficient of variation was 12%. Validations based on independent data from the National Forest Inventory indicated that the function developed in the study was suitable for young stands at medium to highly productive areas. Large deviations between observed and predicted growth for

the two existing functions were revealed in highly productive stands. The tests based on data from the National Forest Inventory indicated also that the existing function developed for spruce in older mixed stands (the Swedish one) was suitable for practical purposes for young stands.

2.3.2 Modelling of Mortality

Logistic models predicting probability of survival for individual trees were developed for Norway spruce, Scots pine, birch, and for other broad-leaved trees. The models were based on data from one remeasurement of a nation-wide grid of permanent sample plots recorded by the Norwegian National Forest Inventory. The models were designed for use in large-scale forestry scenario models for even-aged and uneven-aged forests, as well as for forests with mixed and pure species composition. Although the phenomenon of mortality is a stochastic, rare and irregular event, the model fit and validation tests were fairly good. Given the general uncertainty related to large-scale forestry scenario analyses, and the uncertainty related to mortality as a phenomenon, the mortality models were considered to have an appropriate level of reliability.

A similar approach to mortality for area-based projections has also been considered. A two-step modelling strategy is applied; logistic models for predicting the probability of mortality was developed in a first step, and multiplicative models for stem reduction and diameter calibration in mortality were developed in a second step. Also these models are based on sample plots recorded by the Norwegian National Forest Inventory.

2.3.3 Decay of Coarse Woody Debris of Picea abies Logs

Decomposition rate constants were estimated from 384 cross sections of Norway spruce (*Picea abies*) logs with base diameter >7 cm collected in open areas in the south-eastern Norway. Based on this chronosequence, a simple negative exponential function of time showed an average decomposition rate constant for all cross-sections of 0.033 per year. Cross-section diameter, ground contact, soil moisture, and aspect were all found to have significant impact on the composition rate constant. For different combinations of these factors the decomposition rate constant ranged from a minimum of 0.0165 per year to a maximum of 0.0488 per year.

To find a fast and easy way of recording the density of decayed wood in practical inventories, the relationship between relative density and simple classification systems of decayed coarse woody debris was assessed for the 384 cross-sections. The relative density was computed as the ratio of actual density to the density of fresh wood. Three different classification systems were tested. One consisted of five classes and the two other consisted of eight classes each. All the systems classified the samples according to variables related to bark, wood, and trunk shape. Spearman rank correlation coefficient between relative density and decay class ranged from –0.77 to –0.80. The correlation coefficients of the three classifications did not differ significantly from each other. The mean relative density within each decay class also decreased successively from one decay-class to the next for all classification systems. For the five-class system the mean relative density decreased from 0.97 in the least decayed class to 0.28 in the most decayed class.

3 On-going Research Projects

At present there are 13 research projects related to inventories, economics/planning and biology (production/growth) going on at the department. Among these 7 projects are within the field of resource inventories, 4 within economics/planning and 2 are within biology.

3.1 Resource Inventories

Project title: Site quality classification on aerial photographs
Leader: Sveinung Nersten
Co-workers: Jo Heringstad
Time frame: 1999–2001

Project title: Determination of mean tree height in forest stands by means of digital photogrammetry and image matching
Leader: Erik Næsset
Cooperation: Prevista A.S.
Time frame: 1999–2001

Project title: Estimation of stand parameters by means of airborne laser scanner
Leader: Erik Næsset
Co-workers: Petter Økseter
Time frame: 1999–2003

Project title: Models for prediction of basal area mean diameter and number of trees in stands
Leader: Tron Eid
Co-workers: Petter Økseter
Time frame: 2000–2001

Project title: Positioning with GPS+GLONASS under tree canopies
Leader: Erik Næsset
Time frame: 2000–2001

Project title: Diameter – and height distributions in forest stands
Leader: Tron Eid
Time frame: 2001–2002

Project title: Large scale practical stand inventories by means of airborne laser scanner
Leader: Erik Næsset
Cooperation: Prevista A.S.
Time frame: 2001–2002

3.2 Economics and Planning

Project title: Modelling growth and price systems for broadleaves
Leader: Erik Næsset
Co-workers: Terje Gobakken
Time frame: 1996–2001

Project title: Measures for a sustainable forestry and economic consequences
Leader: Hans Fredrik Hoen
Co-workers: Tron Eid, Petter Økseter
Time frame: 1997– 2001

Project title: Alternative forest treatments
Leader: Tron Eid
Co-workers: Nils Lexerød, Knut Solbraa
Cooperation: Glommen Association of Forest Owners, County council of Hedmark
Time frame: 2000–2001

Project title: Successive intensive inventories in Aas forest
Leader: Tron Eid
Cooperation: Foran A.S, Prevista A.S. and Mjøsen Association of Forest Owners
Time frame: 2001–2003

3.3 Biology

Project title: Models for estimation of natural mortality
Leader: Erik Næsset
Co-workers: Tron Eid
Time frame: 1998–2001

Project title: Growth models for use in large-scale forestry scenario models (Ph.D-study)
Leader: Nils Lexerød
Time frame: 2001–2004

4 Publications 1997–2001

4.1 Resource Inventories

2001

Eid, T. 2001. Bestemmelse av middeldiameter og treantall for bestand i hogstklasse III–V. Norsk Skogbruk 01/01: 34–36 (In Norwegian.)

— 2001. Models for prediction of basal area mean diameter and number of trees in forest stands. Scandinavian Journal of Forest Research 16: 467–479.

2000

Næsset, E., Bjerke, T., Øvstedal, O. & Ryan, L.H. 2000. Contributions of differential GPS and GLONASS observations to point accuracy under forest canopies. Photogrammetric Engineering & Remote Sensing 66: 403–407.

1999

Eid, T. & Moum, S.O. 1999. Bestandsuavhengig bonitering og nøyaktighet. Rapport fra skogforskningen 7/99: 1–25. ISBN 82-7169-905-9. (In Norwegian.)

Næsset, E. 1999. Assessing the effect of erroneous placement of forest stand boundaries on the estimated area of individual stands. Scandinavian Journal of Forest Research 14: 175–181.

— 1999. Effects of delineation errors in forest stand boundaries on estimated area and timber volumes. Scandinavian Journal of Forest Research 14: 558–566.

— 1999. Point accuracy of combined pseudorange and carrier phase differential GPS under forest canopy. Canadian Journal of Forest Research 29: 547–553.

— & Tveite, B. 1999. Stand volume functions for Picea abies in eastern, central, and northern Norway. Scandinavian Journal of Forest Research 14: 164–174.

1998

Eid, T. & Næsset, E. 1998. Determination of stand volume in practical forest inventories based on field measurements and photo-interpretation: The Norwegian experience. Scandinavian Journal of Forest Research 13: 246–254.

Næsset, E. 1998. Positional accuracy of boundaries between clearcuts and mature forest stands delineated by means of aerial photointerpretation. Canadian Journal of Forest Research 28: 368–374.

1997

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— 1997. Flybåren laser til måling av trehøyder og kubikkmasse. Norsk Skogbruk 43(4): 30–32. (In Norwegian.)

— 1997. Bruk av flybåren laser i bestandstakster. In: Årsmelding 1996, Institutt for skogfag, Norges landbrukshøgskole, pp. 7–9. (In Norwegian.)

4.2 Economics and Planning

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Eid, T., Hoen. H.F. & Økseter, P. 2001. Economic consequences of sustainable forest management regimes at non-industrial forest owner level in Norway. Forest Policy and Economics 2: 213–228.

Hoen, H.F., Eid, T. & Økseter, P. 2001. Timber production possibilities and capital yields from the Norwegian forest area. Basic information for policy formulation. Silva Fennica 35: 249–264.

2000

Bolkesjø, T. 2000. Om valg av avvirkningstidspunkt. Aktuelt fra skogforskningen. 1/2000: 28–31. (In Norwegian.)

Eid, T. 2000. Use of uncertain inventory data in forestry scenario models and consequential incorrect harvest decisions. Silva Fennica 34: 89–100.

— 2000. Skogbruksplanlegging i endring. Årsmelding fra Institutt for skogfag, Norges landbrukshøgskole 1999: 6–8. (In Norwegian.)

— & Hobbelstad, K. 2000. AVVIRK-2000 – a large scale forestry scenario model for long-term investment, income and harvest analyses. Scandinavian Journal of Forest Research 15: 472–482.

— , Hoen, H.F. & Økseter, P. 2000. Timber production possibilities of the Norwegian forest area and measures for a sustainable forestry. Pp 126 in Jandl, R., Devall, M., Khorchidi, M, Schimpf, E., Wolfrum; G. & Krishnapillay, B. Forest and society: the Role of research. Abstract of group discussions, Volume II. XXI Iufro World Congress, 7–12 August 2000, Kuala Lumpur, Malaysia. ISBN 983-2181-09-7.

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— 2000. The effect of two different price systems on the value and cross-cutting patterns of Norway spruce logs. Scandinavian Journal of Forest Research 15: 368–377.

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4.3 Biology

2001

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Næsset, E. 1999. Decomposition rate constants of Picea abies logs in southeastern Norway. Canadian Journal of Forest Research 29: 372–381.

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Team Report from University of Helsinki, Department of Forest Resource Management

Markus Holopainen, Jouko Laasasenaho and Simo Poso

University of Helsinki, Department of Forest Resource Management
P.O. Box 27, FIN-00014 Helsinki, Finland
e-mail: markus.holopainen@helsinki.fi, jouko.laasasenaho@helsinki.fi
and simo.poso@helsinki.fi

1 Introduction

Forest Mensuration and Management is one of the two first fields for which a professorship was established when forestry teaching was started at the University of Helsinki in 1907. Nowadays, Department of Forest Resource Management at the University of Helsinki consists of the following scientific fields:

- Forest Mensuration and Management (2 professorships)
- Geographic Information systems (GIS) and Remote Sensing (1 professorship, autumn 2001)
- Forest Growth and Yield
- Forest Technology (2 professorships)
- Wood Technology (1 professorship)
- Applied Statistics

In this paper, we will give short description of the development of research at our department 1997–2001, escpecially in the field of forest mensuration and management.

2 Forests in Geographic Information Systems -Graduate School

In order to develop the use of geographic information systems (GIS) in Finnish forestry, graduate school "Forests in Geographical Information Systems" was established at the department in May 1998. The school is financed by the Finnish Foresters Foundation, the Finnish Ministry of Agriculture and Forestry, and the Academy of Finland. Postgraduate studies can be pursued in the University of Helsinki, University of Joensuu, or in the Helsinki University of Technology. In the first year, 15 research students were admitted to the school.

Main objectives of the school are:

- To initiate an educational program in the fields of forestry, photogrammetry, remote sensing, and geoinformatics.
- To increase co-operation among those interested in GIS research and the use of GIS both in Finland and abroad.
- To develop GIS applications for use in forestry and the environmental sciences.

The graduate school develops methods for planning and maintaining forest information systems, for forest mapping, inventory and monitoring. The main fields of teaching and research include acquisition of GIS data, improvement of GIS

Table 1. Research activities: Acquisition of GIS data.

Title	Aim of the study	Researcher, email address
Global Object Reconstruction	The use of digital airborne photomosaics in forest mapping and its accuracy evaluation.	Mikael Holm, mikael.holm@vtt.fi
GIS for evaluating photo interpretation accuracy and improving data quality	To develop methods for photointerpretation accuracy evaluation of multiscale and multiresolution remote sensing images	Anssi Lohi, anssi.loho@vtt.fi
Usability of high resolution satellite images in forest management planning	To develop methods for the use of high resolution satellite images in forest management planning and their accuracy evaluation.	Anssi Pekkarinen, anssi.pekkarinen@metla.fi
Field inventory system of forest management planning	Develop the new field inventory system for forest management planning	Jyrki Koivuniemi, jyrki.koivuniemi@helsinki.fi
Geometrical Object Reconstruction – Overdetermination and Accuracy	Develop methods for the use of video imageries in forest inventorying and mapping in the field	Jussi Heikkinen, jussi.heikkinen@hut.fi

analyses, and applications for forestry purposes.

Remote sensing has an essential role in GIS data acquisition. However, there are several problems, which should be resolved before effective use of new satellite and airborne imageries (Table 1):

- The suitable image resolution for forest mapping and inventorying
- The geometric and radiometric accuracy of aerial photo mosaics
- The estimation accuracy when combining multisource and multiscale remotely sensed imageries in forest mapping

New methodologies for field measurements and visualization of forests is also needed (Table 1). These studies will be conducted through the co-operation project "GIS data capture by using harvester-mounted GPS", which aims to combine the use of highly accurate timber harvester measurement instruments with satellite-aided positioning (GPS) devices in order to produce cost-efficient timber resource data for forest management purposes.

New methodologies for statistical GIS analyses will be developed and the accuracy of different kinds of GIS data in forest mapping will be evaluated. Important questions in the use of GIS in forestry are what numerical information are needed, how multisource information can be combined effectively, and what its accuracy in forest mapping and inventorying is (Table 2).

The graduate school will probably have an essential role in developing new GIS and remote sensing methodologies for forest mapping, inventorying, visualization, and monitoring in Finland. This is also the first attempt to develop co-operation between surveyors and foresters at this level of education. The establishment of a graduate school also provided an opportunity to create a new GIS curriculum within the department, which should form an excellent starting point for future efforts of this kind.

Thanks to the graduate school program and our other activities, a new professorship of geoinformatics is established at the department in 2001.

Table 2. Research activities: GIS analyses and applications in forestry.

Title	Aim of the study	Researcher, email address
Statistical methods for analysing GIS data	Develop new statistical methods for GIS analyses and accuracy evaluation of GIS data.	Virpi Alenius, virpi.alenius@metla.fi
Spatial statistics on Nature resources using modern server technology	The use of GIS server technology in statistical analyses of environmental resources.	Simo Kainulainen, simo.kainulainen@metsa.fi
Modelling and implementing geo-database for topographic maps in object-oriented GIS environment	Describe and evaluate some design patterns for analysis, map production and multiple representation in GIS.	Leena Salo-Merta, leena.salo-merta@nls.fi
Modelling of requirements for geographic data	Develop methods for modelling requirements for GIS data, combining multisource information, and the effect of data quality in data combination.	Paula Ahonen, paula.ahonen@nls.fi
Reliability of multisource forest inventory	The reliability of forest variable estimates in multisource forest inventory from satellite image pixel resolution to municipality level.	Matti Katila, matti.katila@metla.fi
The utilization of spatio-temporal data in forestry	The use of GIS for updating changes in forests.	Jussi Rasinmäki, jussi.rasinmaki@helsinki.fi
Environmental impact assessment of forestry with the help of geographical information system	Possibilities of geographical information system in environmental impact assessment of forestry.	Juha-Matti Markkola, juha-matti.markkola@helsinki.fi
GIS information requirements in Finnish private forestry	Describe and evaluate GIS information requirements in Finnish private forestry.	Raili Hokajärvi, raili.hokajarvi@oamk.fi

3 Other On-going Projects

Poso, S., Fish S., Kojola, S., Leskinen, J., Nurmio, M., Tuominen, S. SMI-System as a Basis for Acquisition and Maintaining Forest Data. (Project 1999–2000 financed by Ministry of Agriculture and Forestry)

Poso, S., Fish, S., Holopainen, M., Hujala, T., Leskinen, J., Tuominen, S. Using Digital Ortho- and Stereoscopic Aerial Photos for Forest Inventory and Monitoring (Project 1999–2000 funded by Ministry of Agriculture and Forestry)

The most common methodology utilized for providing data for forest management in Finland has been based on the use of compartments. However, this compartment-wise approach has several drawbacks. Compartments are usually quite heterogeneous, and compartment assessment relies largely on subjective considerations resulting easily in unsatisfactory accuracy and bias. The border lines must be updated occasionally because forest treatments rarely follow compartment border lines. In addition, monitoring of change is very complicated if the compartment border lines are changed. The idea of a plotwise approach in forest inventory and management

using 2-phase sampling with stratification has been the basis of the Satellite Images in Forest Inventory (SMI) system developed at the University of Helsinki starting from 1984.

According to SMI methodology, a systematic set of first-phase plots is generated, e.g. in a 20 × 20 m (field) grid. Some easily derivable auxiliary data, such as remote sensing image features, are then acquired for each plot. Using the auxiliary data the first-phase plots are stratified. In each stratum, several second-phase plots are then selected for measurement in the field. Finally, the second-phase plot information is generalized to each first-phase plot. In stratification, image features are stratified into homogeneous groups. The basic stratification method is k-means clustering. Proportional allocation is usually preferred in drawing the field sample plots, if no specific areas requiring specific emphasis are present. Many different methodologies can be used to derive an appropriate estimator. However, until now mean vectors have been the most commonly used method.

Aim of the latter project is to utilize SMI methodology in forest management planning, and to evaluate the accuracy of the method in practice.

Korpela, I. Automatic Mapping of Trees from Metric Aerial Photos

Sustainable use and management of natural resources sets demands on the monitoring of the dynamic ecosystems. Detailed, accurate and positioned (in time and space) information is often needed. The data that is collected should be useful also in the future and it should meet the criteria of cost-efficiency. Single trees and their characteristics are the core elements of forest inventories. Large-scale aerial photos, with human interpretation and analogue photogrammetric measurements, have been found useful in the assessment of single tree characteristics. This type of work has two phases:

i) detecting and identifying entities from the photos, and
ii) matching the same entities on all photos involved (solving the stereo correspondence problem).

Automating these two processes is the basic tasks of digital photogrammetry, the fast developing field that is applied in this study. The objective in this study is to further develop and test methods for single tree and treetop isolation from projections on digital metric aerial photos (phase i). Secondary objective is to develop further a matching algorithm that solves the correspondence problem in the object space, that is the space occupied by the forest canopy (phase ii). The detection algorithm should be as invariant as possible to

a) the varying object-sun-camera geometry of the central projection in aerial photographs,
b) size of the tree, scale of the imagery, and
c) shape and reflectance properties of different tree species.

Model-based feature detectors exist for single tree detection and their applicability in Finnish conditions will be assessed. Research work is ongoing with the matching algorithm, and initial tests have proven promising results. The utterly ill-posed matching problem is solved using geometric constraints and multiple (> 2) views. Treetops are found with small omission and commission error rates, and treetops are given 3D-coordinates.

Melkas, T., Rasinmäki, J., Räty, M. & Koivuniemi J. The New Updating Method of Forest Resources

Harvesters produce reliable and accurate information of the removed trees. This information can been localized by using a satellite-aided positioning system. The development of digital mapping and satellite-aided positioning systems (e.g. GPS) within timber harvesters has been rapid in recent years. Also the accuracy of location has improved. Today, the main aim of using digital maps and GPS is to help harvester's drivers in their logging work. The aim of the research is to develop a method to collect position-accurate stand data in connection with logging and, at the same time, to develop a method to use this information for practical needs (of forest industry, local and governmental authorities and private forest owners, for example). Attribute data (like stem volume) accumulate during the logging work and location data is obtained by using harvester's GPS. The

key aims of this research are:

1) to develop a method to collect position accurate stand data using harvester mounted GPS,
2) to create and maintenance a databank and study the usability of collected data for remote sensing,
3) to update forest management databases with harvester-GPS data, and
4) to develop and test new field measuring instruments.

The new updating method of forest resources can be utilized in search of potential cutting areas, and in follow-up regeneration of forests. In the long run the aim is to create an application, that can be utilized by forest industry and local and governmental authorities, as well as by private forest owners.

4 Publications 1997–2001

1997

Holopainen, M. & Wang, G. 1997. Regression calibration of digital aerial photographs. Proceedings of the FIRS International Workshop, Application of Remote Sensing in European Forest Monitoring. 14th–16th October 1996, Vienna, Austria. pp. 457–464.

Poso, S. 1997. Metsätalouden suunnittelun perusteet. 3rd edn. University of Helsinki, Department of Forest Resource Management, Publications 5: 1–152. (In Finnish).

Wang, G., Waite, M-L. & Poso, S. 1997. SMI User's Guide for Forest Inventory and Monitoring. University of Helsinki, Department of Forest Resource Management, Publications 16: 1–336.

1998

Holopainen, M. 1998. Forest Habitat Classification by CASI Airborne Measurements. For. & Landsc. Res. 1998(1): 431–446

Holopainen, M. 1998. Forest habitat mapping by means of digitized aerial photographs and multispectral airborne measurements. University of Helsinki, Department of Forest Resource Management, Publications 18.

Holopainen, M. 1998. Forest habitat mapping by means of high-resolution airborne data. Proceedings of the 27th International Symposium on Remote Sensing of Environment, Information for Sustainability. June 8–12, 1998, Tromsø, Norway. pp. 403–406.

Holopainen, M. & Wang, G. 1998. The calibration of digitized aerial photographs for forest stratification. International Journal of Remote Sensing, 19: 677–696.

Holopainen, M. & Wang, G. 1998. Accuracy of digitized aerial photographs for assessing forest habitats at plot level. Scandinavian Journal of Forest Research, 13: 499–508.

Holopainen, M. & Wang, G. 1998. Digitized aerial photos for Assessing Forest biodiversity. In Bachmann, P., Köhl, M. & Päivinen, R. (eds.) Assessment of Biodiversity for Improved Forest Planning. EFI Proceedings No. 18. pp. 249–254.

Jauhiainen, S. & Holopainen, M. 1998. Land use and climate change impact on peatland ecosystems. In: Climate change impact on agriculture and forestry. Proceedings of the European School of Climatology and Natural Hazards Course held in Volterra, Italy, 16–23 March 1996. pp. 375–378.

Poso, S. & Tuominen, S. 1998. Kaukokuvat metsien inventoinnissa ja seurannassa. (Remote Sensing Imageries for Forest Inventory and Monitoring) Project Paper. 35 p.

Wang, G., Poso, S., Waite, M-L. & Holopainen, M. 1998. The use of digitized aerial photographs and local operation for classification of stand development classes. Silva Fennica 32(3): 215–225.

1999

Holopainen, M. & Laasasenaho, J. Forests in Geographic Information Systems -Graduate School. In Proceedings of the Remote Sensing and Forest Monitoring, IUFRO, 1–3 June 1999, Warsow, Poland. pp. 97–102.

Holopainen, M. & Jauhiainen, S. 1999. Detection of peatland vegetation types using digitized aerial photographs. Canadian Journal of Remote Sensing 25: 475–485.

Poso, S, Wang, G. & Tuominen, S. 1999. Weighting alternative estimates when using multi-source auxiliary data for forest inventory. Silva Fennica 33(1): 41–50.

Poso, S. 1999. Metsänarvioimisen uudet menetelmät. (New Methods in Forest Mensuration and Management). Academia Scientiarum Fennica. pp. 123–132.

2000

Holopainen, M. & Laasasenaho, J. 2000. Forests in Geographic Information Systems -Graduate School. In proceedings of the Forestry Information Systems 2000, 16.–20.5.2000, Hyytiälä, Finland.

Holopainen, M. & Laasasenaho, J. 2000. Forests in Geographic Information Systems. In proceedings of the XXI IUFRO World Congress 2000, 7–12 August 2000, Kuala Lumpur.

Wang, G., Holopainen, M. & Lukkarinen, E. 2000. Data Fusion of Landsat TM and IRS images for Forest Classification. Proceedings of the IUFRO Conference – Integrated Tools for Natural Resources Inventories in the 21st Century, held August 16–20, 1998, Boise, Idaho, USA.

Doctoral theses:

Holopainen, M. 1998. Forest habitat mapping by means of digitized aerial photographs and multispectral airborne measurements. University of Helsinki, Department of Forest Resource Management, Publications 18.

Licentiate theses:

Korpela, Ilkka. 2001. 3D matching tree tops using digitized panchromatic aerial photographs.

Master's theses:

Fish, Stuart. 2000. Combining geostatistics and geographic information systems to provide locally specific estimates of basal area and volume per hectare from forest inventory plots.

Hokka, Timo. 1999. Paikannetun puustotiedon hankinta sekä leimikon rajojen kartoitus hakkuukoneen GPS-paikantimen avulla. (Acquisition of GIS-data with GPS in Harvester).

Kojola, Soili. Maastotiedon keruu sovellettaessa kaksivaiheista otantaa metsäsuunnittelutietojen päivityksessä. (Ocular observations for improving the efficiency of two-phase plot sampling for local information).

Markkola, Juha-Matti.1998. Puu- ja metsikkökohtaiset tilavuustaulukot Pinus Ocarpalle ja Caribiealle. (Tree and Stand Volume Models for Pinus ocarpa and Caribea).

Melkas, Timo. 2000. Kuusen kuorimallin laadinta. (Model for Spruce Bark).

Mustonen, Jouko. 1998. Männyn oksien suunnan ja paksuuden ennustaminen.

Sved, Johnny. Puuston tiheyden vaikutus kuusien runkomuotoon. (The Effect of Stand Density on Stem Form of Spruce).

Miettinen, Jukka. 1998. Digitaalisten ilmakuvien visuaalisen tulkinnan soveltuminen metsän koealainventointiin. Visual Stereo Interpretation of forest sample plots by Digitized Aerial Photographs).

Mikkola, Katariina. 1997. Pinus oocarpa -metsiköiden tilavuuskasvumallit Hondurasissa. (Volume Growth Models for Pinus oocarpa -stands in Honduras).

Pakkala, Pekka. 1997. Brittiläisen Kolumbian metsälain vaikutukset puuntuotannollisiin mahdollisuuksiin: Tapaustutkimus Revelstoken puuntuotantoalueella.

Pekkarinen, Anssi. 1997. Kahden, kasvukauden eri vaiheissa otetun Landsat TM -satelliittikuvan käyttökelpoisuus monilähteisessä metsien inventoinnissa.

Poranen, Ossi. 1999. Puuttuvien tietojen ennustaminen muuttuva-alaisilla pysyvillä koealoilla. (Estimation of Lacking Data when Using Variable Permanent Sample Plots).

Räisänen, Matti. 1997. Hevea brasiliensisin tilavuus- ja biomassayhtälöiden laadinta. (Volume and Biomass equations for Hevea brasiliensisin) Pro gradu thesis.

Savurinne, Sami. 2000. Pysyvien koealojen soveltuvuus metsikködynamiikan tutkimiseen (Using Permanent Sample Plots for analysing of forest stand dynamics).

Schulman, Filip. 2000. Bältebeståndets lämplighet vid skogstaxering med utnyttjandet av Landsat TM data (Inventory of Forest Resources based on sample plots, sample strips and Landsat TM imagery).

Strandström, Mikael. Landsat TM kuvalta estimoitavien latvuspeiton ja lehtipinta-alaindeksin käyttökelpoisuus metsän kaukokartoitukseen Keski-Suomessa. (Remote Sensing of Forest through Crown Closure and Leaf Area Index in Central Finland).

Tuomainen, Tarja. 2000. Männyn paksuuskasvun estimointi (Estimation of diameter increment of pine).

Utunen, Mikko 1997. Growth response of paper birch crown to thinning in moist warm Interior Cedar-Hemlock-subzone of British Columbia.

Vuoristo, Mikko 1998. Hakkuusuunnite-ero ja sen tekijät Metsähallituksen ja Metsäntutkimuslaitoksen MELA-laskelmissa. Vertailututkimus Kainuun alueella. (Difference between Cutting budgets prepaired by Finnish Forest and Park Service and Finnish Forest Research Institute).

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

Matti Maltamo, Perttu Anttila, Kalle Eerikäinen, Mikko Lehikoinen, Satu Löfman, Jukka Malinen, Timo Pukkala, Jouni Pykäläinen and Susanna Sironen

University of Joensuu, Faculty of Forestry
P.O. Box 111, FIN-80101 Joensuu, Finland
e-mail: firstname.lastname@joensuu.fi
http://www.forest.joensuu.fi/

1 General Information

1.1 Goals

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 nature resource.

1.2 Staff and Students

- 10 professors
- 8 senior assistants and assistants
- 80 researchers
- 20 other staff including office and laboratory staff
- 250 undergraduate students with admittance of 45 new students every year
- 60 graduate students

The Faculty awards about 40 Master's degrees and 10 Doctoral degrees every year.

1.3 Research

The Faculty of Forestry at the University of Joensuu forms the core of diverse forestry know-how based in Joensuu, eastern Finland. Increasingly, post-graduate students work for their doctorate within graduate school programmes. The Faculty participates in graduate school programmes "Forests in GIS", "Forest Ecology, Wood Science and Engineering", and "Forest Economy and Marketing". Research group "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. In addition, the Faculty has special expertise in timber procurement planning, remote sensing, forest planning and forest modelling. The Faculty is or has been involved in more than ten research projects funded by the European Union, two projects being co-ordinated by the Faculty. The Faculty also co-operates actively with local and national business life.

Forest mensuration has two active main branches: forest modelling and remote sensing. In forest modelling the efforts have concentrated on diameter distribution modelling and on modelling of the development of plantation forests in countries of south-eastern Africa. The research has focused on the use of modelling techniques such as mixed linear models, projection models and non-parametric methods. In remote sensing, the recent target has been extraction of detailed forest information using high-resolution images,

additional spatial information, and advanced methods in image interpretation. In forest planning several modern methodologies have been applied. Besides standard optimisation methods, GIS, Internet and visualisation applications have been used. In addition biodiversity issues and regional planning have been studied in forest inventory and planning.

The Faculty members have also published several textbooks during recent years in our own Silva Carelica -series. These books include e.g. forest mensuration, remote sensing and GIS topics. During 1996–2001 several students have defended their doctoral thesis in forest mensuration and forest planning. The persons and the topics of their doctoral thesis are listed below:

1997:

Mauno Pesonen: Estimation of potential allowable cut using modelling of landowners strategic decision making

Jari Varjo: Change detection and controlling forest information using multi-temporal Landsat TM-imagery

1998:

Hans Gustavsen: Volymtillväxten och övre höjdens utveckling i talldominerade bestånd i Finland – en utvärdering av några modellers validitet i nuvarande skogar.

Matti Maltamo: Basal area diameter distribution in estimating the quantity and structure of growing stock

Timo Tokola: Critical aspects in establishment of satellite remote sensing based regional forest inventory system.

1999:

Olavi Rautiainen: Growth dynamics and management of Shorea robusta forests in Southern Nepal.

2000:

Danaza Mabvurira: Modelling the growth, yield and management of Eucalyptus grandis (Hill) Maiden plantations in Zimbabwe

2001:

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

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

The following sections introduce the current research staff of forest mensuration and forest planning. In addition, several other people have contributed to the Faculty's research during 1996–2001 as can be seen in the list of publications.

2 Personnel and Research Activities in Forest Mensuration and Planning

2.1 Forest Modelling

Docent Matti Maltamo is an acting professor of Forest Mensuration. He has long experience in forest modelling, especially in the use of non-parametric methods. During the recent years, Dr Maltamo has participated in research projects "Inventorying, monitoring and updating forest information for forest management planning", "Quality and value relationships of Norway spruce logs", "Tree seedling production and management of plantation forests", "Description of commercial roundwood and its distribution in analysing future timber production possibilities", and "Integrating landscape ecology into forest planning". Currently he is involved in projects "Updating forest information", "Databases of timber procurement enterprises and forest mensuration as a basis for operational planning", and "Statistical modelling in forest management planning".

The specific research topic of Dr Maltamo is diameter distribution modelling. He has examined e.g. alternative ways to predict diameter distribution in boreal conditions and also in tropical plantation forests. In addition to the traditional way of describing diameter distribution using probability density functions, he has developed and applied non-parametric and distribution free

methods. In co-operation with Docent Annika Kangas, also methodologies for calibrating predicted distribution using additional information has been developed. The possibilities to combine remote sensing based single tree pattern recognition methods and tree and stand level models have also been examined. Dr Maltamo has also studied stand structure in relation to forest biodiversity in boreal and tropical conditions.

Ms Susanna Sironen, M.Sc.(For.), is an assistant in Forest Mensuration science. She studies the use of non-parametric methods in constructing tree level growth models, in particular. The methods include Most Similar Neighbour (MSN) inference, k-nearest neighbour regression, and generalised additive models. When using non-parametric methods the growth of a tree is predicted as a weighted average of the values of neighbouring observations. The selection of the nearest neighbours is based on the differences between tree and stand level characteristics of the target tree and the neighbours. Her future studies concentrate on modelling of regional and long term growth variation, and the effect of thinning on tree growth. In addition to non-parametric methods, the coming studies will also include stand level growth modelling using projection models.

Mr Kalle Eerikäinen, M.Sc.(For.), works as a researcher of Forest Mensuration. He has specialised on modelling tree and stand characteristics and forest growth and yield. His international working experience includes two longer visits to south-eastern African countries: Zimbabwe in 1995–96, and Tanzania, Zambia and Zimbabwe in 1998–99. He has worked as a researcher in the INCO-DC concerted action project "Tree seedling production and management of plantation forests", which ended in October 2000. At the moment Mr Eerikäinen is working for the EU funded ITM project "Implementing tree models as forest management tools". He is finalising his doctoral thesis "Modelling the stand development of *Pinus kesiya* (Royle ex Gordon) plantations in south-eastern Africa".

Mr Jukka Malinen, M.Sc.(For.), works as a researcher of Forest Mensuration. The purpose of his research work is to develop and test non-parametric methods for wood procurement planning. An application of the developed methods will be a part of a stem database in Finnish forest enterprises and it should predict characteristics of a marked stand with accuracy demanded by bucking simulation. A stem database includes representative samples of stands and stems, applications to control and update data and applications to utilise the database. The stem database study materials consist of two different kinds of data: harvester collected stem data and previously collected forest inventory data. In addition, non-parametric methods are tested with the Norway spruce data, which was originally collected by Finnish Forest Research Institute. In the prediction of stand characteristics for wood procurement the k-nearest neighbour MSN method has been found useful and flexible tool. In the k-nearest neighbour MSN method k most identical previously measured observations are used for predicting the characteristics of the target observation. The distance measures of similarity are produced from canonical correlation analysis. The k nearest neighbour MSN method has been further developed to be more flexible in situations where the estimation depends on the location of the target in relation to used reference data.

2.2 Remote Sensing and GIS

Ms Satu Löfman, M.Sc.(For.), is a senior assistant of Forest Information Systems. Recently she has concentrated on the regional structure of forest landscape and the landscape changes caused by forestry. The study material consists of multitemporal aerial photographs, that are analysed for stand development classes. Interesting questions include the test of theoretical landscape transformations models in the Finnish landscape, the appropriate scale for comparing forest areas at multiple times, the amount and structure of edge habitat and the fragmenting effect of forest roads.

Mr Perttu Anttila, M.Sc.(For.), works as a researcher at the Faculty. He is studying updating of standwise inventory data applying aerial photographs. In the first study, a stand simulator

and visual interpretation of aerial photos are used in updating. In the second study, k-nearest-neighbour inference, textural features calculated from aerial photos and old inventory data are utilised to predict stand attributes. In the third study, tree crowns are automatically segmented from aerial photos with a commercial software. The estimates of stand characteristics are calibrated with the aid of old inventory data. The work is part of the research project 'Updating Stand Level Forest Information'.

Mr Mikko Lehikoinen, M.Sc.(For.), is currently involved in a joint research project aiming at producing European forest maps by combining forest statistics and remote sensing data. His other research interests include single tree pattern recognition and the use of Internet in forest planning.

2.3 Forest Planning

Dr Timo Pukkala is a professor of Forest Planning. He has a long experience in a variety of areas in forest mensuration and planning including inventory methods, tree modelling, remote sensing, plantation forestry, forest management, optimisation and decision support. His recent interests include multi-criteria decision analysis, participatory planning, integration of landscape ecology into forest planning, visualisation of forest for decision support and management of plantation forests.

Dr Jouni Pykäläinen is an assistant of Forest Planning. His special research interest covers areas of interactive participatory planning. In more detail, his recent studies include interactive decision analysis in participatory strategic forest planning, thematic interviews in defining forest owners goals and priority models for forest planning on the landscape level involving multiple ownership.

3 On-going Research Projects

Project title: Database of timber procurement enterprises and forest mensuration as a basis for operational planning.
Leader: Pertti Harstela
Co-workers: Jukka Malinen (researcher), Matti Maltamo, Metsäteho
Financer: Academy of Finland
Time frame: 1998–2001

Project title: Diameter distributions and stand structure
Leader: Matti Maltamo
Time frame: Continuous

Project title: Earth Observation for Natura 2000 (EON 2000)
Leader: Timo Pukkala
Co-workers: Lauri Vesa (researcher), National Remote Sensing Centre, UK, Geospace Austria, Scottish Natural heritage Scotland
Financer: EU Centre for Earth observation
Time frame: 2001–2003

Project title: Evaluation of the suitability of the ICP data set for forest biodiversity monitoring.
Leader: Matti Maltamo
Co-workers: Petteri Packalen (researcher)
Financer: Joint Research Centre (JRC) project contract No. 18674-2001-11 FIEI ISP FI
Time frame: 2001–2002

Project title: Forest and Tree Groupings Data Base of the EU 15 and Pan-European area derived from NOAA-AVHRR Data
Leader: Matti Maltamo
Co-workers: Mikko Lehikoinen (researcher), European Forest Institute, VTT Automation
Financer: Joint Research Centre (JRC) project contract No. 17223-2000-12 F1SC ISP FI
Time frame: 2001

Project title: Forest landscape transformation in Finland 1940–1990
Leader: Satu Löfman (Ph.D. study)
Supervisor: Jari Kouki
Financer: Academy of Finland
Time frame: 1998–

Project title: FORSTOOLS – Tools for Managing Forest Ecosystems
Leader: Timo Pukkala
Financer: European union/5th Frame Work
Time frame: 1999–2002

Project title: ITM – Implementing Tree Growth models as Forest Management Tools
Leader: Timo Pukkala
Co-workers: Kalle Eerikäinen (researcher), Jari Miina, Taneli Kolström, Institute of Forest Growth Research, University of Agricultural Sciences, Austria, Chair of Forest Yield Science, Ludwig-Maximillian University, Germany, Faculty of Forestry, Technical University, Slovak Republic, Forest Research Station of Lower Saxony, Germany, Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Portugal, Danish Forest and Landscape Research, Denmark,
Forest Research Institute, NAGREF, Greece
Financer: The European Union
Time frame: 2001–2003

Project title: MSAFOR – Developing Management Support for the Indigenous and Plantation Forests and Agroforestry Systems in South and East Africa
Leader: Timo Pukkala
Financer: 4th Frame Work / INCO DG XII-B, DG XII/B3 ja DG XII/B4
Time frame: 2001–2002

Project title: Modelling the stand development of *Pinus kesiya* plantations in southeastern Africa
Leader: Kalle Eerikäinen (Ph.D. study)
Supervisor: Timo Pukkala
Time frame: 1998–2001

Project title: Multicriteria forest planning
Leader: Timo Pukkala
Co-workers: Jouni Pykäläinen
Time frame: Continuous

Project title: Non-parametric methods in prediction of growth
Leader: Susanna Sironen (Ph.D. study)
Supervisors: Annika Kangas, Matti Maltamo
Financer: Postgraduate school of forestry
Time frame: 2000–

Project title: Statistical modelling in forest management planning
Leader: Jyrki Kangas (FFRI)
Co-workers: Matti Maltamo, FFRI, Kannus Research Station
Financer: Academy of Finland
Time frame: 2001–2003

Project title: Updating forest information
Leader: Jari Varjo, Kari T. Korhonen (FFRI)
Co-workers: Perttu Anttila (researcher), Matti Maltamo, FFRI, Development Centre TAPIO, Forest Centre of North-Savo
Financer: Joint research funded by Ministry of Agriculture and Agriculture
Time frame: 1999–2002

Project title: Updating Forest modelling -textbook.
Leader: Matti Maltamo
Co-workers: Kalle Eerikäinen, Annika Kangas, Kari T. Korhonen, Jari Miina, Harri Mäkinen
Financer: Metsämiesten säätiö
Time frame: 2001

Project title: The Usability of Single Tree Laser Scanning in Forest Planning
Leader: Matti Maltamo
Co-workers: Juho Pitkänen, Timo Pukkala, Finnish Geodetic Institute
Financer: Academy of Finland
Time frame: 2001–2004

4 Publications

4.1 Refereed Scientific Publications

Eerikäinen, K. In press. A site dependent simultaneous growth projection model for Pinus kesiya plantations in Zambia and Zimbabwe. To appear in Forest Science.

Eerikäinen, K. 2001. Stem volume models with random coefficients for Pinus kesiya in Tanzania, Zambia and Zimbabwe. Canadian Journal of Forest Research 31: 879–888.

Eerikäinen, K., Mabvurira, D. & Saramäki, J. 1999. Alternative Taper Curve Estimation Methods for Eucalyptus cloeziana (F. Muell.). Southern African Forestry Journal 184: 12–24.

Erkkilä A. & Löfman S. 1999. Forest cover change in the Ohangwena Region, Northern Namibia: a case study based on multitemporal Landsat images and aerial photography. Southern African Forestry Journal. No. 184: 25–32.

Forss, E., Maltamo, M. & Saramäki, J. 1998. Static stand and tree characteristics models for Acacia mangium plantations. Journal of Tropical Forest Science 10: 318–336.

Haara, A., Maltamo, M. & Tokola, T. 1997. The k-nearest-neighbour Method for Estimating Basal-Area Diameter Distribution. Scandinavian Journal of Forest Research 12: 200–208.

Heikkilä, J., Nevalainen, S. & Tokola, T. In press. Estimating defoliation in boreal coniferous forests by combining Landsat TM, aerial photographs and field data. To appear in Forest Ecology and Management.

Heinonen, J., Saramäki, J. & Sekeli, P.M. 1996. A polynomial taper curve function for Zambian exotic tree plantations. Journal of Tropical Forest Science 8: 339–354.

Hyppänen, H. 1996. Spatial autocorrelation and optimal spatial resolution of optical remote sensing data in boreal forest environment. International Journal of Remote Sensing, 17: 3441–3452.

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Hyppänen, H., Pasanen, K. & Saramäki, J. 1996. Päätehakkuiden kuviorajojen päivitystarkkuus. Folia Forestalia – Metsätieteen aikakauskirja 4/1996: 321–335. (In Finnish).

Ihalainen, M., Alho, J., Kolehmainen, O. & Pukkala, T. 2000. Expert models for berry and cowberry yields in Finnish forests. Forest Ecology and Management 5413: 1–8.

Kangas, A., Kangas, J. & Pykäläinen, J. 2001. Outranking methods as tools in natural resources planning. To appear in Silva Fennica.

Kangas, A. & Maltamo, M. 2000a. Calibrating predicted diameter distribution with additional information. Forest Science 46: 390–396.

Kangas, A. & Maltamo, M. 2000b. Percentile based basal area diameter distribution models for Scots pine, Norway spruce and birch species. Silva Fennica 34: 371–380.

Kangas, A. & Maltamo, M. 2000c. Performance of percentile based diameter distribution prediction and weibull method in independent data sets. Silva Fennica 34: 381–398.

Kangas, J., Leskinen, P. & Pukkala, T. 2000. Integrating timber price scenario modelling with tactical management planning of private forestry at forest holding level. Silva Fennica 34: 399–409.

Kangas, J., Loikkanen, T., Pukkala, T. & Pykäläinen, J. 1996. A participatory approach to tactical forest planning. Acta Forestalia Fennica 251. 24 p.

Kangas, J. & Pukkala, T. 1996. Operationalization of biological diversity as a decision objective in tactical forest planning. Canadian Journal of Forest Research 26: 103–111.

Kangas, J. Pukkala, T. & Pykäläinen, J. 1996. Vuorovaikutteinen heuristinen optimointi yksityismetsien suunnittelussa. Folia Forestalia 3/1996: 231–244. (In Finnish).

Kangas, J., Pukkala, T. & Kangas, A. In press. HERO: Heuristic optimisation for multi-criteria forestry decision analysis. In: Schmoldt, D., Kangas, J., Mendoza, G. & Pesonen, M. (eds.). The AHP in natural resources and environmental decision making. Kluwer Acedemic Publishers.

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Löfman S. & Kouki, J. 2001. 50 years of landscape transformation in managed forests of Southern Finland. Scandinavian Journal of Forest Research 16: 44–53.

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Mabvurira, D. & Miina, J. In press a. Individual-tree growth and mortality models for Eucalyptus grandis (Hill) Maiden plantations in Zimbabwe. To appear in Forest Ecology and Management.

Mabvurira, D. & Miina, J. In press b. Simultaneous growth and yield models for Eucalyptus grandis (Hill) Maiden plantations in Zimbabwe. To appear in The Southern African Forestry Journal.

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Maltamo, M. & Uuttera, J. 1998. The angle-count sampling in description of forest stand structure. Forest and Landscape Research 1: 448–471.

Maltamo, M., Uuttera, J. & Kuusela, K. 1997. The variation of mineral soil forest stand structure by forest ownership groups in five forestry districts in southern Finland. Journal of Environmental Management 51: 145–167.

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Muinonen, E., Maltamo, M., Hyppänen, H. & Vainikainen, V. 2001. Forest stand characteristics estimation using a Most Similar Neighbor Approach and Image Spatial Structure. Remote Sensing of Environment 78: 223–228.

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Möykkynen, T., Miina, J. & Pukkala, T. 2000. Optimizing the management of a Picea abies stand under risk of butt rot. European Journal of Forest Pathology 30: 65–76.

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Pasanen, K., Vesterlin, V., Keskimölö A., Soimasuo, J. & Tokola, T. 1997. Alueellisten energiapuuvarojen analysointimenetelmä. Metsätieteen aikakausikirja – Folia Forestalia 1/1997: 25–35. (In Finnish).

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Pykäläinen, J., Kangas, J. & Loikkanen, T. 1999. Interactive Decision Analysis in Participatory Strategic Forest Planning: Experiences from State Owned Boreal Forests. Journal of Forest Economics 5(3): 341–364.

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tion of tree stand characteristics through computer visualisation. Landscape and Urban Planning 764: 1–10.

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Tokola, T. 2000. The influence of field sample data location on growing stock volume estimation in Landsat TM -based forest inventory in eastern Finland. Remote Sensing of Environment 74: 421–430.

Tokola T. & Heikkilä, J. 1997. A priori site quality information in satellite image based forest inventory. Silva Fennica 31: 67–78.

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Tokola T. & Shrestha S. M. 1999. Comparison of cluster-sampling techniques for forest inventory in southern Nepal. Forest Ecology and Management 116: 219–231.

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Uuttera, J. 1998. Impact of Management History on Forest Structure and Composition in Eastern and Central Finland. Ph.D. thesis summary. Annales Universitatis Turkuensis, Ser. A II, Tom. 106. 135 p.

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4.2 Other Scientific Publications

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Multisource Inventory Methods

Determination of Stand Parameters in Large-Scale Forest Inventories by Means of Airborne Laser Scanner

Erik Næsset

Agricultural University of Norway, Department of Forest Sciences
P.O. Box 5044, N-1432 Ås, Norway
e-mail: erik.naesset@isf.nlh.no

Abstract

A practical two-stage procedure for determination of stand parameters of entire forest stands by means of field plots and airborne laser scanner data has been developed and tested. In the first stage, geo-referenced field sample plots are related to the corresponding laser data, and relationships (regressions) between field data and various canopy height and canopy density metrics that can be derived from laser data are estimated. In the second stage, the entire forest area in question is divided into a regular grid with cell size equal to the size of the field sample plots. Stand parameters of each grid cell are predicted by means of the estimated regression models and the laser data that correspond to each cell. Stand parameters of entire stands are finally computed from the individual cell predictions.

The procedure has been tested in a forest area of 1000 ha. 173 systematically distributed sample plots in very young ($h < 10$ m) to mature forest were used to regress dominant height, mean height, mean diameter, stem number, basal area, and volume against the laser data. The derived models were used to predict corresponding parameters in 73 subjectively selected test stands. Verification of stand estimates revealed a negligible bias for most parameters. The precision was promising: the RMSEs of the predictions were 0.61–1.17 m, 0.57–1.33 m, 1.32–1.61 cm, 128–400 ha^{-1} (16.9–22.2%), 2.33–2.54 m^2 ha^{-1} (8.6–11.7%) and 18.3–31.9 m^3 ha^{-1} (11.4–14.2%) for mean height, dominant height, mean diameter, stem number per hectare, basal area, and volume, respectively (Næsset 2002, Næsset & Bjerknes 2001). The proposed procedure was applied in a practical stand-level inventory in an area of 6000 ha during summer 2001.

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Estimating Tree Stocks Using an Approach Combining Single Tree Recognition from Digital Video Image and a Diameter Distribution Model

Matti Maltamo[1], Timo Tokola[2] and Mikko Lehikoinen[3]

[1]University of Joensuu, Faculty of Forestry, P.O. Box 111, FIN-80101 Joensuu, Finland
[2]Soil & Water Ltd., Jaakonkatu 3, FIN-01620 Vantaa, Finland
[3]Oy Arboreal Ltd., Niskakatu 1, FIN-80100 Joensuu
e-mail: matti.maltamo@forest.joensuu.fi, timo.tokola@poyry.fi
and mikko.lehikoinen@arbonaut.com

1 Introduction

Traditionally, forest inventories have been carried out through intensive field work. Field inventory process is expensive and time-consuming, but it has been the only method for obtaining accurate data for small areas. The last two decades have seen an increase in the utilization of digital remote sensing in forest inventories (e.g. Poso et al. 1984, Tomppo 1993, Tokola et al. 1996, Trotter et al. 1997). Satellite images and digital aerial photographs have been used to reduce inventory costs or to achieve more accurate local results using additional information. Using satellite images, reliable estimates of forest characteristics can be obtained for areas larger than 50 to 150 ha (Tokola and Heikkilä 1997). Digital video images have also been utilized in assessments of natural resources (Pellikka 1998). Traditionally, high-resolution aerial photographs have been interpreted visually (e.g. Needham and Smith 1987), but this method is a rather slow inventory tool and quite sensitive to systematic errors. Recently, numerical interpretation of digital aerial photographs has become an alternative (e.g. Holopainen and Lukkarinen 1994). Digital aerial photographs have been used, for example, in forest habitat mapping and monitoring forest health (Franklin et al. 1995, Heikkilä 1998, Holopainen and Wang 1998).

The rapid development of computers and remote sensing has enabled semi-automated single tree crown delineation, which can be applied to almost all kinds of high-resolution remote-sensed data. The research in this field is very active and several promising results have been achieved (e.g. Gougeon 1995, Dralle and Rudemo 1996, Brandtberg 1997, Gougeon 1997, Brandtberg and Walter 1998, Uuttera et al. 1998, Hyyppä and Inkinen 1999, Korpela 2000, Pitkänen 2001).

The inventory using semi-automated image interpretation methods is cost-effective and it can be used for many purposes, especially when combined with some field measurements. These studies include the detection of individual damaged or dead trees, the recognition of tree species and the determination of stem number and spatial distribution of trees. According to Dralle and Rudemo (1996) the number of stems can be detected accurately in thinned stands but in unthinned dense stands considerable underestimates are obtained. After tree crown size has been detected and interpreted using pattern recognition techniques, it is possible to utilize linear correlation between crown and diameter at breast height

(Ilvessalo 1950) to estimate tree- and stand-level forest characteristics.

The most serious problem, considering the use of single tree pattern recognition methods, is that only dominant trees, which are visible from above, can be recognised. Suppressed trees will then be ignored, and this causes considerable underestimates for stand volume and especially number of stems estimates.

Diameter distribution models have been traditionally used in such forest inventory situations where tree diameters have not been measured (e.g. Kilkki et al. 1989). The prediction or recovery of parameters of some known probability density function is based on stand mean characteristics, which are expected to be known (e.g. Borders et al. 1987). The most often applied theoretical function is the Weibull distribution (Bailey and Dell 1973). One benefit of the Weibull function is that the cumulative distribution is also known. It is therefore easy to define the number of trees equal to or smaller than a certain diameter (Bailey and Dell 1973, Kilkki et al. 1989).

The aim of this study is to demonstrate the combined use of pattern recognition of single trees from digital video imagery and the theoretical diameter distribution to predict forest characteristics.

Big trees ($d_{1.3} > 17$ cm) are estimated from optimized digital video imagery using pattern recognition to detect tree crowns and predict tree diameters. The theoretical Weibull diameter distribution is applied to calculate the amount and tree characteristics of small trees ($d_{1.3} < 17$ cm). The results presented in this paper are based on the original studies of Lehikoinen (1999) and Maltamo et al. (in press).

2 Material and Methods

The study area is located in eastern Finland, in the municipality of Ilomantsi, near the research station of the University of Joensuu. The field material used in connection with the video imagery was based on circular sample plots in 13 stands. The sample plots were identified from a digital image mosaic. The airborne video image data were taken on 19 August 1997 in Ilomantsi, Finland, by Enso Forest Development Ltd.

The data processing can be divided into three different steps:

1) Processing the video image
2) Preparing the tree and stand model based on field information
3) Combining models and actual video image measurements.

Video image processing includes image material improvement with super-resolution techniques (Beauchemin and Barron 1995) and crown pattern recognition (Fig. 1). The input for the process is a high-resolution digital image, which has to be rectified. After rectification every single stand or sample plot has to be separated manually or automatically into individual images, which can then be used as input for the segmentation algorithm.

The processing of the super-resolution image consists of five main steps:

1) Forming the input image sequence (2-n images) and selecting the base image
2) Finding iteratively the optical flow between the base image and the other input images
3) Calculating the synthetic video sequence
4) Comparing the original and synthetic video sequence (minimization problem)
5) Optimizing the super-resolution image from the sequence (minimization problem).

The optimization algorithm by Saastamoinen (1997) was applied. The resolution can be significantly improved with super-resolution techniques (Fig 2).

The image interpretation process has four main steps:

1) Pre-filtering the base image
2) Extracting the seed point
3) Determining the segmentation algorithm based on region growth
4) Calculating statistics for individual segments and for the sample plot.

The segmentation method used is very flexible, quick and easy to use. The segmentation is controlled by the user. There are four parameters, which have to be adjusted for each input image separately:

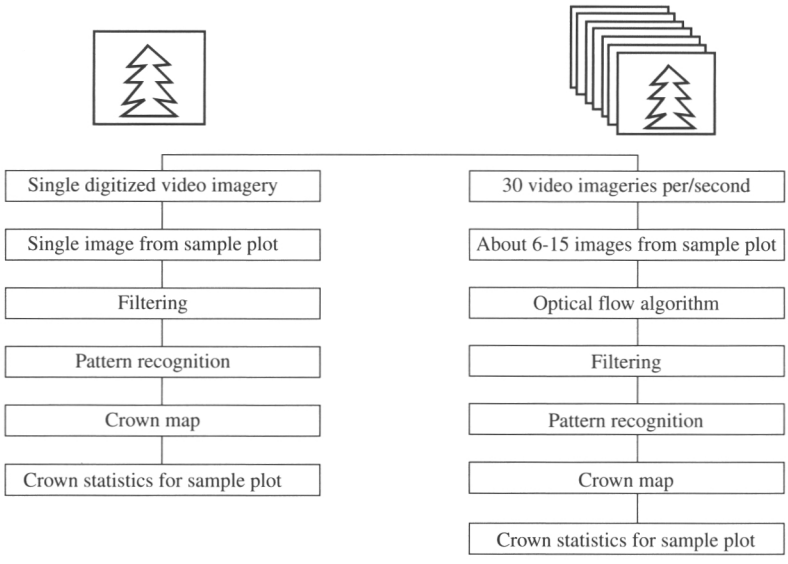


Fig. 1. The main steps of image processing of the study. Left work flow shows the traditional method in image interpretation and right one the method which was applied in this study.

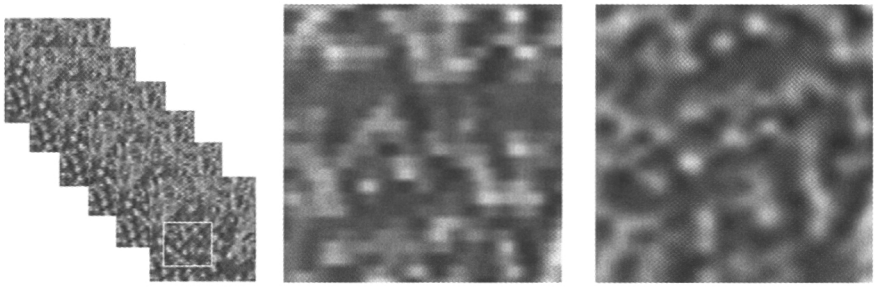


Fig. 2. The original false colour video image sequence on the right, enlarged video frame from the sample plot on the middle and the super-resolution image on the right.

1. *Cut Ratio* defines the relative (%) intensity at each seed point (local maximum point)
2. *Difference Value* defines a constraint which allows the derivative to be positive locally and how much increase there can be between neighboring pixels
3. *Mask size* defines the size of the operator window for the Gaussian filter
4. *Seed Threshold* parameter defines the minimum tone value for seed points in each channel

The parameters of the segmentation algorithm depend on the resolution of the image and the size of the dominant trees in the image. The values for the parameters were found experimentally first for the whole material and then separately for each stand. The algorithm first identifies a large amount of initial tree locations and then starts to recognize the tree crown area. Final verification of the interpretation procedure was done using the estimation of stand characteristics as the criteria.

The estimation of the stand characteristics for a single stand is based on the measurement of the area of individual tree crowns, from which the required stand characteristics can then be derived. A simple linear regression model was used to predict tree diameter at breast height using measured crown area as the independent variable. All tree species were combined into one model,

because automated tree species classification was not available. Tree heights were calculated using Näslund's (1936) height curve and tree volumes were calculated using the treewise models presented by Laasasenaho (1982).

The diameter distribution model used was the two-parameter approach of the Weibull distribution. The mean characteristics information needed for predicting the parameters of Weibull distribution was obtained from the resulting distribution of trees recognized from digital video imagery. The used truncation point of the distributions was 17 cm. The value of the cumulative distribution function of Weibull was solved using 17 cm as a random variable. After that the total number of stems per hectare was calculated using information about the share of small trees and the estimated number of large trees obtained from digitized video imagery. The basal area and volume of small trees were calculated using artificial tree diameters obtained from the Weibull distribution in 1 cm classes. The principle of combining information sources is presented in Fig. 3.

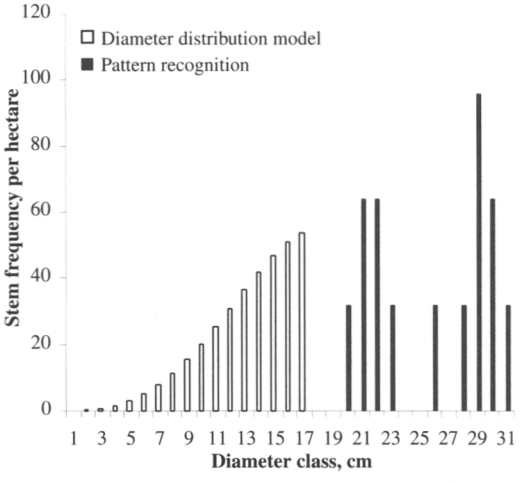


Fig. 3. The principle of combining tree stocks obtained from pattern recognition and theoretical diameter distribution model.

The criteria used in the comparison of the accuracy of predicted stand characteristics were RMSE (root mean square error) and bias. The corresponding relative values were obtained by dividing the absolute value by the average of the estimate.

3 Results and Discussion

The results for the prediction of stand variables such as number of stems, stand basal area and volume are presented in Table 1. The results are shown both for the method based on pattern recognition only and for the combined approach using the segmentation parameters optimized for each stand separately. The results are presented for all stands and separately for middle-aged and mature stands.

The use of the theoretical diameter distribution

Table 1. Results of the prediction of stand variables pattern recognition based on stand-level optimized segmentation parameters and the diameter distribution model.

Information source	Whole data (n = 13)			Middle aged and mature stands (n = 9)		
	Number of stems	Basal area, m^2ha^{-1}	Stand volume, m^2ha^{-1}	Number of stems	Basal area, m^2ha^{-1}	Stand volume, m^2ha^{-1}
Pattern recognition						
RMSE	663.45	3.64	41.26	287.45	3.39	42.45
RMSE %	176.62	18.76	25.2	79.81	17.17	25.23
Bias	489.76	2.32	10.68	230.04	2.48	26.52
Combined pattern recognition and diameter distribution model						
RMSE	411.33	4.71	52.26	182.07	3.60	39.31
RMSE %	54.70	19.60	27.24	25.95	15.15	20.41
Bias	113.48	–2.32	–17.42	–111.35	–1.57	2.15

improves the results considerably. Only exceptions are stand basal area and volume in the whole study material. Especially, in the case of the number of stems the accuracy was improved considerably by 120–130 %-units. In the case of basal area and stand volume the improvement achieved using the diameter distribution models usually varied from 15 to 30 %-units. Underestimates were produced in most cases.

The material of this study was quite modest. Therefore the results should be considered as preliminary and only locally reliable. These results indicate that the accuracy of stand characteristics, especially number of stems, can be improved considerably using the combined method presented. However, the main goal of this study was to demonstrate the principle of the presented method.

The pattern recognition method developed in this study is useful especially in mature stands. Difficulties are expected in dense young stands or in groups of trees, where single trees cannot be identified. In dense parts the crown area is usually underestimated, because trees grow partly interlocked, and in such cases the segmented crown areas should be corrected, for example, with the calibration model. It is also obvious that only crowns in the top layer can be detected and the smaller trees underneath remain invisible. It was also observed that the closer the sample plot was situated to the nadir point, the more successful the super-resolution optimization was.

The combined method presented improved results in 10 stands out of 13. In the remaining stands the theoretical distribution was useless. It seems that in stands where the number of stems is quite low the accuracy of pattern recognition is good. However, more research should be carried out to find out if such stands could be classified beforehand. For example, structural characteristics such as variograms of the remote sensing material could be utilized (Hyppänen 1996).

At present, most Finnish forest planning systems are based on compartment inventory. Aerial photographs are used only in the preliminary delineation of compartments. As a result of fieldwork, mean stand characteristics, usually median diameter, basal area and age of the tree stock, are assessed specieswise. Stand volume is then derived using diameter distribution models, and treewise height and volume models (Kilkki et al. 1989, Veltheim 1987, Laasasenaho 1982). The accuracy of this approach has been examined in several studies and the obtained RMSE values of stand volume have varied from 16 to 45 % (Poso 1983, Poso et al. 1987, Pussinen 1992, Ståhl 1992, Tokola and Heikkilä 1997, Hyyppä 1997). Compared to the results of this study it can be said that the methodology presented here could be comparable in certain situations, e.g. in mature stands. Due to the lack of an expensive fieldwork phase the costs of this approach are considerably smaller. On the other hand, the variation in the properties of remote sensing material requires special attention. Furthermore, the methods can not be applied for seedling or sapling stands.

With improved remote sensing material and pattern recognition methods, tree species can most probably be separated and diameter distribution and tree models for each species can be constructed. Instead of using digital video imagery also materials such as digital aerial photographs or laser scanning data could be applied. Correspondingly, the diameter distribution modeling can be based e.g. on non-parametric methods (e.g. Maltamo and Kangas 1998). A usable truncation point parameter needs to be estimated for each type of remote sensing material separately. If material and interpretation techniques become more reliable, the truncation point diameter will decrease and we can rely more on image interpretation based estimates.

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Image Segmentation in the Estimation of Timber Volume at Sample Plot Level

Anssi Pekkarinen

Finnish Forest Research Institute
Unioninkatu 40 A, FIN-00170 Helsinki, Finland
e-mail: anssi.pekkarinen@metla.fi

1 Introduction

Remote sensing is an interesting source of information for forest inventory and monitoring purposes. Therefore the applicability of satellite images, such as Landsat TM, to different forest inventoring and monitoring tasks, has been widely studied (e.g. Häme 1991, Tokola et al. 1996, Tomppo 1996, Tokola and Heikkilä 1997, Trotter et al. 1997, Häme et al. 1998, Tomppo et al. 1999). Although some of the presented applications have proven to be useful for large area inventory and monitoring purposes, doubts have been presented concerning the applicability of satellite image based approaches to the forest management planning in general (Holmgren and Thuresson 1998). These doubts are supported by the fact that the sample-plot level estimation errors of the multi-source inventory approaches have generally been quite high (Tokola et al. 1996, Katila and Tomppo 2001, Mäkelä and Pekkarinen 2001).

One reason for the unsatisfactory stand- and plot-level results may have been the limited spatial resolution of the image material. The spatial resolution has, however, rapidly improved and very high spatial resolution (VHR) images, such as digital and digitised aerial photographs and imaging spectrometer and VHR satellite images, are nowadays increasingly available. Unfortunately, the pixel-based feature extraction and traditional pixel-by-pixel image analysis methods are not applicable to VHR image material. This is due to the fact, that a pixel of VHR image does not necessarily represent the object of interest (stand, tree) but may cover only a small part of it. Therefore, special attention has to be paid to the feature extraction and determination of image analysis units.

From the viewpoint of an operational multi-source forest inventory system, the feature extraction process should be simple and efficient, and the extracted features should describe the forestry content of the training area as well as possible. Two alternatives for feature extraction have been usually considered in applications employing satellite images and field data gathered from sample plots: features have been extracted from a single pixel on which the plot is located, or from its local neighbourhood. In applications employing VHR image material the choice is obvious; in order to extract features which describe the area of a sample plot and/or its surroundings some kind of local neighbourhood has to be applied.

The simplest approach to the local feature extraction is to use features from square-shaped windows surrounding the field plots. This kind of approach is efficient, but it has a drawback, which is more serious the larger the extracting window is: the window may intersect several stands having different spectral and forest characteristics. Therefore the extracted features may not describe the properties of the plot on which the centre of the extracting window was located.

One possible solution to this problem is to apply image segment based approach. In an ideal case,

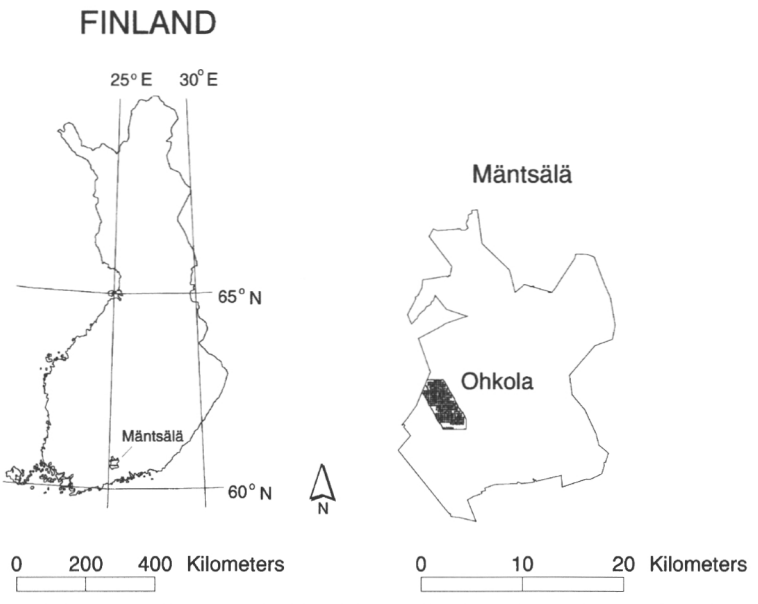


Fig. 1. Location of the municipality of Mäntsälä within the borders of Finland and the location of the Ohkola test area within the borders of Mäntsälä.

image segmentation succeeds in delineation of stands and thus the within segment forest characteristics are homogeneous. In that case, the spectral characteristics of a stand could be extracted by segments, and directly employed in the image analysis. In practice, the within stand variation of forest characteristics may be large and information gathered from sample plots is not necessarily representative at the stand (or segment) level. Therefore, if plot-based data is applied, the extraction of spectral features has to be restricted to the immediate neighbourhood of the plots.

This paper presents an experiment, which combines features of local and segment based feature extraction approaches. The employed spectral features were extracted from the spectrally homogeneous parts of the local windows and applied in the estimation of the timber volume at the plot level. The performance of the spectral features extracted by this method was compared to the results achieved with local window-based features.

2 Material

2.1 Field Data

This study was carried out using the previously established test area of Ohkola in the municipality of Mäntsälä, Southern Finland (Fig. 1). The test area was originally established for imaging spectrometer studies by the National Forest Inventory (NFI) team of the Finnish Forest Research Institute (FFRI) (Mäkisara et al. 1997).

A systematic grid of 254 field plots covered the test area. The distance between the plots was 250 m in both north-south and east-west directions. Locations of the plots were determined using a compass and measuring tape. Both circular sample plots with a fixed radius of 12.52 metres and relascope sample plots having a maximum radius of 12.52 metres were applied. Every seventh tallied tree of the relascope plots was measured as a sample tree that was measured in a more detailed way. All measurements were carried out from July to September 1996.

The volumes of sample trees were determined applying volume functions (Laasasenaho 1982)

Table 1. Timber volume characteristics of the input data set, m^3/ha.

Species	Mean	Std	Min	Max
Pine	28.5	44.7	0	220.2
Spruce	70.3	99.5	0	397.6
Deciduous	16.6	25.2	0	142.7
Total	115.3	103.3	0	408.8

and generalised to the tallied trees with help of diameter at breast height ($d_{1.3}$), upper diameter ($d_{6.0}$) and some stand characteristics (Tomppo et al. 1998). Here, trees measured from circular sample plot were employed and the stand's volume per area unit (V, m^3/ha) was determined employing the total volume of the trees and the area of the plot. If the plot intersected several stands the volumes of trees of each stand were summed and divided by the area of the plot belonging to that particular stand. Subplots having a proportional area smaller than 0.5 were removed from the material because their volume estimates were considered unreliable. The characteristics of this data set are given in Table 1, and a more detailed description of the field data has been given by Mäkisara et al. (1997).

The locations of the field plots were matched to the geo-referenced image data by displaying each plot on the AISA image and checking its location on the screen. The ground-truth information of the plot (or subplot) was assigned to an artificial plot, which was established clearly inside the stand if the plot (or subplot) was located near the stand border (Mäkisara et al. 1997).

2.2 Image Data

An imaging spectrometer (AISA) image of the test area was acquired on June 23, 1996. The image mosaic covering the study area consists of data from seven flight lines and 30 spectral channels. The size of the subset image used in this study was 3500 × 3750 pixels and the pixel size was 1.6 × 1.6 m^2. The image data was radiometrically and geometrically corrected by the NFI team of the FFRI.

In order to reduce the computation time needed for the image processing steps the number of the spectral channels was reduced from 30 to 3 by means of generalisation. The original channels employed in the generalisation were selected so, that the wavelength areas of the resulting bands would correspond as well as possible to the bands of new generation VHR satellite images. The generalised pixel values were computed using the original pixel value and the width of the employed channels as:

$$p_i = \frac{\sum \lambda_j p_j}{\sum \lambda_j}$$

where

p_i = resulting pixel value of channel i,

p_j = pixel value of the original channel j, and

λ_j = bandwidth of original channel j.

Finally, the pixel values of the generalised image were linearly scaled to the range from 0 to 255 using global minimum and maximum values of the generalised channels. The original spectral configuration of the AISA channels and the channels employed in the generalisation are presented in Table 2 and an example of the generalised image in Fig. 2.

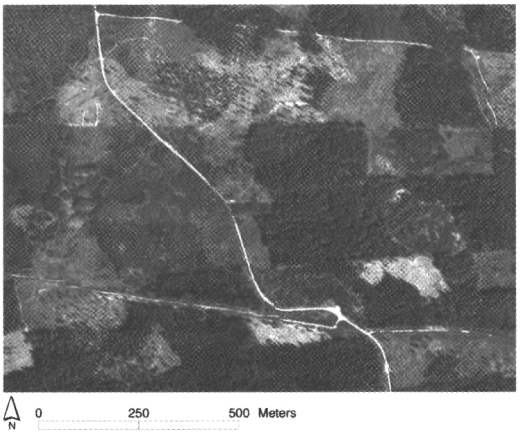


Fig. 2. An example of generalised AISA data. Channel 3 (Red).

Table 2. The original spectral channel (Ch_o) configuration of AISA and the channels applied in the generation of new (Ch_g) blue (R), green (G), red (R) and near-infrared (NIR) channels.

Ch_n	Ch_o	Centre, nm	Width, Nm	Ch_n	Ch_o	Centre, nm	Width, nm
B	1	470.1	7.3		16	701.4	4.6
B	2	487.6	7.3		17	710.5	4.6
B	3	505.1	7.3		18	725.7	7.6
G	4	522.6	7.3		19	733.3	4.6
G	5	541.5	7.3		20	742.4	4.6
G	6	550.2	7.3		21	750.0	4.6
G	7	564.8	7.3	NIR	22	775.8	4.6
G	8	579.4	7.3	NIR	23	784.9	4.6
G	9	599.8	7.3	NIR	24	794.1	4.6
	10	623.1	7.3	NIR	25	803.2	4.6
R	11	646.7	7.6	NIR	26	818.4	4.6
R	12	668.0	7.6	NIR	27	844.2	4.6
R	13	675.6	7.6	NIR	28	853.3	4.6
R	14	686.2	4.6	NIR	29	860.9	4.6
	15	696.8	4.6	NIR	30	865.4	4.6

3 Methods

3.1 Image Segmentation and Feature Extraction

A two-phase segmentation approach was applied to the generalised image. First, initial segments were created by a method based on ideas of Narendra and Goldberg (1980) (INISEG) and after that, the final segments were composed applying a t-ratio based region merging (REGMERG) algorithm (Hagner 1990).

The original idea of the "Segmentation with directed trees" was to detect regions without using absolute thresholds (Narendra and Goldberg 1980). First step of the suggested implementation was the use of local edge and gradient operators in the detection of edge and plateau pixels of the image. After that, all edge pixels were processed and linked to the direction of the smallest edge gradient. If such a direction did not exist, the edge pixel was assigned as a root. After the processing of the edge pixels, plateau elements were arbitrarily linked to the pixels of the same plateau. The links were tracked and the formation of directed cycles was prohibited. If an allowed neighbouring pixel was not found, the plateau pixel was labelled as a root pixel. Finally, all the root pixels were given unique labels and the pixels of each directed tree were given the label of the root pixel of that tree (Narendra and Goldberg 1980).

The beginning of INISEG was somewhat similar to the implementation presented

by Narendra and Goldberg (1980). After filtering of irrelevant details by applying Gaussian filter to the generalised image the INISEG started by dividing an image to edge and plateau pixels using edge (e) and edge magnitude (M) operators and a threshold value (T). Edge value (e) was defined for each image pixel (i,j) employing its neighbouring pixels $N(i,j)$ and the original gray value $g(i,j)$ (Equation 1). The resulting image was used as an input to the magnitude operator (Equation 2) and pixels having $M(i,j)$ larger or equal to threshold T were defined as edge pixels and the rest of the pixels as plateau ones.

$$e(i,j) = \sum_{n=1}^{nbr} \sum_{k,l \in N_8(i,j)} \left| g_n(i,j) - g_n(k,l) \right| \quad (1)$$

$$M(i,j) = \max_{(k,l) \in N_8(i,j)} \left[e(i,j) - e(k,l) \right] \quad (2)$$

where

nbr = the number of channels and

N_8 = neighbourhood of pixel i,j.

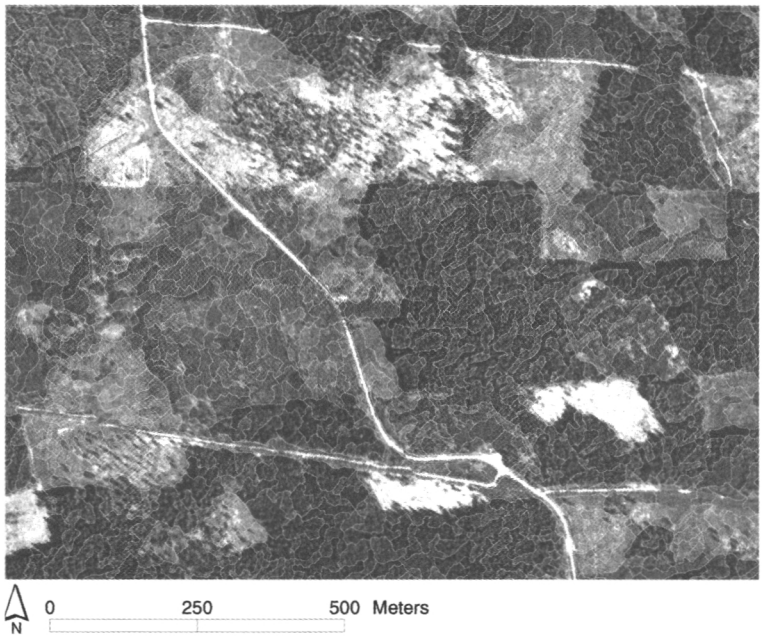


Fig. 3. An example of the borders of final segments.

The next step of the INISEG was the actual image segmentation. It was carried out with help of three sequential passes over the image. During the first pass, all edge pixels were considered. Edge pixels having $G(i,j) < 0$ were marked as plateau pixels and the rest of edge pixels were linked to the direction of the smallest edge magnitude.

During the last two passes, all the connected plateau components were assigned unique labels using a sequential connected component labelling (CCL) algorithm (Jain et al. 1995). The segment labels for edge pixels were found following the links to the direction of the smallest edge magnitude.

Because the INISEG tends to create relatively small sub-stand segments especially when VHR material is employed, the result needs to be further processed in order to achieve reasonable feature extraction units. Here, an implementation of a region merging algorithm (REGMERG) somewhat similar to the one presented by Hagner (1990) was applied. The algorithm searched for segments smaller than a specified minimum size (300 pixels) and combined them to the most similar neighbouring segment. In addition, if two spectrally similar neighbouring segments were observed, they were combined. The REGMERG was controlled by three parameters: minimum and maximum segment size and a similarity threshold. The similarity of two segments was measured by means of the t-ratio (Equation 3). An example of the result of the segmentation is shown in Fig. 3.

$$t\text{-ratio} = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{3}$$

where

$\bar{x}_i$ = the mean intensity of segment i,
s^2_i = the variance of segment i, and
n_i = the number of pixels in the segment i.

Two methods were tested for the feature extraction. In the first one, the average and standard deviation of spectral values were extracted from a square shaped window surrounding the plot pixel. This feature set is referred as window features (WF). In the second method, the average and standard deviation of values of those pixels within the window that belonged to the same segment as the plot pixel, were extracted (SF). Two different window sizes, 15 × 15 and 31 × 31 pixels, were applied. The selection of the window sizes was

based on the applied plot size so that the smaller window size is approximately of the size of the plot and the size of the larger window was about 4 times as large as the plot.

3.2 Feature selection and evaluation

An algorithm based on stepwise forward selection was applied in order to find out the best spectral features for the estimation. The algorithm started by selecting the feature giving the lowest RMSE (Equation 4) and proceeded by adding the feature that gave the best performance with the already selected features. The procedure was repeated until five best features were found, and the RMSE of the last iteration was recorded. The procedure allowed each of the original features to be selected once or more.

The RMSE was determined during each feature selection step by means of cross-validation technique and a non-parametric k nearest neighbour estimator ($k$nn) (Tomppo 1996, Tokola et al. 1996, Trotter et al. 1997, Tomppo et al 1999). The estimates for each plot were determined as a weighted mean of k spectrally nearest neighbours found among the rest of the plots. These neighbours were determined using the Euclidean distance in the feature space. Each of the k nearest neighbours was proportionally weighted by inverse squared Euclidean distance (Equation 5). The weight was applied in order to decrease the bias of the $k$nn-estimator (Altman 1992). The number of the applied nearest neighbours was set to five based on the earlier observation that the decrease of the RMSE starts to slow down when $k > 5$ (e.g. Pekkarinen, 2001).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y})^2}{n}} \quad (4)$$

$$\hat{y} = \sum_{i=1}^{k} \frac{1}{d_i^2} y_i \Big/ \sum_{i=1}^{k} \frac{1}{d_i^2} \quad (5)$$

where

y_i = observed value of certain forest parameter,

$\hat{y}$ = $k$nn estimate of y,

n = number of observations, and

d_i = Euclidean distance to the i'th nearest neighbour.

Table 3. Results of the estimation tests employing segment (SF) and window (WF) based features. Window size of 15 × 15 pixels.

	RMSE			
	SF		WF	
Species	m³	%	m³	%
Total	70.98	61.6	**65.30**	**56.6**
Pine	**41.84**	**146.8**	43.02	150.9
Spruce	**68.44**	**97.4**	69.29	98.6
Broadleaved	22.29	134.2	**20.27**	**122.1**

Table 4. Results of the estimation tests employing segment (SF) and window (WF) based features. Window size of 30 × 30 pixels.

	RMSE			
	SF		WF	
Species	m³	%	m³	%
Total	**69.06**	**59.9**	69.87	60.6
Pine	**41.76**	**146.5**	**41.76**	**146.5**
Spruce	**73.71**	**104.9**	77.08	109.6
Broadleaved	22.08	133.0	**19.35**	**116.6**

4 Results and Discussion

The study revealed that the difference between the performance of segment- and window-based features is very small. The window-based features (WF) gave smaller relative RMSE for estimates of total volume and volume of broad-leaved trees, if the smaller window size was applied. Even though enlarging the extracting window improved the performance of the segment-based features (SF) the best overall relative RMSEs of total volume and the volume of spruce were observed with WF employing 15 × 15 pixels window. The results are presented in Tables 3 and 4.

The results of this study are quite similar to those observed with Landsat TM image material and somewhat similar estimation methods. Tokola et al. (1996) reported relative standard error from 66.3 to 68.2% for total volume. The estimation errors of the individual species were larger than 100%. Mäkelä and Pekkarinen (2001) applied segment based local features and reported errors of about 80% for total volume and errors larger than 100% for individual species. In a recent study, Tuominen and Poso (2001) reported

errors from 58.3% to 67% for the estimate of total volume in a study applying different kinds of auxiliary data sources including also digitised aerial ortophotos, which can be considered as VHR material.

The most interesting comparison can be made between the results of this study and the one reported by Mäkisara et al. (1997), because both of the studies employ practically same field data and estimator. In addition, both of the studies employ AISA data using segment restricted local feature extraction. The difference between the approaches is that in Mäkisara et al. (1997) the segments were derived manually.

This study supports the earlier conclusion that AISA features perform better than TM features (Mäkisara et al. 1997). The difference between the performance is clear (15% to 20%) in accuracy of the estimate of total volume but less evident elsewhere. In fact, in the case of pine, TM features performed better than AISA features employed in this study (see Mäkisara et al. 1997).

From the viewpoint of automated image segmentation, the results are encouraging. The applied segmentation method is capable of delineating sensible feature extraction and image analysis units. This is supported by the fact, that the performance between the segment-based features and similar features extracted from manually delineated segments applied in Mäkisara et al. (1997) is comparable. The fact that the results of this study are generally slightly worse is most probably due to the fact that some of the original AISA channels were not applied in the generalisation process. It seems that the wavelength area from about 700 nm to 750 nm includes useful information that should be included in the analysis.

In general, this study supports the observation that the plot-level estimation errors of multisource inventory approaches remain high even in applications employing VHR image material. Image segmentation does, however, provide a useful tool for the determination of units for feature extraction and image analysis. Considering the fact that the earlier studies include variety of estimation techniques and image data sources, I argue that the general reason for poor plot-level results is due to one or both of the following reasons:

A) the features applied in the estimation do not describe the forest characteristics of estimation units, or

B) neither circular nor relascope sample-plots are optimal data collection units for image analysis.

Therefore, studies concentrating on these issues are needed.

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Allocation of Field Sample by Means of Aerial Photographs and Image Segmentation

Anssi Pekkarinen and Sakari Tuominen

Finnish Forest Research Institute
Unioninkatu 40 A, FIN-00170 Helsinki, Finland
e-mail: anssi.pekkarinen@metla.fi and sakari.tuominen@metla.fi

1 Introduction

In Finland, the data for forest management planning has been traditionally gathered by stand-level field inventories using visual assessment. From the viewpoint of forest inventory and monitoring, this kind of method has two major drawbacks. First, the delineation of the stands is subjective and the delineations carried out by different interpreters are seldom similar. Second, the stand borders tend to change during the planning period due to management operations and natural disturbances, which makes the compartments unsuitable for monitoring.

As an alternative to the stand-level assessment, a two-phase plot sampling method has been suggested (Holmgren & Thuresson 1995, Poso & Waite 1996). The method is based on the idea of establishing a dense systematic grid of first phase sample plots (1pp) to the area of interest. These plots are assigned remote sensing or other auxiliary information, and stratified to homogeneous strata. The second phase sampling is done within these strata based on, for example, the size of the strata, and second phase plots (2pp) are measured in the field. Finally the gathered information is generalised to the 1pp using an appropriate estimator like the mean vector (within strata) or the k-nearest-neighbour (k-nn) method. The optimal grid density of 1pp depends on the forest stand-class and applied auxiliary data. As a general recommendation, a grid density of 20 $\times$ 20 m^2 has been suggested for studies aiming to forest stratification with help of aerial ortophotos (Holopainen & Wang 1998).

Even though the sample plot-based approach may serve forest monitoring purposes well, it has some drawbacks when the allocation of the field sample is considered. For example, in applications employing aerial photographs or very high spatial resolution (VHR) images in general, the suggested grid density is sparse in relation to the spatial resolution of the image material. Considering the fact that a single pixel of a VHR image does not represent the spectral properties of a stand, it is obvious that the spectral information of the first phase sample plots has to be generalised from the local neighbourhood of a sample plot. In practice, the average of the pixel values within a window surrounding each plot has been used (Holopainen & Wang 1998). The problem in that kind of an approach is that the spectral and informational contents of the extracting window may be heterogeneous. This is the case especially near the edges between stands, and stands and other land-use classes. Thus, the stratification of 1pp using these spectral features may assign 1pp observations of different informational classes to the same stratum. This can be avoided at least to some extent if a more sophisticated feature extraction method is applied.

This study suggests an image segment based approach as a solution to the allocation problem. Instead of plot-based feature extraction we determine homogeneous image segments and apply their spectral content in the stratification. Our

study hypothesis is that the spectral content and forest characteristics within the strata derived from segment-based features are more homogeneous than in the strata derived from sample plot-based features. The hypothesis was tested by creating two alternative feature sets based on plot-based and segment based approaches. Based on these features the image data was stratified in to spectrally homogeneous strata and the within-strata variability of forest characteristics was examined.

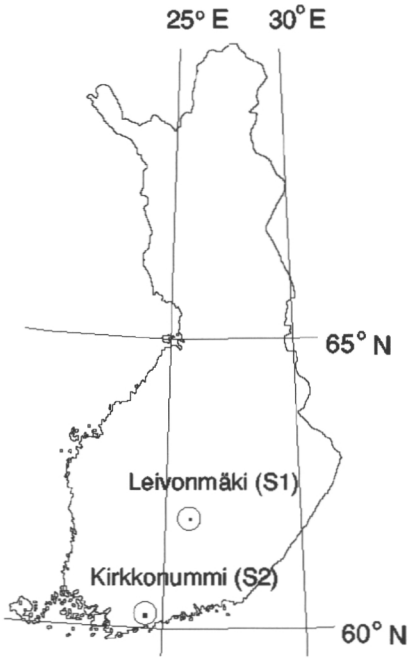


Fig. 1. Location of the study areas.

2 Material

The study was carried out in two separate areas in Southern Finland (Fig. 1). Study area 1 (S1) was located in the municipality of Leivonmäki. Its forest area covers about 1800 ha and it is entirely state owned and managed by the Finnish Forest and Park Service (Metsähallitus). Study area 2 (S2) is located in the municipality of Kirkkonummi. Its forest area covers about 1000 ha and it consists mainly of small-scale forest holdings in private ownership.

The main forest characteristics of the study areas are presented in Table 1. The mean volume of S1 was significantly smaller than the mean volume of S2. In addition, the forests of S1 were dominated by pine whereas the dominating species was spruce in S2.

Both study areas were covered by ortho-rectified colour-infrared aerial photographs. The images from the S1 were acquired on July 1999 and the images from the S2 on June 1998. The original negatives of the images were scanned using red, green and blue filters and an image mosaic was composed for both areas. The spatial resolution of both mosaics was 0.5 meters.

Even though the spectral channels of image mosaics had quite similar mean values the spectral variation in S1 was significantly larger especially in blue and green bands (Table 2). An example of the image material is presented in Fig. 2.

Field data of earlier studies was available from both study areas. In S1, 388 field sample plots were measured during the summer of 1999;

Table 1. Main forest characteristics of the study areas S1 and S2

	Mean values					
	Volume, m^3/ha				BA, m^2	Height, m
Area	Total	Pine	Spruce	Broadl.		
S1	93.8	43.2	34.0	16.6	12.7	10.7
S2	157	50.2	68.1	38.6	17.0	19.3
	Standard deviations					
	Volume, m^3/ha				BA, m^2	Height, m
Area	Total	Pine	Spruce	Broadl.		
S1	100.5	61.0	71.9	34.3	10.6	7.8
S2	106.4	62.5	92.5	52.0	9.8	6.6

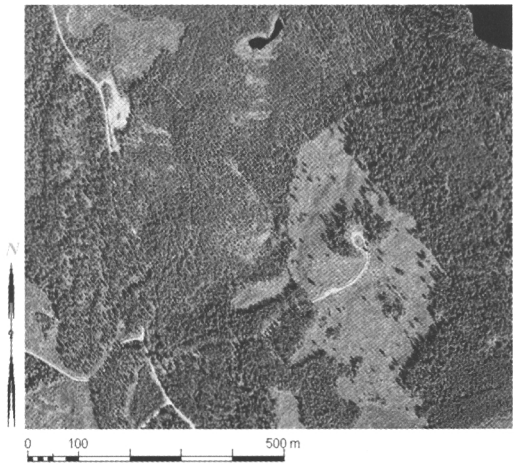


Fig. 2. An example of the image material of S1.

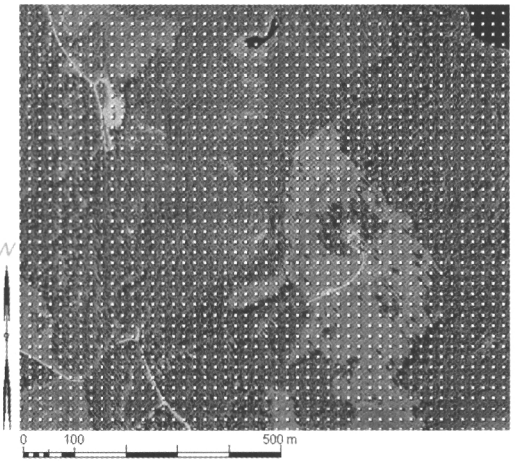


Fig. 3. The grid of first phase sample plots.

Table 2. Image properties

	S1		S2	
BAND	Mean	Std	Mean	Std
Blue	64.3	32.6	66.2	28.5
Green	97.2	38.5	97.7	26.0
Red	93.3	42.3	86.1	39.9

194 plots had been measured as circular field sample plots with variable radii and 194 plots as relascope sample plots (factor 1). In S2 the field data consisted of 233 relascope field sample plots (factor 1), measured during the summer 2000. The sample plots were located in the field using compass, distance measurement and a hardcopy of the digitized image mosaic, on which the plot centre points were plotted.

3 Feature Extraction and Stratification

Two different feature sets, F1 and F2, were derived for the stratification of both study areas. For extraction of F1, systematic grids of sample plots (1pp) were generated for S1 and S2. The distance between centres of 1pp was 20 m in both north-south and east- west directions, and the spectral features were extracted for each plot as an average and standard deviation of pixels within 20 m × 20 m (40 × 40 pixels) window surrounding it. An example of the 1pp grid is presented in Fig. 3.

Prior to the extraction of F2 the original image material was pre-processed and segmented. First, the image was re-sampled to the pixel size of 1.5 m and after that a Gaussian filter was applied to the re-sampled image. The size of the smoothing window was 3 × 3 pixels and 15 sequential smoothing passes over the image were applied. The initial segmentation of the pre-processed image was carried out with help of a modified implementation of the "Segmentation with directed trees" -algorithm (Narendra & Goldberg 1980). The algorithm tends to produce a large number of small segments when VHR material is applied and therefore the result of the initial segmentation was further processed by means of a region-merging algorithm. The applied algorithm searched segments smaller than a user-defined minimum size and merged them to the spectrally most similar adjacent segment. The spectral similarity of the segments was measured by means of the t-ratio between them (equation 1, Hagner 1990).

$$t\text{-ratio} = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (1)$$

where

$\bar{x}_i$ = the mean intensity of segment i,
s^2_i = the variance of segment i, and
n_i = the number of pixels in segment i.

The applied minimum segment size was 300 pixels (675 m^2). Finally the spectral averages and standard deviations of the final segments were extracted to F2. An example of the final segments is shown in Fig. 4.

F1 and F2 of both study areas were stratified into 40 strata on the basis of the extracted spectral features. The stratification was carried out using the k-means clustering algorithm (MacQueen 1967). The algorithm was carried out in the following phases. First, the initial cluster centres were selected as the set of observations that maximise the distance between the cluster centres. In the second phase each observation of the feature set was assigned to the spectrally nearest cluster centre. After that, the centroid vector of each cluster was recalculated as a mean vector of the observations assigned to that cluster. The process was iterated until the cluster centres remained unchanged.

After the clustering each field sample plot of S1 and S2 was allocated to the strata. In the sample plot based approach each plot was assigned spectral information from its local neighbourhood and the allocation was carried out in the way that each field plot was assigned to the spectrally nearest stratum. Euclidean distance measure was applied. In segment based approach, the field plots were assigned to the strata of the segment on which the plot was located. After the allocation, the within strata standard deviations of the stand parameters were examined. The strata having zero or single field observations (and therefore zero standard deviations) were excluded from further analysis, because their standard deviation had no meaningful content for the analysis. Otherwise weighted mean standard deviations were applied for each data set. In other words, when calculating the overall mean standard deviation, the contribution of each stratum was weighted by the area of the stratum. In addition to the overall mean standard deviations, the distributions of pixel values of red, green and blue channels of F1 and F2 were examined in both study areas.

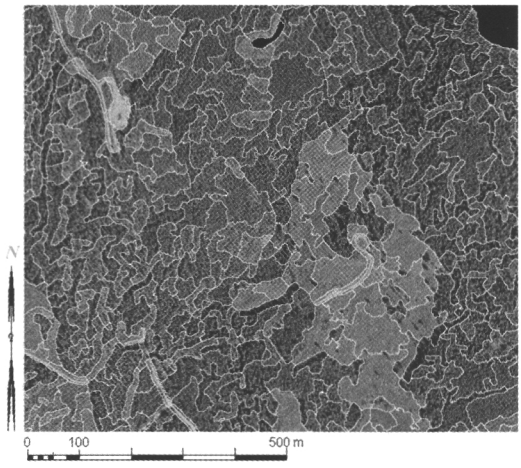


Fig. 4. An example of the result of the segmentation of the image material.

4 Results and Conclusions

There were small differences in the spectral characteristics of F1 and F2 in both of the areas. These differences support our assumption that the plot-level approach averages the original feature space more than the segment-based approach. Figs 5 and 6 show that the distributions of the spectral values of F2 (segment based approach) were wider than in F1 (plot based approach). These differences were, however, quite small compared to already mentioned differences in the dynamic range of the pixel values between the study areas. On the other hand, the average area of the feature extraction units affects the distributions. The basic hypothesis is that the larger the extraction units are, the more averaging occurs in the spectral values. Considering that the average area covered by the segment is much larger than the area covered by 20 × 20 m^2 window in the plot-based approach, this should further emphasize the differences in the distributions of the spectral values.

In S1 the segment based approach gave better results than the plot-based approach. In the case of

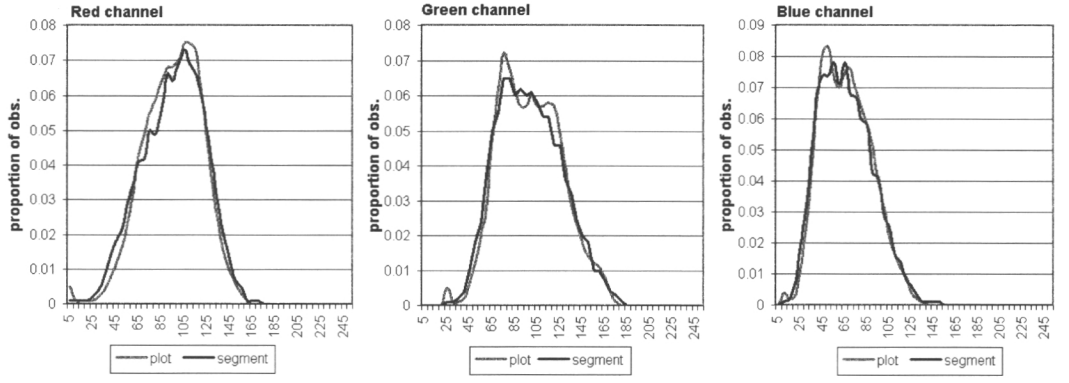


Fig. 5. The spectral distributions of plot and segment data sets in the study area 1.

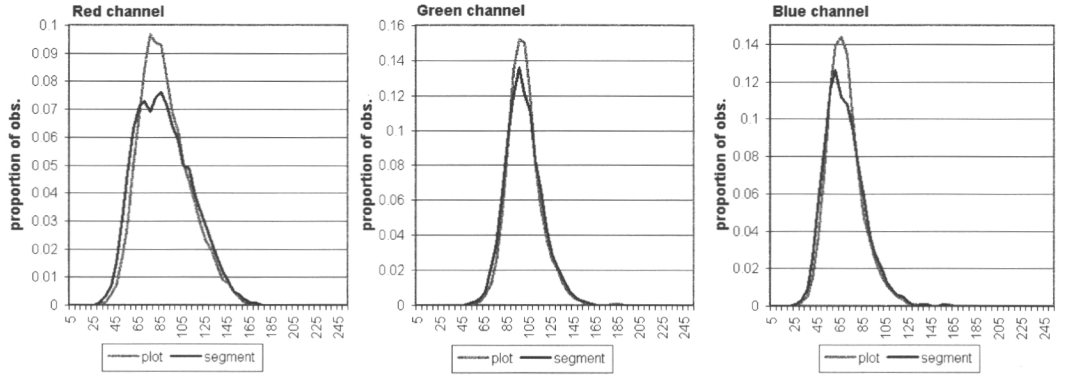


Fig. 6. The spectral distributions of plot and segment data sets in the study area 2.

Table 3. Weighted averages of standard deviations of forest parameters of S1 and S2.

Variable	S1		S2	
	F1	F2	F1	F2
Total volume, m^3/ha	76.1	61.6	82.3	86.9
Pine volume, m^3/ha	46.1	42.7	47.6	49.1
Spruce volume, m^3/ha	46.9	40.5	61.5	65.4
Broad-leaved volume, m^3/ha	23.6	24.2	40.7	39.0
Basal area, m^2/ha	8.1	6.5	7.5	7.9
Height, m	6.3	5.4	5.0	5.5

total volume the average within stratum variation of segment-based approach was 18.8% smaller than variation of the plot-based strata. When this within strata variation was studied by tree species, it was observed that only the variation of the volume of broad-leaved species was slightly larger in the strata based on F2.

The results of S2 showed an opposite trend. The variation of the applied forest parameters was generally smaller in plot-based strata. Once again, the volume of the broad-leaved trees was an exception. In S2 the differences between the methods were, however, very small. The weighted averages of standard deviations of the stand variables that were tested are presented in Table 3.

Our conclusion is that the segment-based stratification can be recommended if the allocation of field sample is considered. First of all the

segment-based approach eliminates the problem of mixed plots near stand borders. Furthermore the segment-based features include more of the original spectral variation than the plot-based features. Our presumption is that the fact that the results of S2 did not support out hypothesis is due to the small spectral variation present in the image mosaic. Small amount of spectral variation confuses the stratification process and therefore the strata of both of the methods have larger variation in S2 than in S1.

Finally, we want to emphasize that in addition to its ability to preserve more of the original spectral variation of the image material and produce more homogeneous strata, the segment-based allocation approach has some additional advantages when compared to the plot-based approach. These advantages are obvious when an operational multi-source inventory application is considered. First, the segment-based approach is able to utilise the whole spatial domain of the study area in its original spatial resolution. In addition, the resulting segment borders are crisp, and their locational accuracy may be controlled by controlling the level of smoothing in the pre-processing phase of the method. Furthermore, image segments are area-like features that are easier to locate during the field work compared to point-like features like centres of sample plots. Finally, if the remote sensing based monitoring of forest resources is considered, the segment-based approach has the advantage that it is not as sensible to the errors in image registration as the pixel- or plot-based approaches.

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Updating Stand Level Inventory Data Applying a Stand Simulator and Visual Interpretation of Aerial Photographs

Perttu Anttila

University of Joensuu, Faculty of Forestry
P.O. Box 111, FIN-80101 Joensuu, Finland
e-mail: perttu.anttila@joensuu.fi

1 Introduction

In Finland, privately owned forests cover 60% of the total forested land. The forest management plans for these are based on stand-wise field inventories. In 1999, Forestry Centres surveyed 800 000 ha of the privately owned forests (Forestry Development Centre Tapio, personal communication). There is a large need to increase planning area, but this cannot be done with the current surveying procedure. Field inventories are labour-intensive and thus expensive.

In the same time, old inventory data already exist for 70% of the privately owned forest land (Forestry Development Centre Tapio, personal communication). Development of a stand can be predicted based on initial stand data. Human activities, like cuttings, can also be simulated. So, in principle, old stand data could be updated with a stand simulator. The problem is that performed silvicultural treatments and cuttings are not known in the Forestry Centres.

Rapid changes (such as clear-cuttings) can be detected even with automatic methods from multitemporal aerial or satellite images (Varjo 1997, Hyppänen 1999). Because aerial photos must be purchased for the delineation of stand boundaries preceding conventional field inventory, aerial photo interpretation combined with updating former inventory data seems especially attractive. However, the problems originating from low flight altitude make numerical analysis of aerial photographs more complex than that of satellite images. Consequently, visual interpretation of aerial photos could offer the fastest solution.

The aim of this study was to examine the reliability and time consumption of updating stand level inventory data with a stand simulator and visual aerial photo interpretation. Two updating procedures were developed and tested. In both procedures, old stand data were updated with a stand simulator and the acceptability of the updated data was checked visually with aerial photographs. If the updated data were not accepted, new stand attributes were assessed with photo interpretation and by simulating cuttings.

2 Material and Methods

Old stand data collected with conventional field inventory in 1987 were transferred into MELA96 (Siitonen et al. 1996) stand simulator, and the development of the growing stock between 1987 and 1999 was simulated. Next, the stand data were moved into Xforest geographical information system (Xforest PC – Käyttöohje 1999). In Xforest, stand boundaries were displayed in the foreground and three scanned aerial orthophotos from 1999 covering the study area in the background. The scale of the false-colour photographs was 1:20 000.

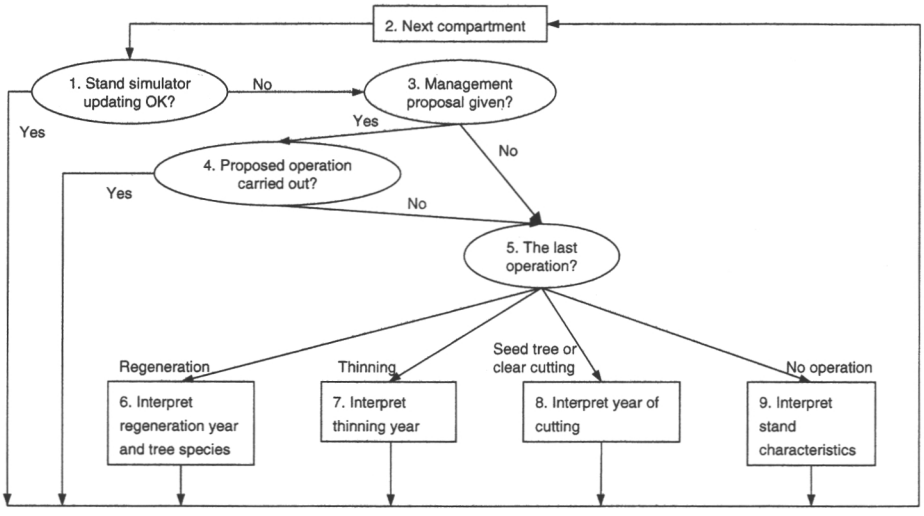


Fig. 1. Photo interpretation procedure 2.

Twelve forestry engineers were divided into two groups, which had different aerial photo interpretation instructions. Based on a photo interpretation, the interpreters in both groups had to decide for each stand whether the simulated development of growing stock was acceptable or not. The stand boundaries were predefined in such a way that the stand characteristics could not be affected by any differences in the delineation of stands.

If there had been a cutting or the stand's simulated data did not otherwise correspond to the scene; the mean age, diameter, height and basal area or number of stems for each tree species was interpreted in procedure 1. In procedure 2, however, it was possible to utilise management proposals given in the field in 1987 (Fig. 1). If a cutting or other operation had been proposed and it looked like the operation had been realised, the interpreters accepted the proposal. Otherwise the last implemented operation and the implementation year were interpreted. However, if no operation had been carried out during the updating period and the growth model updated data were nevertheless unacceptable, the same compartment characteristics were estimated as in procedure 1. Stands where proposals had been accepted or operations interpreted were later updated again in MELA96 so that the program simulated the operations.

Updated stand attributes were compared to attributes of accurately measured stands. In 1999, a total of 66 stands in the study area were field checked by placing 5–9 sample plots systematically in each stand. Root mean square error (RMSE) and systematic error for each attribute and interpreter were calculated.

3 Results and Discussion

Fig. 2 illustrates the productivity of interpreters as a function of accuracy in updating stem volume. Procedure 2 was both more accurate and faster than procedure 1. The RMSE of procedure 2 was 56.5 m^3ha^{-1} (30.2 %) and productivity 83.75 ha h^{-1}. A surprising result was that the conventional field inventory which was done in the study area in 1999 was only as accurate as updating with procedure 2. The productivity of a stand level field inventory is usually 3.3–5 ha h^{-1} (Forestry Development Centre Tapio, personal communication). Thus updating old inventory data can be assumed to be 15–25 times faster than a field survey, while sheer visual photo interpretation with a stereoscope is only three times faster (Pussinen 1992).

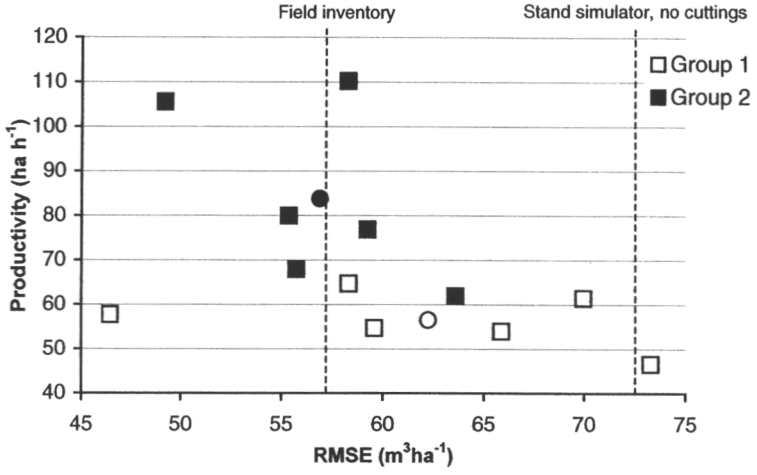


Fig. 2. Productivity of interpreters as a function of accuracy of updating stem volume. The accuracy of standwise field inventory and stand simulator updating, when no cuttings have been simulated, are marked with dashed lines. Dots are group mean values.

The reason for the rather low accuracy of field inventory in the study area may be that the surveyor was quite inexperienced. Sometimes forest engineers also intentionally underestimate volume (or basal area and mean height) to make sure the forest owner will not be disappointed at the time of cutting (Poso 1983). Yet the results show that the accuracy of field inventory is not always high and comparable accuracy can be achieved without visiting forest.

Although this kind of updating is subjective and may thus easily lead to biased estimates, it was seen worth further development. A follow-up study where procedure 2 was improved was made in 2001. Those stands, like seedlings, that are hard to interpret from aerial photo are not interpreted at all, but are surveyed in the field later. Potential applications of updating include inventory of forest estates not willing to buy a forest plan, marketing plans and guiding forest owners. The developed updating procedure is simple and ready to put into practise.

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Two Methods for Correcting Map Errors in Multisource Forest Inventory

Matti Katila

Finnish Forest Research Institute, Unioninkatu 40 A, FIN-00170 Helsinki, Finland
e-mail: matti.katila@metla.fi

1 Introduction

The Finnish multisource national forest inventory (MS-NFI) utilises optical area satellite images and digital maps, in addition to field plot data to produce geo-referenced information, thematic maps and small area statistics. A non-parametric *k*-nearest neighbour method (*k*-NN) is used in the estimation. Field data from surrounding calculation units (municipalities), in addition to the unit itself, are utilised when estimating results for one unit (Tomppo 1996).

In the MS-NFI, forestry land (FRYL) has been delineated directly from the numerical map data (Tomppo 1991). The problem with the current MS-NFI map data is that it is not necessarily up-to-date, it includes locational errors and it does not correspond exactly to the NFI landuse classes.

Recently, a calibration method has been introduced to reduce the effect of 'map errors' on multisource forest resource estimates (Katila et al. 2000). The method is based on the confusion matrix between landuse classes of the field sample plots and corresponding map information. The applied map strata are assumed to be homogeneous with respect to the 'map errors'. The FRYL area estimates of the calibration method are consistent with large region post-stratified estimates, while for small areas the estimator is synthetic. A method to compute the calibrated field plot weights was also presented. These weights are in turn used to calculate the small area estimates, e.g. for municipalities. The calibration typically increases the mean volume estimates and decreases the FRYL area estimates of small areas, if the FRYL is overestimated on the basis of map data. Despite the rather simple idea of the calibration, it is quite laborious when implemented in the MS-NFI: the calculation is more complicated than in the original MS-NFI and some field plots obtain negative weights.

Another method, called stratified MS-NFI, has been presented to reduce the effect of inaccurate map data on the forest resource estimates (Katila and Tomppo 2002). In this method, *k*-NN estimation is applied by strata. All the field plots within each map stratum, independent of the field measurement based landuse class, are used for estimating the areas of landuse classes and forest variables of the particular stratum. In the original and calibrated MS-NFI, only those field plots, which completely belong to FRYL, are used. The stratified MS-NFI method has the advantage of including all the sample plots within each stratum in the training data. In this sense it resembles the field inventory estimation. The final estimates for the stratified MS-NFI are derived by combining the stratum-wise estimates.

2 Materials

The three types of MS-NFI estimates were calculated in a realistic setting using data from the ninth NFI. Two study areas, Central Finland and Western Finland, were applied. The Central Finland study area was within the Landsat 5 Thematic Mapper images 188/16 and 188/17, date 24.8.1996, and the Western Finland study area

within the image 191/16, date 13.6.1997. The NFI field measurements employed were from the same year as the satellite images. The two study areas contained 56 municipalities, 29 in Central Finland and 27 in Western Finland (Katila and Tomppo 2002).

A systematic cluster sampling design was applied in the NFI field data measurements. A total of 6816 and 7695 field plots, of which 4706 and 4832 on FRYL, were measured within the Central Finland and Western Finland training data areas, respectively.

A stratification of the study areas and field plots was produced combining the various map data sources. Each 25×25 m^2 pixel of the study area was delineated into one of the defined strata. The stratification was designed to form homogeneous strata with respect to the NFI based land use classes. For the stratified MS-NFI there were five strata: mineral soil on FRYL, peatland on FRYL, arable land, built-up land and roads and water. The need of sufficient amount of field plots in the training data limited the possibility of increasing the number of strata in the stratified MS-NFI, whereas in the calibrated MS-NFI the number of strata was between 9 and 11; well-classified categories can have smaller field samples (Czaplewski and Catts 1992).

3 Results

The stratified and calibrated MS-NFI reduced the bias in the FRYL area estimates of original MS-NFI, caused by errors in the map data. The FRYL area estimates from stratified MS-NFI for large regions remained between the original MS-NFI estimates and the calibrated MS-NFI estimates. The calibrated MS-NFI region estimates are equal to the post-stratified FRYL area estimates (Katila et al. 2000). The stratified MS-NFI may either increase or decrease the mean volume estimates of large regions compared to the field inventory estimates, whereas the calibrated MS-NFI typically increases these estimates. However, the stratified and calibrated MS-NFI volume estimates were within the double standard error of the field inventory estimates.

The municipality level estimates of mean and total volumes and mean and total volumes by tree species based on stratified MS-NFI differ more from the original MS-NFI estimates than those based on calibrated MS-NFI; the latter calibrates the MS-NFI estimates more or less systematically upwards or downwards from original MS-NFI. The stratified MS-NFI is essentially a different estimation method. The stratified MS-NFI and calibrated MS-NFI did not produce significant errors when the estimates of FRYL area and volume were compared to the field inventory estimates of nine sub-regions (1728–4238 km^2 FRYL). The stratified MS-NFI estimates of mean and total volume by tree species were more accurate compared to the field inventory estimates than the two other MS-NFI methods in subgroups of municipalities: original MS-NFI estimates and calibrated MS-NFI estimates failed to follow the dominant tree species changes within the Western Finland study area.

The stratified MS-NFI was found statistically simple and its results were more balanced than those from the calibrated MS-NFI for the most part of the results.

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Improving the Accuracy of Multi-Source Forest Inventory Estimates by Reducing Plot Location Error – a Multi-Criteria Approach

Merja Halme[1] and Erkki Tomppo[2, 3]

[1]Helsinki School of Economics
Runberginkatu 14–16, FIN-00100 Helsinki, Finland
[2]Finnish Forest Research Institute
Unioninkatu 40 A, FIN-00170 Helsinki, Finland
e-mail: merja.halme@hkkk.fi, erkki.tomppo@metla.fi
[3]Corresponding author

Abstract

This paper recalls the procedure, introduced by Halme and Tomppo (2001), to reassign satellite image information to field plot data of forest inventory by a multi-criteria approach. The method can be utilised in satellite image aided forest inventories, e.g., as in the Finnish Multi-Source National Forest Inventory since 1990. This inventory method presumes that the field sample plots are geographically accurately located and each individual field plot can be identified with a specific picture element of the applied satellite image. Small area estimation errors are highly sensitive to the location errors of field plots with respect to the satellite image. In spite of current GPS-systems, an accurate location is extremely difficult to achieve due to map errors and errors in rectifying a satellite image on a map. Satellite image information is reassigned to the field plots within an $n \times n$ image window around the assumed location. A weighted function of the correlation coefficients of the selected image and field variables is used as a scaling function in this multi-criteria optimisation approach. The root mean square errors of estimates, produced with a non-parametric k-nn estimation method, are applied as a criterion when judging the final goodness of the relocation. The relocation reduces the pixel-level root mean square error of total volume per ha by 36%.

Keywords: natural resources, multiple criteria analysis, forest inventory, satellite images, k-nn method

1 Introduction

The increasing availability of supplementary data, e.g. remote sensing data (satellite images), has made it possible to increase the efficiency of inventories and to satisfy the new information needs at reasonable costs (Franco-Lopez et al. 2001, Nilsson 1997, Tomppo 1991). Satellite image data is usually inexpensive but much less accurate than field measurement. The Finnish Multi-Source National Forest Inventory, conducted by the Finnish Forest Research Institute,

has utilised satellite images and digital map data, in addition to field measurements, operationally since 1990. A traditional way to study satellite images in forest inventories has been to measure a number of field plots and to define a number of classes, e.g. on the basis of tree species dominance or vegetation type. The plots are grouped into those classes on the basis of field data. In the image analysis, each pixel of a satellite image is classified into one class using techniques such as discriminant or similar analysis. This approach is far from satisfactory for the requirements of a real forest inventory and forestry. Usually, the estimates of all variables (the number can be several hundred) are needed for the area units which are applied in forest management. These units can be municipalities or forest holdings and are called computation units in this article. The non-parametric k-nearest neighbour (k-nn) method differs from the traditional estimation and classification methods. An essential property of the method is that all inventory variables can be estimated at the same time. The method also preserves the covariance structure of the variables (Tomppo 1991). It can be applied in a straightforward way in different forest conditions and with different remote sensing materials (Nilsson 1997, Eisele 1997, Tomppo et al. 1999, Franco-Lopez et al. 2001).

Crucial conditions concerning the accuracy of the estimates are that the coordinates of the field plots are accurately known and that satellite images are accurately rectified on the map applied. Maps of high accuracy are a key prerequisite, because the pixel-level estimates are extremely sensitive to field plot dislocations and rectification errors. Errors can be controlled to some extent by the value of the parameter k (the number of the nearest neighbours) (Tokola et al. 1996, Franco-Lopez et al. 2001). The high value of k, however, shifts the pixel-level estimates of the variables (e.g. volumes by tree species) towards their large area mean values and reduces the pixel-level variation. The selection of the estimation parameters, e.g. the value of k, and their effect on the estimates are studied in Katila and Tomppo (2001). The use of a global positioning system (GPS) helps in getting accurate locations of field plots but does not reduce the map errors and satellite image rectification errors.

The total assignment error of a field plot to a satellite image pixel in the current system, which has a pixel size of 25 m, varies from 0 to 70 m, the average being 10 m (Tomppo 1996), see also Section 2.2. This implies that the correct location of the field plot on the satellite image with respect to the assumed location can be found within a 7 × 7 pixel window around the assumed location. In the subsequent discussion, this window is called the field plot's window. One Landsat image covers an area of 3 million hectares. The number of field plots on forestry land in such an area in the Nordic Countries is typically approximately 10000. Due to the fact that all methods to reassign the field plots to satellite image pixels must be based on the covariation of image variables and field plot variables, the number of different location configurations is around n^{10000}, where n is the number of pixels within the area (window) in which the the correct location can be found.

A simple method is recalled here to reassign the pixels of satellite images to field sample plots using a multi-criteria assignment approach. The method has bee originally presented by Halme and Tomppo (2001). The aim is to determine the location for each plot within a fixed $n \times n$ window. The estimates of the root mean square errors and biases of the estimates of some basic forest inventory variables are used as final criteria in judging the performance of the relocation.

2 Material

2.1 Field Measurements

The study area is located in southwest part of Finland and covers parts of Forestry centres Rannikko, Lounais-Suomi and Häme-Uusimaa (between 60°00'–62°00'N and 21°00'–26°00'E). Areas corresponding to the cloud-free parts of satellite images were selected (Section 2.2). The total land area is 2.50 million hectares with 1.82 million hectares of forestry land. The remaining area belongs to land use classes such as arable land and built-up areas. Forestry land is divided into forest land, other wooded land, waste land and forestry roads on the basis of the definitions of the Finnish National Forest Inventory (Kuusela

and Salminen, 1969). Waters cover 9.8% of the study area. The main tree species are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and birch (*Betula* spp.), with some aspen (*Populus tremula* L.) and alder (*Alnus* spp.), see Table 2.

The field data from the 9th Finnish National Forest Inventory from the years 1998 and 1999 were employed. A systematic cluster sampling design is applied in the inventory. One cluster contains either 14 (temporary clusters) or 10 (permanent clusters) field plots located along a rectangular tract, 250 m apart. A total of 10043 field plots, of which 9059 are on land, 6591 are on forestry land (52 on forestry roads) and 6172 are on forest land (a subset of forestry land) were used in the study. Trees were measured on those field plots which intersect forest or other wooded land. Trees are selected using PPS-sampling, the inclusion probability of a tree being proportional to its cross section area at a height of 1.3 m.

2.2 Satellite Image and Digital Land Use Data

Two adjacent Landsat 5 TM images from the same date of summer 1999 were employed, with path 190 and rows 16 and 17. Only the cloud-free parts of the image were applied. Both images were rectified to the national coordinate system. A common practice in image analysis is to identify points (e.g. small islands on water) from both satellite images and base maps and to fit a regression model to the image coordinates and map coordinates of the points. Polynomial regression models of second order with 50 control points were applied:

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

where u and v are the image coordinates, x and y the map coordinates and ε_u and ε_v the random errors.

An image element, i.e. a pixel, can be assigned to each ground element with the estimated model. The nearest neighbour method was applied for the re-sampling of the images to a pixel size of 25×25 m^2. The absolute values of the residuals in the model estimation, i.e., $\hat{\varepsilon}_u$ and $\hat{\varepsilon}_v$, ranged from 0.3 pixels to 0.6 pixels. The prediction error for an individual observation is thus from 0.5 to 1.5 pixels. The base map error has been estimated to be from 5 to 15 metres. i.e. ~0.5 pixels. The field plots are located in the current inventories either with a precision compass and a tape or with a GPS system. The average field plot location errors in the Finnish National Forest Inventory has been estimated to be 20 m. The maximum error in assigning spectral values to ground elements can therefore be assumed to be 3 pixels, i.e. the correct location can therefore be found within a 7×7 window around the assumed location of the pixel.

3 Methods

3.1 Multi-Source National Forest Inventory Method

The same method for forest variable estimation is applied as is used by the Finnish Multi-Source National Forest Inventory (FMS-NFI). In computing forest inventory estimates from pure field data, each field plot has a certain area representativeness, a weight. This weight can be, e.g. the total land area divided by the number of field plots if either systematic or systematic cluster sampling, e.g., is applied (Kuusela and Salminen 1969). The FMS-NFI can be considered as a method where new area weights, that are not equal for each plot, are computed for each field plot (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 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 a distance measure d, defined in the feature space of the satellite image data. The k nearest field plot pixels (in terms of d), i.e., pixels which cover the centre of some field plot $i \in F$, are sought for each pixel p under the forestry land mask of the cloud free satellite image area. The corresponding field plots are denoted by $i_1(p),...,i_k(p)$.

The weight $w_{i,p}$ of field plot i to pixel p is defined as

$$w_{i,p} = \frac{1}{d^2_{p_i,p}} \Big/ \sum_{j\in\{i_1(p),\ldots,i_k(p)\}} \frac{1}{d^t_{p_j,p}}$$
if and only if $i \in \{i_1(p),\ldots,i_k(p)\}$ (2)
$= 0$ otherwise

The most commonly used values for the exponent t in the distance measure are 1 and 2. A pixel-level estimate of the variable M for pixel p is defined as

$$\hat{m}_p = \sum_{i\in F} w_{i,p}\, m_i \quad (3)$$

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

The pixel-level goodness of the estimates can be assessed by means of the estimators of the pixel-level root mean square error (RMSE)

$$\hat{\sigma}_m = \sqrt{\frac{\sum_{i\in F}(\hat{m}_i - m_i)^2}{n_F}} \quad (4)$$

and bias

$$\hat{\bar{e}} = \frac{\sum_{i\in F}(\hat{m}_i - m_i)}{n_F} \quad (5)$$

where m_i is the 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 standard deviation of the quantities $(\hat{m}_i - m_i)$ can be used as the estimate of the standard error of the estimator of the bias. A leave-one-out cross-validation method was applied (Efron and Tibshirani 1993). The statistical significance of the bias can be estimated assuming the independence and normal distribution of the errors and using the usual t-statistics.

3.2 A Multi-Criteria Approach for Finding the Correct Locations for the Field Sample Plots on a Satellite Image

The aim was to find a procedure to identify for each field sample plot the satellite image pixel which geographically, and at the same time in terms of spectral values, best represents that plot. A search was made within a 7 × 7-pixel window around the image coordinates corresponding to the original geographical coordinates of the field plot (formula 1). The 7 × 7 window corresponds to the estimated maximum geographical error between the assumed location and real location of the field plot pixel (see Section 2.2). Actually, a satellite image pixel may contain information from the surrounding area of a field plot, because the area of a plot rarely corresponds exactly to the area of one satellite image pixel. The spectral information is attached to a field plot from that satellite image pixel whose centre point is geographically closest to the centre point of the field plot.

Satellite images also involve random variation caused by, e.g., variation in dispersion in the atmosphere. Selecting the location of the field plots by means of the covariation of one field variable and one spectral variable only may lead to location errors due to random variation of the image. Because different field variables correlate with different spectral variables, the use of several field and spectral variables makes location error due to random variation less likely. This led to the use of several variables.

In the end, a multiple criteria optimisation approach was employed to find for each field plot the correct location on the satellite image. The problem belongs to the category of multiple criteria classification problems (Larichev and Moskovitch 1991). In the current problem, for each sample plot the pixels in its $n \times n$ window represent the potential classes. All the windows were searched simultaneously for the optimal pixel – the problem is thus combinatorial.

Some additional notations are now introduced: forestry land, P denotes the set of pixels within the 7 × 7 image windows which are considered for assignment in the satellite image. An assignment specifies a field plot assigned to a pixel. It can be represented by a function s mapping sample

plots in F to P. Thus $\{(i, s(i)), i \in F\}$ denotes an assignment where each sample plot i is assigned to one pixel $s(i)$ within its $n \times n$ window assigned to it. An assignment is briefly denoted by s.

Denote by $x_l(i)$, $l = 1,...,6$ the natural logarithms of the field sample plot variables:1) total volume (m^3ha^{-1}), 2) the proportion of deciduous trees (volume of deciduous trees divided by total volume), 3) the age of the trees (years), 4) volume of coniferous trees (m^3ha^{-1}), 5) volume of pine (m^3ha^{-1}) and 6) volume of spruce (m^3ha^{-1}). The spectral values of the satellite image spectral bands of pixel $s(i)$ are denoted by $z_j(s(i)), j = 1,...,6$ (Landsat TM bands 1,...,5 and 7). Furthermore $z_7 = (z_4 - z_3)/(z_4 + z_3)$. These six forest variables are important ecologically and economically and highly affect the spectral values of the image bands. Logarithms of forest variables are used instead of the original ones to transform the relationships to be linear.

The aggregate measure that was employed for the goodness of an assignment s was

$$\begin{aligned} R(s) = \\ &\omega_1 r(x_1, z_5(s)) + \omega_2 r(x_2, z_7(s)) + \omega_3 r(x_3, z_5(s)) \\ &+\omega_4 r(x_1, z_6(s)) + \omega_5 r(x_4, z_5(s)) + \omega_6 r(x_5, z_2(s)) \\ &+\omega_7 r(x_6, z_3(s)) \end{aligned} \quad (6)$$

where ω_1, ω_3, ω_4, ω_5, ω_6, $\omega_7 \leq 0$ and $\omega_2 \geq 0$ with $\sum_{i=1}^{7} |\omega_i| = 1$ are weights for the correlation coefficients (r). This specification follows from the correlations in boreal forests being negative, except for the case of $r(x_2, z_7(s))$ for which a positive weight is applied.

The measure R was used as an objective function to be maximised to find the correct assignment. The weighted sum is a scaling function commonly used in multiple criteria optimisation problems to generate Pareto optimal solutions. In combinatorial problems, such as the current one, the weighted sum is not guaranteed to produce all Pareto optimal solutions, i.e. there may exist unsupported Pareto optimal solutions which the weighted sum is unable to generate (Steuer 1986). In this case, the problem was ignored, a) because the radiometric resolution of current natural resource satellite images is rather poor, and b) because the spectral values of a pixel are affected not only by the corresponding ground element but also the neighbouring elements. Further, the spectral values are integers between 0 and 255, which is one reason why there may be multiple optima.

Using an iterative procedure, given a set of weights (ω), a random assignment s was employed initially. Then, in order to find an improved solution "neighbouring assignments" were considered – which plot to move to which pixel within its window to improve the goodness measure R most.

Thus, the neighbouring assignments s', considered to be the solution succeeding s, are such that only one field plot of s' is assigned to a different pixel compared with s. The original plans assumed a tabu search (Glover and Laguna 1997) like procedure would be appropriate. However, the problem turned out to be much simpler than expected, and seemed to have a global optimum. The strategies in tabu search which aim at overcoming the problem of local optima were not successful in our experiments. Experiments were also made with simulated annealing with which we were not able to produce a satisfactory solution within a reasonable time. Consequently, the search proceeded in every iteration with the neighbour producing the steepest ascent.

1. The algorithm for optimal assignment operated in the following steps:
2. Start with random s.
3. Find the neighbour s' such that the $R(s') - R(s)$ is maximal. If there are several s' producing the same maximal improvement in R, one is randomly selected.
4. If there is no neighbour producing an improvement stop. Otherwise go to step 3.
5. Set assignment s' as the current assignment. Go to step 2.

4 Results and Discussion

Volume, being the most essential variable, was used for the first optimisation trials. The weights applied were: $\omega_1 = \omega_4 = -0.5$, $\omega_l = 0$, $l = 2, 3, 5, 6, 7$ (formula 6). The behaviour of the resulting k-nn based RMSE's as a function of the image window was then analysed. The pixel-level RMSE of the total volume decreased from 85.84 m^3ha^{-1} by 34%, 51% and 59% with the window sizes 3 ×

3, 5 × 5 and 7 × 7, respectively. The RMSE's of the other forestry variables did not decrease greatly or even increased. This result confirmed that some other variables, in addition to volume, should be supplemented in the search procedure. This resulted in a multiple criteria approach.

The effect on the pixel's spectral values, caused by dislocating a field plot, is the higher the nearer a stand boundary the field plot is located. The pixel is called a mixed pixel if it gets information from several forest stands, i.e. if the corresponding field plot intersects a stand boundary and consists of two or more sub-plots. All field plots on forestry land were included in the first trials, except those on forestry roads. Some of those 6539 field plots consist of two or more sub-plots, the division caused by an intersecting forest stand boundary. The total number of sub-plots was 8172.

The relative RMSE,
i.e. $(\hat{\sigma}_m / (\sum_{i \in F} \hat{m}_i / n_F))100$ (cf. formula 4), of total volume decreased with reassignment from the original value of 102% to 59% when all plots and sub-plots were used. The corresponding values were 83% and 61% when only field plot parts (sub-plots) with the centre point of the plot were included. To test the reassignment approach, we conducted the analysis with the plots not intersecting stand boundaries (4964 plots). The final decision concerning the weights was made with those plots. The relative pixel-level RMSE of the total volume with the original locations for the 4964 plots was 71%.

The relative RMSE's of pixel-level estimates based on satellite image aided inventories are always rather high, e.g. (Tokola et al. 1996, Nilsson 1997, Poso et al. 1999, Tomppo et al. 1999, Franco-Lopez et al. 2001). Note however, that the relative RMSE's decrease rapidly when the area in question increases.

The goodness of an assignment measure R (formula 6), with multiple correlations, was maximised. The analysis was done within a window of 7 × 7 pixels.

Several values were tested for weights ω_l, l = 1,...,7. The final weights, based on the trial and error procedure, were $\omega_1 = -0.167$, $\omega_2 = 0.167$, $\omega_3 = -0.133$, $\omega_4 = -0.100$, $\omega_5 = -0.233$, $\omega_6 = -0.067$ and $\omega_7 = -0.133$. They were selected on the following basis: the reduction of the RMSE of total volume estimate was kept as close as possible to the reduction corresponding to single-criterion optimisation. The maximum reduction of the RMSE's of other estimates was simultaneously searched.

The final multiple criteria based RMSE's for estimates of the investigated six forest variables, as a function of the window size, are given in Table 1 and the biases in Table 2. Note that a reduction of 36% in the RMSE of total volume was achieved while gaining a 14 to 27% reduction in the RMSE's of the other variables, except for the variable other broad leaved trees. The relative RMSE of the total volume was 45%. These results were obtained with a tolerance $2 \cdot 10^{-6}$ (minimum reduction of R). The number of iterations needed was somewhat higher than the number of field plots.

Our RMSE is noticeably lower than the earlier ones reported from similar conditions. Tokola et al. (1996) reported a relative RMSE of 64% when only plots not closer than 30 m from the nearest stand boundary were used. The relative RMSE's reported by Poso et al. (1999) with Landsat TM data and a stratification approach were even higher: 73% and 81% in two study areas in Finland.

The RMSE's as a function of the parameter k were also studied for the original location of the pixels and the reassignment within a 7 × 7 window. The RMSE's with the reassignment are uniformly lower than the original ones (Fig. 1).

The absolute values of the estimates of the biases of total volume and spruce volume decreased noticeably and the absolute value of the estimate of the bias of pine volume somewhat (Table 2, Fig. 2). None of the estimates of the biases were statistically significant, nor did the absolute values of the estimates of the biases increase with the window size, rather vice versa for most variables.

On the basis of the obtained RMSE's and the estimates of the biases, we are quite convinced that the developed algorithm relocates the field plots on the satellite image in such a way that the possible errors between field plot coordinates with respect to the corresponding image pixel are reduced. The relocation also reduces RMSE's of the estimates. Part of the reduction is caused by the fact that the algorithm searches for that pixel

Table 1. Root mean square errors for the original locations and for the optimised solution within $n \times n$ window, $n = 3, 5, 7$, weighted sum, $k = 5$. 4964 plots not intersecting stand boundaries were used.

Variable	Original	3 × 3	5 × 5	7 × 7
Volume (m^3ha^{-1})	85.84	65.37	57.97	54.68
Pine volume (m^3ha^{-1})	59.96	53.66	51.66	50.56
Spruce volume (m^3ha^{-1})	70.16	56.70	52.94	50.94
Birch volume (m^3ha^{-1})	31.50	27.00	25.05	24.85
Other br. l. (m^3ha^{-1})	15.96	16.55	16.27	15.81
Age (year)	35.94	33.13	32.32	31.05

Table 2. Means of the variables, and biases for the original locations as well as for the optimised solution within $n \times n$ window, $n = 3, 5, 7$, weighted sum, $k = 5$. 4964 plots not intersecting stand boundaries were used.

		Mean			Bias
Variable	Original	3 × 3	5 × 5	7 × 7	
Volume (m^3ha^{-1})	121.31	–1.73	–1.54	–1.30	0.26
Pine volume (m^3ha^{-1})	48.54	0.71	0.03	–0.25	0.49
Spruce volume (m^3ha^{-1})	54.02	–1.84	–0.59	–0.27	0.21
Birch volume (m^3ha^{-1})	16.16	–0.60	–0.96	–0.69	–0.30
Other br. l. (m^3ha^{-1})	2.80	0.00	–0.02	–0.09	–0.14
Age (year)	55.24	–0.18	–0.47	–0.65	–0.24

whose information corresponds to the information of the satellite image pixel to the greatest extent. In other words, the geographically correct assignment may not be the best one from the parameter estimation point of view. Part of the reduction may be caused by random variation in the satellite image data.

The results are very significant when accurate pixel-level or forest stand-level estimates are needed, e.g. in producing forest resource maps for forestry or ecological purposes. It is possible to preserve the original variation of forestry variables in their estimates because the absolute values of the correlations of the forest variables with the spectral variables increases in the ground truth data. Thus the variance of forest variables (m_i in formula 3) of field plots used for one pixel is smaller. The averaging does not shift the estimates as much towards the mean as in the case of lower correlation (formula 3). Higher correlations of image and field data lead also to improved estimates for the non-plot pixels. The presented relocation method can be applied in a straightforward way to other image classification and estimation methods as well.

In the computation, spectral information has been used from five of the six relevant spectral bands of Landsat TM images. Band 1, not applied, has a low signal to noise ratio. Thus, most of the image information has been utilised in the reassignment. All spectral bands have been used in the non-parametric forest parameter estimation. A minor amount of the field information, i.e. a small part of the number of the measured field variables, has been utilised in the reassignment. The variables used are those that have the highest impact on the spectral information. The role of site variables, e.g. site fertility class and moisture of the soil, could be included. The site fertility is inferred from the proportion of the broad-leaved trees.

Forthcoming research will study the effect of the reassignment on the error of estimates of forest variables for larger areas as well as the effect of random variation of the image data. Whether the result can be improved by employing a larger number of forest variables will also be studied.

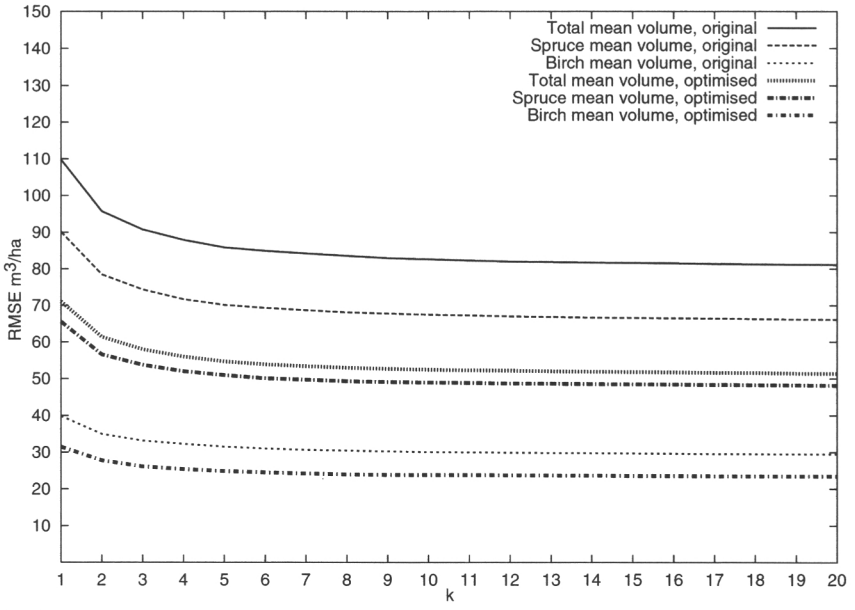


Fig 1. The root mean square prediction errors of the pixel level estimates of total mean volume, spruce mean volume, pine mean volume and birch mean volume (m^3ha^{-1}) as functions of the number of the nearest neighbours (k) for the original locations of the pixels and for the reassignment. 4964 plots not intersecting stand boundaries were used.

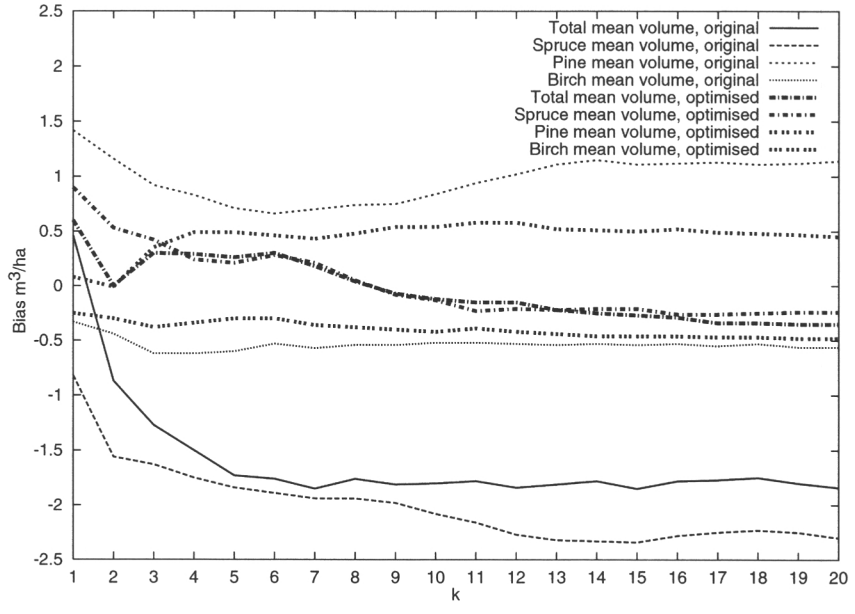


Fig 2. The biases of the pixel level estimates of total mean volume, spruce mean volume, pine mean volume and birch mean volume (m^3ha^{-1}) as functions of the number of the nearest neighbours (k) for the original locations of the pixels and for the reassignment. 4964 plots not intersecting stand boundaries were used.

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Special Inventory Topics

Re-Measured Relascope Plots in the Assessment of Inventory Update Methods

Juha Heikkinen and Helena Henttonen

Finnish Forest Research Institute
Unioninkatu 40 A, FIN-00170 Helsinki, Finland
e-mail: juha.heikkinen@metla.fi and helena.henttonen@metla.fi

1 Introduction

As a part of the project "Updating of the Finnish National Forest Inventory using Remote Sensing Data", we have studied and developed methods for assessing the performance of stand volume updating models on the basis of data from re-measured relascope plots. The general setting of our study can be defined as follows. Suppose we wish to test a given model, M, designed to update stand volumes from time t_1 to time t_2. Furthermore, suppose that, at time t_1, a set of sample plots is established and a relascope sample, S_{1i}, is measured in each plot, i=1,...,n, including trees that have reached the breast height (1.3 m) with inclusion probabilities proportional to the (breast height) basal area. Then a (usually rough) estimator of the time t_1 mean volume of growing stock per unit area in the stand containing plot i is given by the standard formula

$$v_{1i} = q \sum_{k \in S_{1i}} \frac{v_{1k}}{b_{1k}} \tag{1}$$

where q is the relascope factor, v_{1k} is the (time t_1) volume of tree k , and b_{1k} its (time t_1) basal area. Our generic update model, M, uses this estimate, usually together with some other stand characteristics, to form a prediction,

$$\hat{v}_{2i} = M(v_{1i};\text{stand information}) \tag{2}$$

of the time t_2 volume. To assess the accuracy of these predictions, we take, at time t_2, new relascope samples, S_{2i}, from the same plot centres, compute the reference values,

$$v_{2i} = q \sum_{k \in S_{2i}} \frac{v_{2k}}{b_{2k}} \tag{3}$$

and examine the distribution of the plot-level residuals $e_i = \hat{v}_{2i} - v_{2i}$.

There is a confounding factor, however, resulting from relascope sampling: A tree that was not sampled at time t_1 may have grown sufficiently between the sampling occasions to be included at time t_2. Because such trees contribute to v_{2i} but not to $\hat{v}_{2i}$, they introduce an extra random component to the residuals, e_i, resulting in overestimation of standard deviation of the predictions.

The relascope effect can be studied by comparing the e_i to modified estimators, $\tilde{e}_i = \tilde{v}_{2i} - v_{2i}$, from which the extra random component is (at least partly) eliminated. This can be achieved by taking the new trees of the time t_2 sample into account also in the estimation of time t_1 volumes, thereby letting them contribute to $\tilde{v}_{2i}$. More precisely, the modified updates are

$$\tilde{v}_{2i} = M(\tilde{v}_{1i};\text{stand information}) \tag{4}$$

where

$$\tilde{v}_{1i} = q\left(\sum_{k \in S_{1i} \setminus S_{2i}} \frac{v_{1k}}{b_{1k}} + \sum_{k \in S_{2i}} \frac{v_{1k}}{b_{2k}} \right) \tag{5}$$

is a modified estimate of time t_1 volume, taking into account the new trees $k \in S_{\text{new},i} = S_{2i} \setminus S_{1i}$

(Roesch et al., 1989). For those trees that reached breast height only after t_1, we take v_{1k}=0.

In practice, t_1-dimensions of the new trees are of course unknown. The problem of back-predicting them on the basis of t_2-measurements was the main concern in our study. A theoretically sound solution has been given by Roesch et al. (1993), but the test material of our project had some features (to be clarified below), which made it necessary to develop a more robust alternative.

2 Material

Our study area consisted of six (former) forestry board districts in southern Finland (Fig. 1). In that area, the measurements of the 8th National Forest Inventory were carried out in 1986–88 (our time t_1). In order to update the results of the 8th inventory of southern Finland, 38% of the sample plots were re-measured in 1994 (time t_2). The plots were not initially established as permanent, and therefore the exact locations of the trees were not recorded. Hence we can not always be certain which tree, if any, in the time t_1 data set is the same as a given tree in the time t_2 data, or vice versa. This information is obviously required in order to apply formula (5). What we do know, is that the trees were tallied (recorded) in the same order (clockwise) and starting from the same direction at both times.

An automatic algorithm was developed in the project to generate the most likely pairings of tree level measurements. However, plausible pairing could not be found in every plot. Potential reason for a failure may be a change in stand boundaries (either a real change or difference in interpretation) or a mistake in the order or starting direction, when tallying the trees.

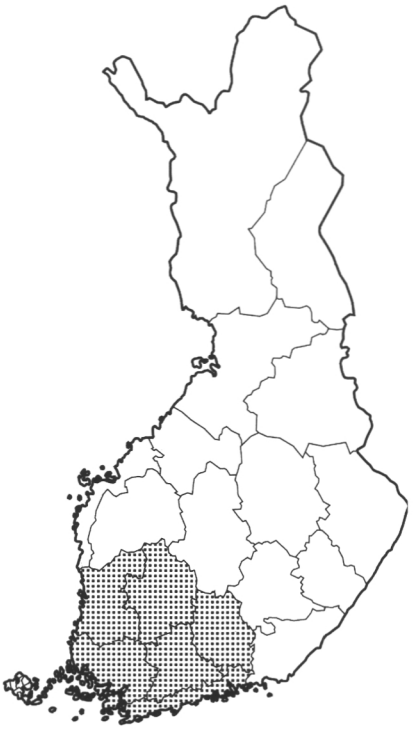


Fig. 1. Location of our study area (dotted) and the boundaries of the (former) forestry board districts of Finland.

3 Predicting Earlier Dimensions of New Trees

Having completed the pairing, we have plenty of data, on which to build the back-prediction models for the time t_1 dimensions of the new trees, $k \in S_{new} = S_2 \setminus S_1$, namely all trees, $k \in S_{old} = S_1 \cap S_2$, measured in both sampling occasions (here S_j denotes the union, $\bigcup_{i=1}^{n} S_{ji}$, of the time t_j relascope samples over all plots). However, the straight-forward approach of fitting a back-prediction model to trees $k \in S_{old}$ and applying it directly to $k \in S_{new}$ is not appropriate, because the fastest growing trees are under-represented in S_{old} and over-represented in S_{new}, the respective inclusion probabilities being proportional to b_{1k}/b_{2k} and $(b_{2k} - b_{1k})/b_{2k}$. Apparently, the earliest studies addressing this problem are by Söderberg (1986) and Lappi and Bailey (1987), but they mainly

focussed on forward-prediction. Roesch and Van Deusen (1993) derived unbiased back-predictions for basal area, and Roesch et al. (1993) modified their formulae to the case of improved time t_1 volume estimation using the new trees, that is, exactly the case we are dealing with.

Note that in (5), the quantity of interest, unknown for the new trees, $k \in S_{\text{new}}$, is v_{1k}/b_{2k}. Its regression on the (known) v_{2k}/b_{2k} for the new trees has the following expression as a function of regressions in the whole time t_2 sample, S_2 (Roesch et al. 1993)

$$\mathrm{E}\left\langle \frac{v_{1k}}{b_{2k}} \middle| \frac{v_{2k}}{b_{2k}}; k \in S_{\text{new}} \right\rangle = \frac{\mathrm{E}\left\langle \frac{v_{1k}}{b_{2k}} \middle| \frac{v_{2k}}{b_{2k}}; k \in S_2 \right\rangle - \mathrm{E}\left\langle \frac{v_{1k} b_{1k}}{b_{2k}^2} \middle| \frac{v_{2k}}{b_{2k}}; k \in S_2 \right\rangle}{1 - \mathrm{E}\left\langle \frac{b_{1k}}{b_{2k}} \middle| \frac{v_{2k}}{b_{2k}}; k \in S_2 \right\rangle} \quad (6)$$

Roesch et al. (1993) suggest estimating the components on the right hand side of (6) by weighted linear regressions fitted to trees $k \in S_{\text{old}}$; the appropriate weights are the ratios b_{2k}/b_{1k} of inclusion probabilities in S_2 and S_{old}.

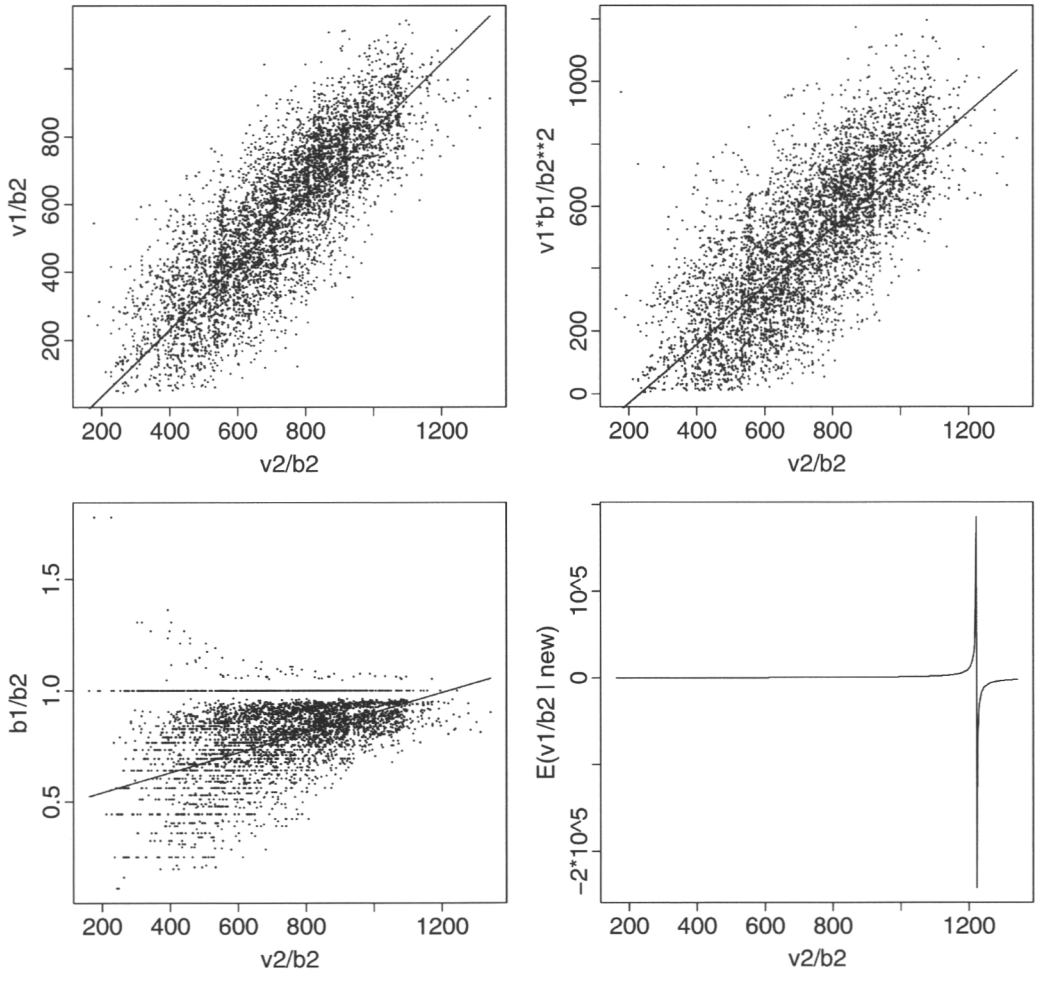


Fig. 2. Models of Roesch et al. (1993) fitted to those pine trees, for which we found an acceptable pairing of the measurements from the two sampling occasions.

At least with our data, this approach led to highly unstable results. An apparent reason for this instability was rather easy to find: as v_{2k}/b_{2k} grows (and generally as the tree size grows), b_{1k}/b_{2k} tends to one, which implies that the denominator of (6) tends to zero. We actually found that the linear predictors of b_{1k}/b_{2k} were often greater than one well within the observed range of v_{2k}/b_{2k}-values (see Fig. 2 for an example).

Several interesting phenomena are revealed by Fig. 2. First, it is evident that our data are rather noisy, due to uncertainty in pairing (Section 2) and rounding of diameters to 1cm classes. This imposes a challenging robustness requirement to the applicable methods. Secondly, unlike for the other components, linear model is not appropriate for the regression of b_{1k}/b_{2k} on v_{2k}/b_{2k}. We tried omitting observations with $b_{2k} \leq b_{1k}$ and replacing linear with logistic regression, guaranteed to yield predictions between 0 and 1, but even then the results were not acceptable: for large values of v_{2k}/b_{2k}, the predicted values of v_{1k} were clearly greater than v_{2k} (Fig. 3)

The general problem seems to be that parametric models of highly restricted form may produce unpredictable anomalies, when inserted into an expression like (6). With that in mind, we developed a more direct, although also a little more *ad hoc*, approach aiming at better robustness properties. The details will be given elsewhere; here we present some preliminary results.

4 Preliminary Results

For comparison with the (bottom) right diagrams of Figs 2 and 3, Fig. 4 shows our predictions of v_{1k}/b_{2k} for the new pine trees as a function of v_{2k}/b_{2k}. We can see that our approach gives reasonable predictions at least in the sense that $v_{1k}<v_{2k}$ for all trees.

One of the update methods tested in our project was based on the stand increment model of Nyyssönen and Mielikäinen (1978), calibrated for the updating period using annual growth indices (Henttonen 2000). The effect of relascope sampling on the performance assessment was studied on a subset of sample plots, where no cuttings had taken place between the two measurements and an acceptable pairing of the tree measurements was found by our automatic algorithm. This subset consisted of 1362 sample plots.

Fig. 5 shows the residuals, $e_i = \hat{v}_{2i} - v_{2i}$, when updating the usual time t_1 volume estimates, v_1, and the modified ones, $\tilde{e}_i = \tilde{v}_{2i} - v_{2i}$, from which the extra random component is (partly) eliminated. Apparently, the relascope effect is considerable. For a quantitative comparison, the standard deviation of e_i is 27.3 m^3/ha, and that of $\tilde{e}_i$ 17.0 m^3/ha.

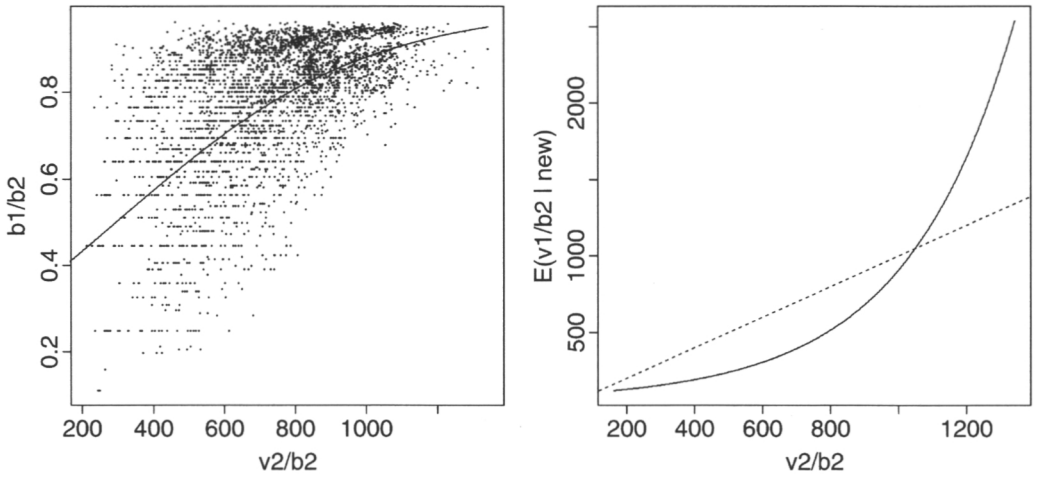


Fig. 3. As (bottom row of) Fig. 2, but with logistic regression of b_{1k}/b_{2k} on v_{2k}/b_{2k} and observations with $b_{2k} \leq b_{1k}$ omitted; the dotted reference line shows where $v_{1k}=v_{2k}$.

5 Discussion

According to our preliminary results, the variation in stand level volume estimates, caused by trees growing into the relascope sample, is clearly noticeable and should be accounted for in any analysis based on re-measured relascope plots. In our example, 37.5% of the standard deviation of update errors was explained by this relascope effect. In reality, this percentage is probably even higher, because the models we used in eliminating the effect, were quite coarse.

In order to utilise all measurements, including those of the new trees included only in the re-measurement, it was necessary to back-predict their dimensions to the time of the first measurement. Perhaps the most suitable information, on which to base the predictions, is the data on those trees that were sampled at both occasions. However, faster growing trees have a greater inclusion probability in the "new" sample than slower ones, so we should not apply the growth model estimated from the "old" sample as such. Roesch et al. (1993) suggest that this bias could be corrected using weighted linear regression. Theoretically, it should do the job, but we found that in practice it can lead to highly unstable results, at least with noisy data.

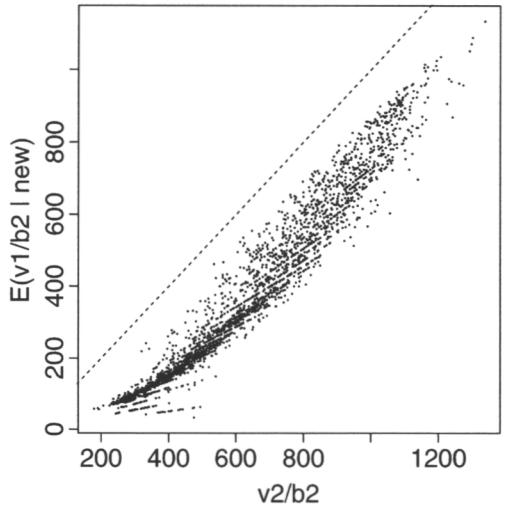


Fig. 4. Predictions v_{1k}/b_{2k} given by our alternative approach for the new pine trees (sampled in 1994, but not in 1986–88), plotted as a function of v_{2k}/b_{2k}; the dotted reference line shows where $v_{1k}=v_{2k}$.

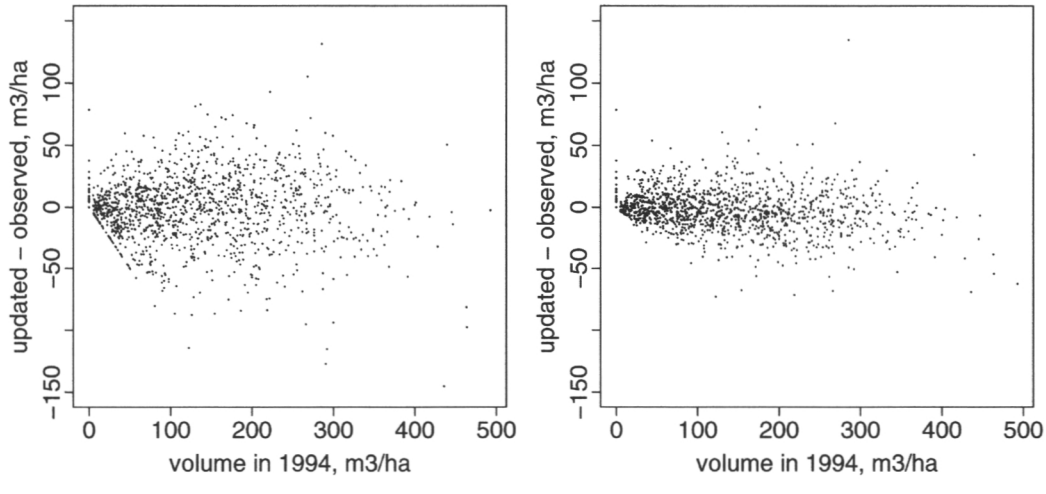


Fig. 5. Estimates, e_i, of update errors of plot-level mean volumes as a function of mean volume in 1994 (left) and the modified estimates, $\tilde{e}_i$, from which the relascope effect is partly eliminated (right).

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Guided Transect Sampling for Assessing Sparse Populations

Anna Ringvall

Swedish University of Agricultural Sciences,
Department of Forest Resource Management and Geomatics
S-901 83 Umeå, Sweden
e-mail: anna.ringvall@resgeom.slu.se

Abstract
For the monitoring of forest ecosystems, there is often a need to survey element of importance for threatened species or populations of some indicator species. Such populations are often sparse and scattered and, hence, inventories tend to be expensive. To improve the efficiency of such surveys a new method, guided transect sampling, has been proposed. The method use prior information with a high spatial resolution together with line-based survey methods. Instead of being laid out straight as in general, the lines or strips will wind between potentially interesting areas. Different ways for selecting the route of the strip or survey line has been proposed. In the field the surveyor follow the predetermined lines with the aid of GPS. In this paper, the method is presented together with some results from theoretical and practical evaluations.

Keywords: Auxiliary data, GPS-navigation, multiresource forest inventory strip survey, two-stage design

1 Introduction

Sparse populations generally pose substantial problems in sampling. This is the case in forestry, e.g., when studying elements of importance for biodiversity or a population of some indicator species. The plot-based methods generally used for timber cruising tend to give imprecise estimates and low cost-efficiency for sparse populations, since only a small area is covered and a relatively long time is spent walking between plots. Thus, transect-based methods like strip surveying should be more cost-efficient since a larger area is covered for the same walking distance (Lämås 1996).

In sampling theory, it is well known how auxiliary information about the population under study can be utilised to enhance the precision of estimates. Techniques such as stratification or sampling with inclusion probabilities proportional to the size of the object (PPS) use the information for selecting the samples, while, e.g., ratio and regression estimators use the information for estimation purposes (e.g., Thompson 1992). Today, remote sensing information with high spatial resolution can be obtained from most areas. While it is quite straightforward to use such prior information in the selection of samples with plot-based methods, it is not straightforward to do this with transect-based methods. Often, one would like the transects to wind through the terrain rather than being straight. This aim of this paper is to present a newly developed method, Guided Transect Sampling (GTS) (Ståhl et al. 2000) that

makes use of auxiliary information with high spatial resolution in the design of line-based inventories.

2 Guided Transect Sampling

An overview of GTS is given in Fig. 1. Prior to conducting the survey, the area is partitioned into grid-cells of a suitable size. For each cell, a covariate value is assessed e.g., from satellite imagery or aerial photos. For example, the covariate could be the estimated volume of deciduous trees in case the population studied is known to prefer deciduous trees to conifers in mixed stands. In the first stage, strips too wide to be surveyed in their entirety are randomly laid out (Fig. 1, left). These strips can be selected in various ways, e.g. with simple random sampling or with selection probability proportional to the sum of covariate values inside the strip. In the second stage, the selected first stage strips (the primary units) are sub-sampled with a survey line or survey strip (Fig. 1, middle). The route of the survey line is determined by a selection of grid cells across the first stage strips on the basis of existing information. In practise the surveyor will use GPS to follow the predetermined lines. For derivation of estimators and variance expressions, see Ståhl et al (2000).

The selection of the second stage transect, here referred to as the 'strategy for the second stage guidance', can be made in different ways. Three straightforward alternatives are:

Case 1) Transitions are only allowed to a neighbouring cell in the next column;

Case 2) Transitions are allowed to any cell in the next column forward;

Case 3) Random simulation of entire connected transects through the first stage strips, without reference to the covariate data.

In the first two strategies (Fig. 1, right), the probability of transition to a given cell is proportional to its covariate value. In the last strategy, a large number of transects are generated, and one transect is selected with selection probabilities

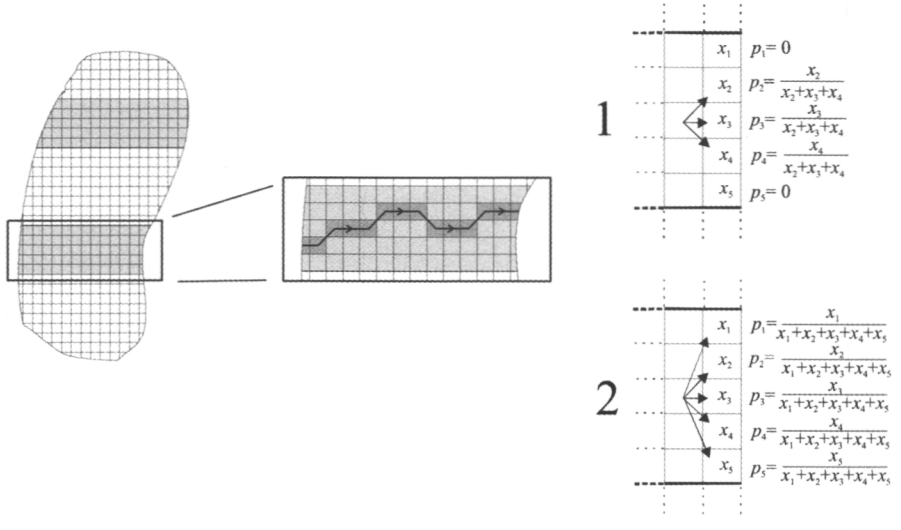


Fig. 1. An overview of GTS. In the first stage (left), wide strips are selected. In the second stage (middle), these are sub-sampled along a survey line selected with the help of existing information. The second stage currently comprises a survey of all entire grid-cells through which the sample line passes (the darker grey cells). The illustrations in the right show examples of two strategies for the second stage sub-sampling. In (1) transitions are allowed only to the neighboring cells in the next column, and in (2) transitions are allowed to any of the cells in the next column. The probabilities of transition to a cell (the p-values) are determined from the covariate values (x-values) in the next column.

proportional to the sum of the covariate values for all cells passed by the transect. GTS is intended to be a general methodology, which can be used in combination with different line-based methods. In the development of the methodology so far, the second stage survey has been conducted as a strip survey, approximated by a survey of entire grid cells crossed by the transect (see Fig. 1, middle). However, in practical applications, it is intended that the survey should be conducted in a continuous band along the selected transect.

In addition to the strategies mentioned above, an 'optimal strategy' has been developed (Ringvall 2002). This strategy is based upon Case 1 (as described above) but in contrast to Case 1, where the probability of transition to a cell is proportional to the grid-cell's covariate value, the transition probability resulting in the smallest possible variance was searched for. The idea is to use a model for the relationship between the covariate data and the variable of interest to create a 'model population'. The transition probability to a grid-cell is then selected with the aim of minimising the variance in this model population. Hopefully, the design found to be optimal for the model population is efficient also for the real population.

3 Theoretical and Practical Evaluation

To give an indication of the efficiency of GTS, the three straightforward cases for the second stage guidance were evaluated in comparison with a standard strip survey. In each case, first stage strips were selected with simple random sampling. In the standard strip survey, strips were selected using simple random sampling and had a width of one grid-cell. Comparisons were made in terms of the true variance obtained with each strategy and with the strip survey, for a given sampling effort. For both GTS and the standard strip survey, the variances were calculated using derived variance formulae (see Ståhl et al 2000).

The evaluation was made in simulated forest types. The covariate was considered to be the volume of deciduous trees, since many red-listed species depend on them (e.g., Berg et al. 1994). In addition, it is possible to estimate this variable from satellite images or digital aerial photos. The feature of interest was the abundance of species dependent on deciduous trees. In all cases the covariate data were assumed to have a high geometric accuracy (normally aerial photos).

The performance of the 'optimal strategy' was evaluated in terms of the variance obtained in realisations of the assumed model using the design found to be optimal in the model population. To test the influence of the correspondence between the model population and the real population, realisations were simulated with an, on an average, smaller or larger discrepancy between the model population and the realisation. The transition probabilities between grid-cells that minimised the variance in the model population were determined with a simulated annealing algorithm (e.g., Downsland 1992).

The idea of GTS is to select more interesting areas with a higher probability, hence it is of importance that the surveyor really follows the selected survey lines. In practise the surveyor will use GPS to follow the predetermined lines, however the surveyors will never be able to follow the theoretical survey lines perfectly. This will have an effect on the accuracy of estimates. The effects of navigational errors on estimates were evaluated in terms of the bias incurred and the increase in standard error (Ringvall et al. 2002). The bias and variance of estimates when taking navigational errors into account were determined using a Monte-Carlo simulation in simulated forest types. To simulate the surveyors' deviation from the survey line a 'Brownian bridge' process (e.g., Ross 1993) was used. A Brownian bridge is a form of continuous random walk, tied down at both the start and end points. To determine the extent of surveyor's deviation from a survey line and estimate the parameters in the Brownian bridge model, needed for simulation purposes, a field test was carried out. The field test was performed in two stands, one open pine forest and one dense spruce forest. For the test, two straight lines, 1000 m long, were laid out and divided into sections 200 meter long. The co-ordinates of the endpoint of each section were determined using carrier-phase GPS. During the field test these nodes were entered as waypoints in the GPS and

the surveyor navigated to them using real-time differential GPS. Another person walked behind and measured the surveyor's deviation from the correct line every 10th meter.

4 Results and Discussion

An example of the comparisons between the results of GTS and of a standard strip survey is shown in Fig. 2. The abundance of the population of interest is ranging from around 30 objects/ha in Forest I to around 1object/ha in Forest VI. In all cases considered, the three GTS strategies displayed a similar pattern of performance when compared with the standard strip survey. When the species of interest was rather abundant, the differences between the alternatives were small. With decreasing abundance, all the relative standard errors increased, but the increase was less for the three GTS strategies. When the species of interest is uncommon, the best GTS strategy was always much better than the standard strip survey. Of the three strategies, Case 2 was the most efficient. However, it is intended that that survey will be conducted along connected transects, and that is not a feature of this strategy. Hence this method should be considered only as a reference. Case 1 gives connected transect lines, and it was also a considerable improvement to the standard strip survey, when the population of interest was sparse. However, this strategy is somewhat "short-sighted", since at each step only the covariate values in the next column are utilised and the remaining information is ignored. Using this strategy, there is a risk that interesting but isolated areas will have a low probability of inclusion, which can lead to high variances. The third strategy (Case 3) was developed in order to reduce this risk, however the improvement to the standard strip survey was only minor.

To more fully use all the auxiliary information at hand, the 'optimal strategy', seeking for optimal transition probabilities between grid-cells, was developed. A comparison between Case 1 and this strategy showed that its efficiency depended heavily on how well the model population described the true population. In realisations with a good correspondence between the model population and the real population, the alternative strategy performed well for both an integer-valued variable (e.g., the number of a certain species) and a real-valued variable (e.g., the biomass of a certain species). With a larger discrepancy between the model population and the realisations, the relative efficiency decreased in both cases, although not as much for the real-valued variable as for the integer-valued variable. In the latter case, some very large variances were obtained.

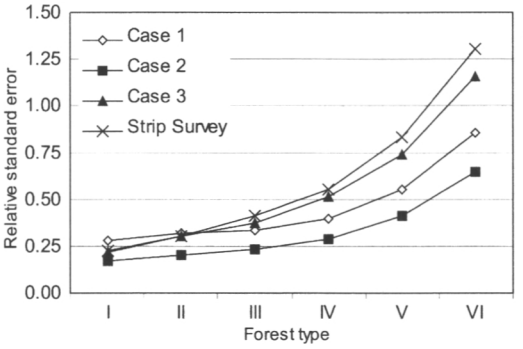


Fig. 2. An example of the comparisons between the results of three different GTS strategies for the second stage guidance and a standard strip survey. The results are shown as the relative standard errors in six forest types, in order of decreasing abundance of the species of interest. The results shown are for the case of a first stage strip with a width of five grid-cells.

The average deviation from the correct survey line in the field test was (in terms of absolute values) 1.9 meter in the open pine stand and 2.4 meter in the denser spruce stand. The maximum observed deviations were 14.2 and 10.9 meters, respectively. Results from the simulation study indicated that deviations of this magnitude have only a minor effect on both bias and standard errors of estimates. The bias was not greater than 2.9 % and the increase in standard error not greater than 3.2 % in any forest type tested. In all cases, the bias was positive, which can probably be explained by the fact that the surveyors covered a slightly larger area than defined in theory.

In summary, it has been shown that GTS has potential, but further development, both practical and theoretical, is needed before the method is

of practical use. For example, further theoretical development is required to use the auxiliary information in the most efficient way at all stages of the survey. In addition, the second stage field survey is not fully developed, it currently relies on the survey of entire grid-cells, although the intention is to survey a continuous band, of the desired width, along the selected transect. The fieldwork is somewhat complicated, so a field computer package incorporating navigation and data registration facilities would be useful. So far, no costs have been considered in the comparisons. When comparing standard strip survey with GTS, an equal area was surveyed, however the cost associated with GTS would be greater because the surveyor would travel a longer distance. The costs for acquiring the auxiliary information must also be taken into account. Further on, to more fully understand under what circumstances GTS is an applicable method, it has to be compared also with plot-based alternatives using the same type of auxiliary information.

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Presence/Absence Sampling in Vegetation Surveys

Göran Ståhl

Swedish University of Agricultural Sciences,
Department of Forest Resource Management and Geomatics
S-901 83 Umeå, Sweden
e-mail: goran.stahl@resgeom.slu.se

Abstract

Monitoring vegetation changes has become increasingly important in large-scale monitoring programmes. Changes in the abundance of a species may indicate changes in ecosystem health, or the change may affect the living conditions of other species. For example, bilberry can be considered as a keystone species in forest ecosystems due to its importance as a forage species for insects, birds, and mammals. A major change in the abundance of bilberry would most likely have major impact on the species that depend on it.

Many methods have been proposed for vegetation monitoring. Direct assessment of cover is one commonly used method. This method is, however, sensitive to surveyor judgement bias. Although deviation among different surveyors during a single year's survey can and must be accepted when this method is used, a major problem is that the judgement reference levels may vary between years, and thus the results may point towards changes that have not occurred in reality. These kinds of conclusions must be avoided.

As a more objective alternative to cover assessments, the point frequency method has been proposed. Using this method, a needle (or a similar thin device, e.g. a laser beam) is used at sample points to assess what species cover single points. From a theoretical point of view, the point frequency method can be used to derive a measure that is close to vegetation cover of a specific species, by calculating the proportion of points at which the species occurs. However, in practice a needle (or similar device) can never be made infinitesimally thin, and thus the point frequency method will not give an unbiased estimate of cover. Especially this is the case for species with very thin leaves, like the common grass species *Deschampsia flexuosa*. In addition, many practical problems arise when the method is applied, and many points must be sampled to obtain reliable estimates of species occurrences within an area.

A third method for vegetation monitoring is presence/absence (P/A) sampling. With this method, only the presence or absence of species on plots is registered. Thus, the registration is either 1 or 0. From a practical point of view, P/A sampling has appealing properties in its simplicity of application. Moreover, many studies indicate that it is less influenced by surveyor judgement than is cover assessment. From a theoretical point of view, changes in the proportion of presences are, however, not very intuitive measures of vegetation change. Clearly, the size of the plots used will influence the results. For example, if very large plots are used, dramatic decreases in abundance of a common species may occur before it is observed in the data. With very small plots, the P/A sampling method becomes identical with the point frequency method.

Due to the appealing properties of the P/A sampling method from the point of view of fieldwork,

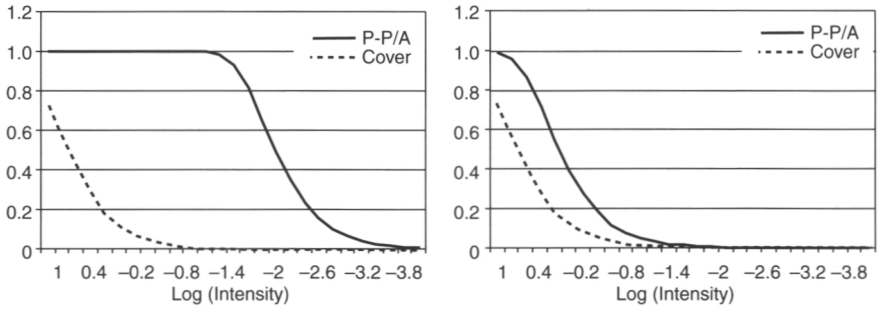


Fig. 1. Theoretical results for vegetation cover and proportion of plots with presence, using circular sample plots with radius 5.64 m (left) and 0.2 m (right). Note the log(10)-scale on the x-axis, which tells the intensity (number of plants per m^2) of the Poisson process.

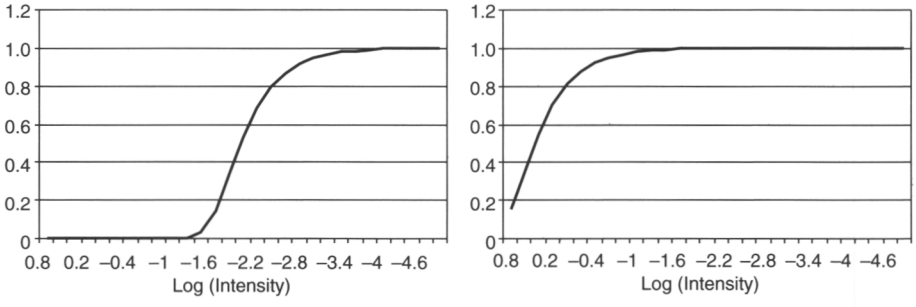


Fig. 2. The ratio between the relative change in the proportion of presences and the relative change in cover, using circular sample plots with radius 5.64 m (left) and 0.2 m (right). Note the log(10)-scale on the x-axis, which tells the intensity (number of plants per m^2) of the Poisson process.

it is interesting to further study its applicability in vegetation surveys. Work in this direction is currently going on at SLU in Umeå. It involves both how to interpret data on P/A changes and the accuracy of P/A estimates of changes, compared to other methods. Although this area has been extensively studied by statistical ecologists in the past, it appears that further work, related to the use of P/A sampling, is still worthwhile.

Some examples of how to interpret changes in presence proportions are presented below, where a simple Poisson assumption has been used regarding the distribution of plants within an area. Moreover, all plants were assumed to be circular in shape (0.2 m radius), and circular plots were assumed for the assessment of presence or absence of plants.

An appealing property of the assessment of vegetation cover is that it is intuitive to interpret figures on changes (provided that there are no measurement errors). This is not the case in P/A sampling, where the size of the plots used plays a prominent role. Therefore, some examples of the correspondence between cover and P/A data are shown in Fig. 1, for different abundances of the model species.

Looking at Fig. 1, it is clear that the plot size plays a very prominent role in the interpretation of results in P/A sampling. With large plots (100 m^2, as in the Swedish national monitoring of forest vegetation), a lot may happen regarding the abundance of a species before this is identified in the P/A data. With small plots, changes are captured in a better way (although more plots are

most likely needed in order to obtain results with reasonable precision).

Regarding the interpretation of results, one nice feature would be if the relative change in P/A data corresponded to the relative change in vegetation cover. For example, if one uses such P/A method (plot size) that a decrease in presences by 50% also implies that the cover has decreased by 50%, then the interpretation of results from P/A sampling would be straightforward. For this reason, the ratios of the relative changes in the proportion of presences and the corresponding relative changes in cover are shown in Fig. 2, for the two cases brought up in Fig. 1.

Studying Fig. 2, it is seen that the relative change in P/A data rather quickly tends to be similar to the relative change in cover, when small plots are used (the ratio quite quickly tends to 1). However, this is not the case when large plots are used, unless the species of interest is very sparse. In this case (under the Poisson assumption) even large plots tell an easily interpreted story about the vegetation changes when P/A sampling is used.

Classification of Protected Forest Areas for International Cooperative Work

Stein M. Tomter

Norwegian Institute of Land Inventory
P.O. Box 115, NO-1431 Ås, Norway
e-mail: stein.tomter@nijos.no

Abstract

UN-ECE/FAO has conducted the Temperate and Boreal Forest Resources Assessment 2000 (TBFRA 2000), which aims at collecting and presenting harmonised forest statistics for Europe, CIS, North America, Australia, Japan and New Zealand. When analyzing the original data received for the assessment, obvious comparability problems were detected for the protected areas. The correspondents were asked to report their country's protected forest area according to the IUCN (The World Conservation Union) categories. Indications were strong that the IUCN categories had been interpreted somewhat differently by the correspondents. In view of these problems it was decided to carry out a supplementary enquiry as a cooperation between the ECE/FAO, the COST Action E4 (Forest Reserves Reserves Network in Europe) and the MCPFE (Ministerial Conference on the Protection of Forests in Europe). On the basis of information on protection regimes which had been included in the data reported for the TBFRA 2000 and a more detailed description of these regimes, it was hoped that it would be possible to improve comparability and obtain a better overview of the situation.

The enquiry forms were distributed by the Timber Section, UN/ECE in December 1999. By end of August 2000, 35 countries out of totally 55 had provided information on their protected forest areas, and 279 different protection regimes had been described. The attributes included in this enquiry were the following:

- IUCN category
- Legal basis
- Management objectives
- Main operations forbidden
- How is compliance with the regime monitored? How are results of regime measured?
- Definitions of forest and other wooded land applied
- Area covered by the regime
- List of areas covered by the regime

An Access database containing the descriptions of the protection regimes has been created. As a basis for discussion on the pan-European approach to a classification for protected forest areas, a proposal was made.

The MCPFE working group in September 2000 concluded that protected forest areas had to comply to the following general principles in order to be classified according to the proposed system:

- Existence of legal basis
- Long term commitment
- Explicit designation as protected area

Main management objectives and restrictions to interventions were taken as distinguishing factors, consequently five different categories were identified:

A0: Management objective biodiversity; no active intervention
A1: Management objective biodiversity; minimum intervention
A2: Management objective biodiversity; management for achieving conservation objective
B: Management objective "protective functions" (soil, water, natural hazards)
C: Management objective "protection of landscapes and specific natural elements"

A preparatory meeting on classification of protected areas was convened in April 2001. The participants discussed the initial MCPFE classification and especially its linkage to the IUCN Protected Area Management categories and European data collection systems. The group confirmed the main conclusions from the previous working group and recommended to re-assign the data to the refined classification.

Before carrying out the classification for all protection regimes, a number of practical problems will have to be solved. Among those are harmonisation of forest definition, assignment of non-homogeneous protection regimes, handling possible exceptions from the main rules and finding unambiguous definitions of the terms describing the categories.

Provided that the requested data can be obtained from a majority of countries, it is expected that the new classification system will contribute to an improvement of future forest resource assessments and to international cooperation like the pan-European process.

Forest Management Planning

Avvirk-2000

Kåre Hobbelstad

Norwegian Institute of Land Inventory
P.O. Box 115, NO-1431 Ås, Norway
e-mail: kaare.hobbelstad@nijos.no

1 Introduction

Avvirk-2000 is a program for strategic planning. The program calculates the yield and economic result of different cutting regimes and different investment regimes in forest regeneration and forest tending. The model can also be used for forest property value estimation and for value compensation in expropriation of forest land.

The model is a deterministic simulation model. The program is specially made for forest planning, and is based on forest stands as input units. It can also be used for regional analyses based on plot data from the national forest inventory as input units. The maximum number of input units is ten thousand units.The model calculates for a 100 years period, which is divided into ten 10-year periods. All activities are supposed to take place in the middle of each 10-year period.

2 Model Structure

The model structure and data flow is shown in Fig. 1.

The model is based on inventory data for forest state information and user defined information concerning treatment assumptions and harvest strategy. The result files describe the consequenses of the strategies with respect to economic result, yield and forest and stand development.

3 Input Data

There are two types of input data. The first type of data describes the current forest state and is based on inventory data from all stands. The second type of data is desicion variables decided by the forest owner. There are two types of decision data, globally and locally. The global data is valid for the whole forest, while the local data is needed when the policy for a single stand for some reason differs from the policy for the whole forest. The local decision variables overrule the global decision variables.

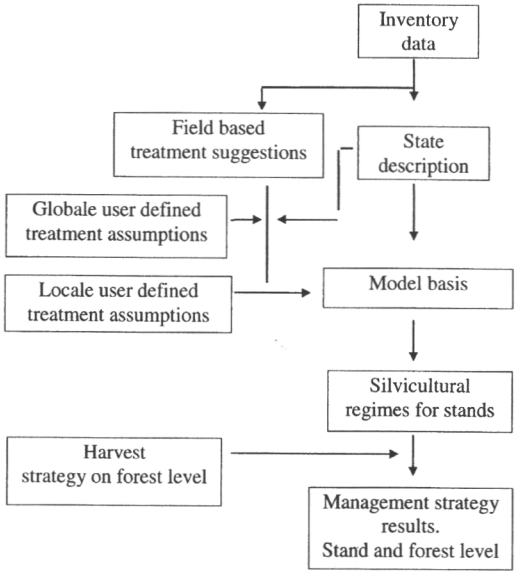


Fig. 1. Main featurs and data flow of AVVIRK-2000.

3.1 Stand Data

The stand data is used for estimation of the future yield, timber value, harvest costs and costs for regeneration and tending etc.

Important variables for yield estimation are: site quality, growing stock, tree species, number of trees, age, mean diameter, mean height, forest treatment etc. Variables needed for price and cost estimation are tree species, mean tree size, timber quality, transport distance, harvesting difficulties etc.

3.2 Global Decision Data

Some of the global data is valid for the whole forest, and some are connected to special area characteristics in the forest, eg. site index. The first type includes price assumptions for different assortments and harvest methods as manual logging system or mechanized logging system. Decision variables connected to site index are lowest age for final cutting, regeneration method (planting, natural regeneration), regeneration period, expected number of trees, expected tree species composition, cost of regeneration and tending, thinning regime, expected timber assortments, increment corrections etc.

The cutting regime has to be chosen by the user. The alternatives are the following: balance quantity, user defined harvest quantity for a number of 10-year periods and then balance quantity, harvest at a certain age depending on site class, harvesting at a certain value increment percentage.

3.3 Local Decision Data

For some reason a stand may be treated differently than according to the general policy. This can be because of the thinning regime, regeneration regime, price and cost conditions etc. For such types of stands local decision variables can be set, which overrules the global decision data.

4 Area Types

It is possible to classify a stand or parts of a stand into four different area types. The four types of area classification are

1. normal treatment,
2. ecological border zone,
3. scenic border zone, and
4. no harvest (key biotopes).

The different area types imply different treatment. In the ecological border zone no cutting is assumed untill a certain age. After that age a stable situation is established where the user is supposed to harvest a quantity corresponding to the increment within a 10-year period.

A scenic border zone is supposed to prevent view into an adjacent area under regeneration until the forest has reached a certain height. Old forest, therefore, is not allowed to be cut, until adjacent areas are regenerated and have reached the decided height, e.g. 2 m.

Areas with no harvest are expected to establish a stable state 40 years after the age for normal mature final cutting age. This area provides no income to the owner.

A switch variable makes it possible to switch one area type to another area type. This makes it possible to calculate the overall effects of different restrictions.

5 Yield Estimation

There are three main tree species in Norway, spruce, pine and birch, and the yield estimation is based on growth functions for these species. For other species approxiations are made. The growth projections are based on the development of the "average tree" defined by basal area mean diameter and mean height weighted by basal area (Fig. 2), and the number of trees per ha for the calculated unit.

The growth functions are based on experimental permanent sample plots administrated by Norwegian Forest Research Institute. The diameter growth models are according to Blingsmo (1984) and the height development models are according

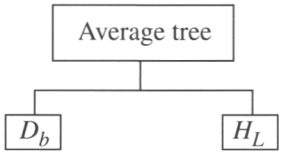


Fig. 2. Average tree

to Strand (1997), Tveite (1967, 1976, 1977) and Braastad (1977).

Mortality functions included in the model are based on Braastad (1982). New models are under development and will be implemented in the programme.

Number of thinnings are defined in the decision variables. There can be 0, 1 or 2 thinnings. The age at thinning is defined in the program according to the number of thinnings and the Hart Becking's density index, and so is also the removal of the thinning.

In young stands the site index, age and number of future trees and tree composition are the basis for yield estimation. No volume or volume increment is estimated until the dominant height of the stand has reached 9 m. At this point the mean basal area is calculated according to Braastad (1975, 1977, 1980), and the mean tree and volume for different tree species is estimated.

New stands established by the model within the computation period are generated according to the regeneration period, number of trees and tree species composition given by the decision variables.

6 Value Estimation

Timber values are estimated by means of functions of Blingsmo & Veidahl (1992) depending on tree species and D_b and H_L for each calculation unit. The functions are estimated for a basic price for sawlogs equal to 100, and a given price difference between basic sawlog price and pulp wood price. The price functions assume optimal crosscutting of the stem according to dimension, assortments and price. The value of the timber are found by multiplying the value from the price function with the corresponding basic price given as decision variable divided by 100. The price is based on theoretical cross cutting, and it is possible to correct for quality reduction both in global and local decision variables.

It is also possible to give the timber value as a decision variable. This can be relevant where it is possible to deliver special assortments.

7 Cost Estimation

7.1 Harvesting Cost

Cost estimates can be made according to manual or mechanized logging systems.

The manual system is based on harvest with chainsaw and a tractor, and the costs are calculated according to a tariff agreed between employers' and employees' organizations.

The mechanized system assumes a harvester and a forwarder, and the cost calculations are based on functions estimating production per hour (Brunberg et al. 1989, Dale et al. 1993, Dale & Stamm 1994, Dale & Kjøstelsen 1995, Eid 1998), and a decision varible given per hour cost for the machines. For both systems the cost relies on forest state variables as D_b, H_L and stems per ha, as well as field variables such as transport distance and other cost factors.

It is also possible to give harvest cost directly as a decision variable.

7.2 Regeneration Cost

Regeneration cost can be given by two different principles:

1. harvest cost or
2. investment cost.

In both cases the cost is given as a decision variable. In the first case the cost is given as a cost per m^3 for each site class, while in the second case the cost is given as a cost per area unit for each site class.

8 Cutting Policy

The cutting policy is user determined. The following options are choosable:

1. balance quantity in volume or income,
2. user determined quantity (volume or income) for some periods, then balance quantity (volume or income),
3. harvesting by a certain age, or
4. harvesting by a certain value increment percentage.

The harvesting priorities between stands are defined by the user. There are four different principles:

1. increment percent,
2. value increment percent,
3. relative priority between stands given by user, and
4. user decided period for cutting for a given stand.

The principles can to a certain degree be mixed for a given calculation.

9 Output

For a given alternative, the program gives a detailed information on both forest and stand level.

9.1 Forest Level

The following information on forest level is given for each 10 year period:

1. cutting volume distributed by thinning and final cutting,
2. cutting volume distributed by tree species and assortments (sawlogs, pulpwood),
3. income,
4. regeneration cost,
5. area distribution by site classes and cutting classes,
6. volume distribution by site classes and cutting classes, and
7. increment distribution by site classes and cutting classes.

In addition the soil expectation value is calculated for the forest based on information concerning the strategic regime for the new established forest.

Net present value is calculated based on the regimes for cutting, regeneration and tending and the state of the forest at the end of the 100 year period.

9.2 Stand Level

9.2.1 Information Related to the Middle of the 10-year Period

For each stand information will be presented for all treatments estimated in the stand for each 10-year period. The information concerning volume, income and cost for cutting (thinning, clear cutting, seed tree cutting etc), regeneration, tending etc. is given.

9.2.2 Information Related to the End of the 10-year Period

All information related to the state of the stand is given i.e. age, number of trees, tree species composition, mean diameter, mean height, volume, increment etc. This information makes it possible to start a new concequence analysis for a new 100-year period at any time within the calculation period.

In addition for each stand the net present value is calculated as well as the soil expectation value for a new established stand.

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Analysis and Planning Systems for Multi-Resource, Sustainable Forestry – the Heureka Research Programme

Ljusk Ola Eriksson and Tomas Lämås

Swedish University of Agricultural Sciences,
Department of Forest Resource Management and Geomatics
S-901 83 Umeå, Sweden
Email: ola.eriksson@resgeom.slu.se and tomas.lamas@resgeom.slu.se

Abstract

The broad range of goods and services desired and the growing concern for degradation of forest ecosystems have created a surge for improved instruments for analyses and decision support. Such tools shall enable integrated analyses of accumulated effects of timber production, other land uses, and indirect anthropogenic influences. Thereby, it should be possible to elaborate and implement management alternatives leading to desired outcomes. The recently started Heureka research programme at the Faculty of Forestry, Swedish University of Agricultural Sciences (SLU), aims at the development of such instruments. The new systems should be designed (i) with a modular structure to allow for the development of different applications, (ii) with the landscape as the basic planning unit, (iii) with the tree as the basic unit of projection of the tree layer, (iv) with models for processes interacting with the management of the tree layer, and (v) with models for risk and uncertainty of data and of model projections. A number of systems aimed at different problem formulations and users are planned. The systems will to some extent use the same model base containing models for tree growth, timber yield etc. One system is intended for regional analyses and another for strategic and tactical planning at large forest companies. These systems will replace today's Hugin system and the Forest Management Planning Package (Indelningspaketet), respectively. A third system is intended for tactical and operational planning at large forest companies. The last system will be designed for non-industrial private forest owners.

Keywords: forest management planning, planning systems, optimisation, heuristic methods

1 Introduction

The complexity of today's forest management requires new tools for management planning and for analyses of accumulated effects of anthropogenic influences. The increased complexity originates from a shift towards multiple resource management and concern for degradation of forest ecosystems. This is in contrast with the former single objective timber management prevailing in the industrial era. The recently started Heureka research programme at the Faculty of

Forestry, SLU, aim at the development of analyses and planning instruments adapted to this new setting for forest management.

During the 20th century, Swedish forestry was mainly production-oriented and timber production was a vital part of the industrial society. In Sweden, computer based analyses and planning instruments for the management of the forest resource were developed at SLU in the end of the 1970's. The most well known of these systems are the Hugin system (Lundström and Söderberg 1996) and the Forest Management Planning Package (FMPP) (Jonsson et al. 1993). These systems are still widely used and are intended for regional analyses and strategic planning at large forest companies, respectively. Apart from the computational power of computers and relevant growth and yield models, mathematical programming (MP) methods have been typical and vital parts of analyses and planning systems (see, e.g., MELA (Siitonen 1995), FORPLAN (Johnson et al. 1986), Spectrum (Camenson 1996). Desirable solutions, such as high economic yield subject to specified constraints, are often found using MP methods. The Hugin system is, however based on simulation and the FMPP had originally a certain method for finding preferred solutions. Nowadays, a linear programming module (i.e., an MP method) is optional in the FMPP (Lappi 1992).

Information concerning the initial state of the forest is another vital part in forest management analyses and planning. In Sweden, there is a strong tradition to base long-term analyses and planning on data acquired by objective methods (probability sampling). This is in line with the long tradition of the Swedish National Forest Inventory (NFI) and forest company surveys using objective methods. Data gathered by subjective methods, which is the typical methods used for data acquisition in stand registers, are in this context less desirable. Systematic errors can lead to severe mistakes when deciding cutting levels over time, including the near future. Analyses using the Hugin system are based on sample plot data from the NFI. The FMPP uses a stratified sample of stands. Each sample stand is inventoried using approximately ten circular sample plots. Another advantage using these objective methods is that individual tree information is obtained. Growth and yield models, models for calculation of cost and revenues from timber, etc., based on individual tree data are then applicable.

The FMPP is typically applied in a hierarchical setting. The system is used for the long term, strategic level where, among other things, harvest levels over time is focused. The result from this level is then transferred to the tactical planning where the formation of harvest tracts is a central task. Here, road systems, ground conditions in accordance with planned harvest season, timber assortments, etc., should be considered. The next planning level is the operational planning where timber delivery agreements and the harvest capacity of available resources are central parts. One obvious drawback using the sample stand approach in the FMPP is the weak connection between the strategic and tactical planning levels. As a result of the strategic planning process, you get good indications on how much to harvest but you are badly informed about where to harvest. Today this problem is approached in FMPP by, firstly, establishing of harvest priorities for the sample stands, and, secondly, transferring the priorities to the non-sample stands using statistical analyses and information in the stand register. The correctness of this procedure depends on what information that is available in the stand register and its accuracy.

The systems mentioned, Hugin and FMPP, are developed mainly for timber production purposes. Management of multiple forest resources increases the complexity in a number of ways. Some resources, such as biodiversity, are hard to describe and to quantify. Different resources and objectives have to be weighted against each other. Moreover, some resources such as biodiversity imply spatial aspects that considerably increase the complexity of the planning problem. For example, some species prefer "interior habitat", e.g., old forest and that is free of edge zones towards younger forest or other land. The state of a stand in terms of the area of interior habitat, is thereby not dependent of the state (age, density, etc.) of the stand itself but also of the state of adjacent stands. Very large combinatorial problems are thereby typically obtained.

The new setting for forest management and the obsolete program architecture used in existing systems have brought about an urgent need for

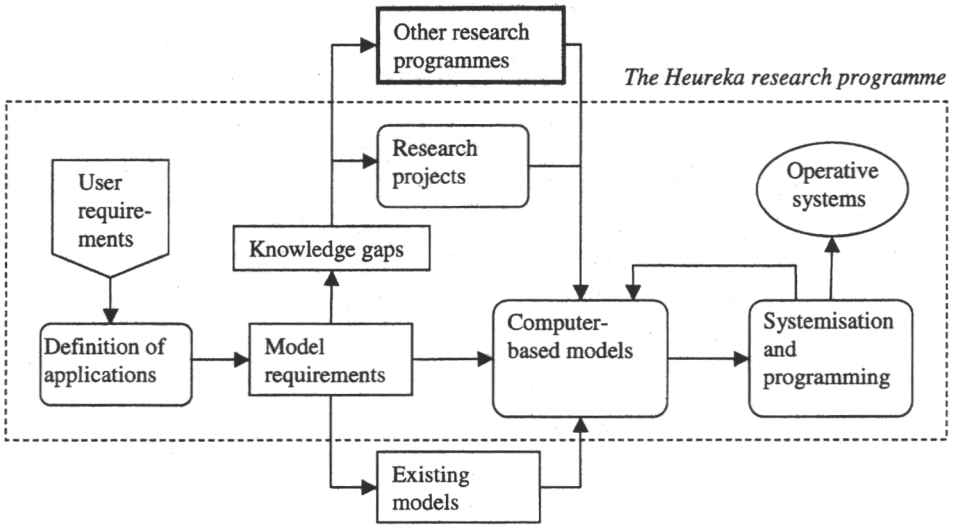


Fig. 1. A schematic view of the Heureka research programme from identification of users needs to operational analyses and planning systems. A number of feed back links do exist although not shown.

the development of a new generation of analyses and planning systems. A research programme aiming at such a development was initiated in year 2000 at the Faculty of Forestry, SLU. As described above, the complex setting makes MP methods not the only, and sometimes a less adequate, option for finding desirable solution. Alternative methods are found in a category of computerised search processes, often considered as heuristic methods. The name given to the research programme, Heureka, stems from this denomination (Dahlin et al. 1997). The research programme is a comprehensive effort to create the next generation of systems for analyses and planning. The programme is multi-disciplinary; knowledge from, e.g., ecology, soil sciences and environmental disciplines and traditional forestry disciplines is integrated in current activities.

Forest resource management can be performed on different levels and for different aims. The research programme takes its basis in the need of the users (Fig. 1). The identified needs have been supplemented with requirements and possibilities identified by researchers. Four different applications have been identified:

(1) scenario analyses on a regional and national level,
(2) strategic and tactical management planning at the (large) enterprise level,
(3) tactical and operational planning at the (large) enterprise level, and
(4) management planning for (small) non-industrial private forest owners.

The necessary models are in many cases the same in the different applications, e.g., growth and yield models. Therefore, it is efficient to develop the models within one and the same framework. In the research programme, a joint model base will be developed (Fig. 2). Necessary models will then be inter-linked to computerised and operational systems corresponding to the four applications.

It can be noticed that application (2) and (3) overlap. Both of these applications include tactical planning. The idea is that application (2), i.e., the strategic and tactical planning procedure, shall present a potential set of harvest units (stands) were considerations concerning costs for opening of road systems, fixed costs for harvest activities, seasonal aspects due to ground conditions, etc., have been taken into account. That is, not only

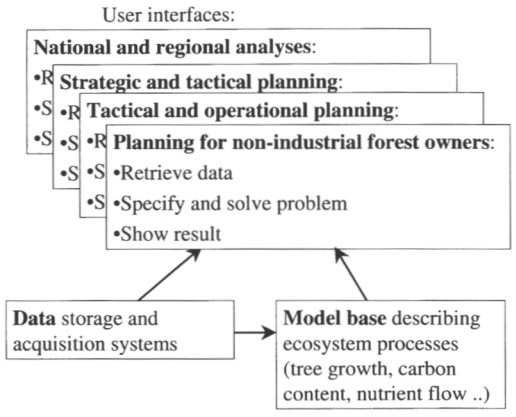


Fig. 2. The four different applications will to a large extent use a common model base. The applications 'Strategic and tactical planning', and 'Tactical and operational planning' are both intended for planning at large forest companies.

the question how much to be harvested but also were to harvest shall be proposed in this planning step. Then, this set of harvest units is refined in the tactical and operational planning procedure (i.e., application (3)) based on prevailing circumstances such as timber delivery agreements, road conditions, etc.

Concerning the application for tactical and operational planning, collaboration has been established with the Forestry Research Institute of Sweden. As this institute has more competence and experience in this field, it has the responsibility for the development of the application.

When building complex and comprehensive systems for forest management analyses and planning, there are many possibilities and alternatives but also pitfalls. How to describe the initial forest state, how to handle to huge number of decision variables and the complexity in spatial problems, are just a few examples. In the following, some central aspects will be discussed on how to model the long-term development of forest ecosystems and solve management problems. How these aspects are coped with will have implications for how growth and yield models and other ecosystem function models are addressed in the system.

2 Basic Model Concepts

The development of a comprehensive forest management planning tools requires certain common definitions. This is even more so as several different applications, as mentioned above, should share the same framework. The complexity of the task stems from the fact that large optimisation or simulation problems should be solved for large areas with many functions and associated ecosystem models.

It has from the outset of the Heureka project been stated that the systems should be able to operate with single tree models. Single tree models represent definite advantages in several respects to other more aggregate growth and yield models. They are more apt to analysis of new management principles favoured by biodiversity considerations. They also permit a more consistent connection between stand structure, management and resulting tree value. The experience from Hugin and FMPP, where single tree models are implemented, is that given that good information on single trees is available reliable projections of growth can be given. These projections will in many instances drive the development of other ecosystem models, such as the occurrence of different species groups.

Building the system on empirical single tree models also means that the system has to be time discrete. Currently, a time step of five years is used in growth projections. This is sufficient for long range projections, but could be too restrictive for tactical planning. Operational planning will be done without reference to the dynamics.

The tree does, subsequently, represent one essential building block of the systems. Two other classes are present; the raster element and the landscape. The raster elements contains trees and most other ecosystem function models. The raster elements are also used for defining spatial relations, such as edges, distances between habitats etc. Raster element would typically have a side of some 10 or 30 meters. The landscape level is an aggregation of raster elements and the biggest that is needed to model ecosystem functions. One example of a landscape level model could be a herbivore population model.

With these building blocks as a basis we will

discuss three issues that encounters the system designer and that somehow affects the way that growth and other processes can be dealt with. One refers to the possibility to look for good strategies (decisions) albeit the models that express ecosystem function are very complex (Decisions and projections). Another relates the properties of the raster model to the use of ecosystem models. And the last issue refers to how spatial problems can be expressed in the system.

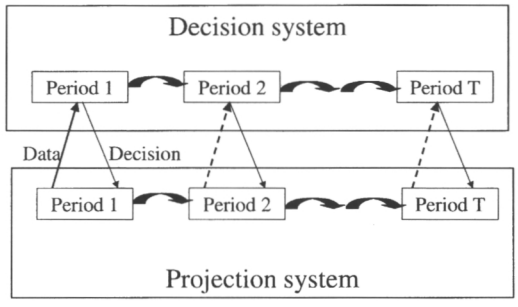


Fig. 3. The interplay between decision and projection system for making a long-range analysis.

2.1 Decisions and Projections

In most long range forest models that exist the analysis of what decisions should be applied in a forest over time and the projection of the effects of these decisions rests on identical data and ecosystem function models. In most systems the connection between analysis of decision and projection is so intimate that one can not distinguish one from the other. This is the case with the aforementioned Hugin and FMPP.

This may not be an optimal design given the large forest areas subject to analysis and the detail of data and ecosystem models. To require that all analyses, regardless of their aim and content, are performed with the same set of elaborate single tree models may mean that some kinds of problems can not be investigated. This may be particularly relevant where optimal solutions are sought. At the same time, you would not like to abandon certain ecosystem functions just because they can not be used in the optimisation process. There are, thus, a number of reasons for explicitly separating the system into a decision system and a projection system, where the former is used for determining what activities should be performed in the forest and the latter describes the result of these activities. This arrangement allows for the use of models that are adapted to the particular decision problem at hand. At the same time, the most accurate models can be used in the projection system in order to make the most reliable simulation of the development of the forest ecosystem. Of course, nothing should prevent the use of the same ecosystem functions in the decision system and the projection system.

The relation between the decision and projection systems could take on different forms. One is that the decision system is first run for the whole planning horizon and the decisions then fed into the projection system. Another is that the decision system is run and the decisions of the first period is fed into the projection system, the activities from the decision system are simulated and the forest system is projected into the second period, the state of the forest in the second period is fed into the decision system, and decisions for the second period are derived etc. (Fig 3).

There are a number of problems that needs to be considered in this approach. One is that you would like the ecosystem models of the decision system to resemble, as much as possible, the working of those of the projection system. Optimal solutions found in the decision system may not at all be optimal once you evaluate them in the projection system if, for instance, there are area production models in the decision system that does not work as the single tree models of the projection system. Another is that the decision variables of the decision system may not be the same as the activity variables of the projection system. For instance, if there are area production models in the decision system, how should the solution be transferred to the tree records of the single tree models of the projection system? Or if the decision system operates with another spatial resolution than the projection system?

2.2 Ecosystem Function Models and the Raster Model

The system will enable analyses that are spatially explicit, i.e. processes that depend on the relative

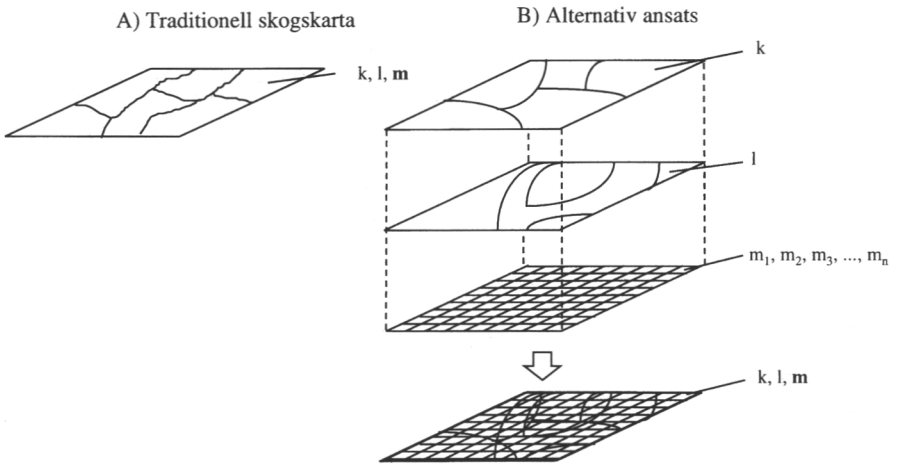


Fig. 4. The traditional forest map with all properties tied to static units (stands or compartments) and the raster model that combines data from different layers.

location of different biotopes etc. are recognised. Spatial coverage is in the Heureka system given by the content of raster elements. We will here discuss the relative merits of this approach in lieu of the operation of the projections system; we will thus not engage in the implications for the decision system.

The most obvious advantage relates to the flexibility of the raster model vis-à-vis different data sources. A traditional forest management model with spatial coverage would consist of stands or compartments. All properties of a stand are attributed to an area that essentially is assumed to be given once and for all (see Fig. 4 A). This may work well when the data sources are limited and originate from, for instance, a traditional timber cruise. As the number of different phenomena you want to project increases, the number of different sources increase as well. The hardwood corridors along creeks, locations of key habitats and places of cultural heritage may all come from different inventories. One way of bringing them together is to project them on sufficiently small raster elements (see Fig. 4 B).

Another advantage comes from the different ecosystem functions that can be integrated in a raster model. Models describing water flows that could affect stream water quality or dispersion models of slow moving, ground based species could efficiently be described in terms of transitions between raster elements. Linked to this is the versatility of the raster model in systems design. A process could be defined as a raster element model, and the systems analyst does only have to worry about the interface of that process and its interaction with other elements and processes. A wide scope of different models could be adapted to this format. This would not generally be possible with a compartment structure where the size and form varies between stands.

A last advantage to be mentioned here is the ease of implementing the code. For the programmer, and in particular for someone with modest training, writing code to manage raster elements is far easier than manipulating vector based information, which would be the alternative with a stand structured model. This hints at the same time to one disadvantage of the raster model, i.e. the size of data storage and computational requirements tend to be larger for a raster model than for a vector model.

A particular problem arises with the combination of raster model, available data and growth and yield functions. The traditional stand structured model is normally tailored such that inventory data and growth and yield models fit together. With average stand data you would use an area production model. With callipered trees from sample plots you could either turn to diameter class models or single tree models, the latter

approach used in FMPP and Hugin.

The problem of associating the raster model with the single tree model is the lack of single tree data in each and every raster element. Inventory data with single tree information can only be expected to exist but for a limited number of sample plots of the forest. One remedy is to use different remote sensing techniques by which sample plots are imputed on the raster elements that lack this information. However, at the current stage of technology more reliable estimates of average raster element properties, such as volume, can be done than to assess structural properties, such as the diameter distribution. We are subsequently left between Scylla and Charybdis; use area production models based on relatively reliable data or single tree models with less accurate information at hand. The dilemma is further compounded in cases where other ecosystem models require single tree information. One example would be the use of dispersion models of root rot. What approach is most appropriate could probably not be assessed generally but will also depend on the purpose of the management analysis.

2.3 Spatial Problems and the Raster Model

The raster model is the model par preference in the projection system as this system is assumed to operate with a full set of ecosystem function models. This is not necessarily the case with the decision system. It has to be tailored to the particular management problem, which may mean that a stand-structured model is to be preferred in certain cases. However, for a general discussion of spatial problems we will assume that the basic spatial element is a raster element (here also termed plot) and focus on the decision system. As the emphasis is on raster elements, we will not explicitly deal with the road building and maintenance problem, although it in some cases may be fathomed in the context described below.

Spatiality is in essence a relation between plots. These relations have two different sources; they are a consequence of managerial constraints or model relationships. Table 1 gives some examples to clarify the point. It should be emphasised that spatiality, to be of interest here, is an endogenous property: a spatial pattern emerges as the result of the solution to the decision problem. Spatial patterns could also be formed in advance, or exogenous, for instance by designating corridor networks in the landscape. However, from a system's point of view this means that one need not analyse the relation between plots in the decision problems as the range of treatments of the corridor elements is already set.

The managerial constraints implicating spatiality are aiming specifically at some arrangement of raster elements while model relationships will connect elements by producing certain outputs or states as a consequence of a certain pattern. These products or states should be associated with a requirement in order to form part of the decision problem; else the models could be left out. The distinction between the two different kinds of spatial relationships is not only principal but hints at some properties of spatial problems. It appears as though managerial constraints are of a 0/1-nature, i.e., either a relation exists or not (e.g. an adjacency requirement is either satisfied or not), whereas model relationships are mediated by continuous variables (e.g. water flux between two elements is influenced marginally by a harvesting action, not turned on or off).

From this typology we could distinguish between the following problem types (Table 2). From a systems analysis perspective the types

Table 1. Different sources of spatial relationships

Managerial constraints
– Adjacency requirements
– Core area requirements
Model relationships
– Wind throw model
– Root rot model
– Water flow model
– Harvesting cost model

Table 2. Different spatial problem types

No.	Spatial managerial constraints	Spatial model relationships
#1		
#2	X	
#3		X
#4	X	X

could be meaningful as we believe that they require different strategies to reduce problem size or complexity, require different solution techniques, result in different coupling problems with respect to the projection system, and, finally, elicit different research needs.

Type #1: This problem type represents the classic a-spatial problem. There are a number of well-known techniques for solving the problem, where linear programming (LP) normally would be at the heart. Still, given the size of a full-scale raster model on the landscape level it is necessary to find ways of reducing problem size.

Type #2: Within this group you will find the most extensively discussed spatial optimisation problems. By and large they are a product of biodiversity related considerations that relate to amount of habitats, size of patches, geometry of patches, connections between patches and, finally, edges. The items would probably also cover issues relevant to other values, such as recreation, hunting and rein-deer herding. Achieving solutions that optimise or satisfies quantities associated with the aforementioned items results, in turn, in a few other classes of spatial problems:

Adjacency problems: This class of problems is normally taken to mean that certain phenomena should not be located too close, i.e. they should not be adjacent. This class has been investigated quite thoroughly and efficient methods exist, ranging from graph theory over integer and non-linear programming to heuristics.

Aggregation problems: Here, certain phenomena achieve their quality by aggregation of land with some property and are often connected to efforts of reducing fragmentation of the landscape. These problems are more problematic than adjacency problems, or at least less effort has been put in solving them. Rarely anything but heuristics has been used for optimisation of problems of considerable size.

Network problems: The problem implicates that certain phenomena should be connected or the diffusion rate between locations should be upheld. The key habitat – corridor landscape planning model is an instance of this class. Few forestry studies of this problem have been described in the literature, possibly implicating that they are very difficult to solve.

Type #3: We assume that this kind of spatiality normally involves continuous variables connecting adjacent plots. A typical example would be the water transport along a slope. A more complex relationship exists where wind throw risks depends on the properties of a whole set of plots. There are few studies forest planning studies of this kind, possibly because the spatial relationships are often encompassed within the compartment. The possibilities to include these aspects in the decision model will hinge on the properties of the relationships. Are relationships continuous and convex, can they be approximated in the decision system etc?

Type #4: This will designate problems that combine interrelationships of type #2 and #3. The difficulty of solving problems of this type could be expected to be even greater than for any one of them as techniques that may be efficient for one of them may not be applicable to the combined problem. For instance, an integer programming formulation of a problem of type #2 may not be efficient when confounded by aspects of type #3. In most cases will heuristics, that are robust with respect to the mathematical structure of the problem, be the likely method for this kind of problems.

3 Concluding Remarks

This paper presents some of the challenges that need to be confronted in the development of a new generation of planning systems. It is emphasised that design principles are applied that are consistent with the management problems, the scientific knowledge of ecosystem processes and the capability of data acquisition systems. The properties of the growth and yield models that are used in the construction of the systems are crucial. They should be capable of answering to the questions of forest management in a multi-resource context. They should also be reliable and conform to available data. The importance of growth and yield models is further stressed as they often act as prime movers for other ecosystem models. As has been pointed out, this may require that a set of different growth and yield models is employed in various phases of the problem solving process.

Yet another challenge in the project refers to the multidisciplinary nature of the project. To bring researchers from different disciplines together is never a smooth process. And we can at this point only anticipate all the bewildered discussions to come. What is encouraging is the commitment with which different research groups have engaged in the project. One reason for this interest is the fact that, with Heureka aiming at assistance to the practical forester, researchers from different areas have come to identify Heureka as a very efficient mediator of research results.

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A Blueprint of the Hugin II System

Torgny Lind

Swedish University of Agricultural Sciences,
Department of Forest Resource Management and Geomatics
S-901 83 Umeå, Sweden
e-mail: torgny.lind@resgeom.slu.se

Abstract

In Sweden, the Hugin system, a system for long-term forecasts of timber yields and potential cut has been used since the beginning of the 1980's. The analyses made by the system have mainly been related to timber production at regional and national level.

Since the start of the development of the Hugin system, aims and direction of the forest management has changed. The forest management nowadays considers sustainability of the entire ecosystem and not only sustainable timber production. The higher demands on the Hugin system as a result of this change are difficult to achieve within present system design and with current form of data describing initial forest state.

Within the Heureka programme, a new system for regional and national planning will be developed aiming at analyses of a broader range of goods and services, such as biodiversity, soil and water, political instruments of control, and carbon sequestration. Raster elements with assigned forest data will be used as basic units for calculations, resulting in a spatial continuous description of the forest landscape. Many available data sources will be used such as national forest inventory data, remote sensing data, digital map data and combinations of these sources.

1 Introduction

In Sweden, the Hugin system (Lundström and Söderberg 1996), a system for long-term forecasts of timber yields and potential cut has been used since the beginning of the 1980's. The analyses made by the system have mainly been related to timber production at regional level. It has been used for three nation-wide analyses in 1985, 1992 and 1999 (Bengtsson et al. 1989, SOU 1992, Skogsstyrelsen 2000)

Since the end of the 1970's, when the development of the Hugin system started, aims and direction of the forest management has changed. The forest management nowadays considers sustainability of the entire ecosystem and not only sustainable timber production (Hytönen 1995). The higher demands on the Hugin system, as a result of this change, are difficult to achieve within present system design and with the current input data.

The new system for national and regional planning, that will be developed within the Heureka programme (Dahlin et al. 1997) and replace the current Hugin system, aims at analyses of a broader range of goods and services, such as biodiversity, climate and soil, political instruments of control, and carbon sequestration. The outcome of the Heureka programme will be four systems for forest management planning at different planning levels; national and regional planning, strategic and tactical planning at companies, operational planning at companies and for small private forest owners.

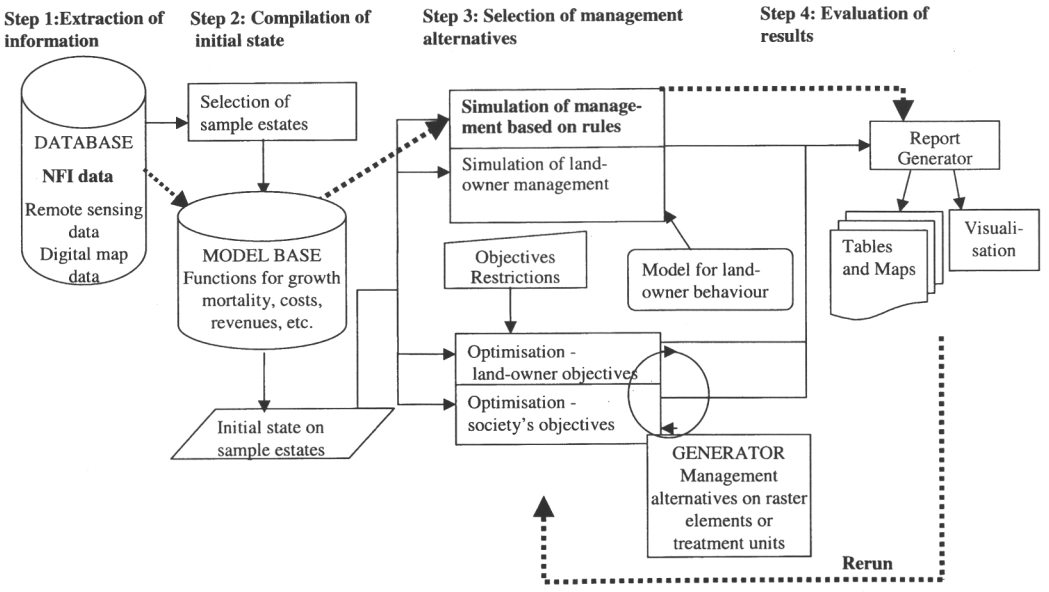


Fig. 1. Outline of the national and regional forest management planning system. (The outline of the current Hugin system is indicated with bold text).

2 The New National and Regional Planning System

In the new system, raster elements will constitute the basic calculation units in contrast to the current Hugin system using national forest inventory (NFI) sample plots as the basic calculation units (Ranneby et al. 1987). This because many of the new analyses demand spatially continuous description of the forest landscape to be able, in an adequate way, to answer what will happen with the ecosystem in the future. Another principal idea is to some extent use the same model base in all systems to decrease the development costs. The outline can be divided in four steps in accordance with executing order (Fig 1).

2.1 Extraction of Information (Step 1)

The type of analysis determines which data sources that will be used, together with costs for and quality of the data source. The best possible data sources and efficient combinations of them will be used, such as NFI data, digital map data, and remote sensing data. These data will be assigned to raster elements by using best possible method for assignment, for instance the kNN method (e.g. Nilsson 1997, Katila and Tomppo 2001) (Fig 2).

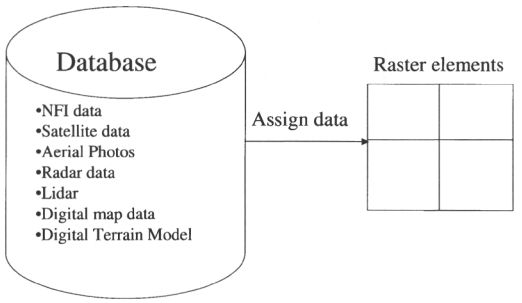


Fig. 2. Data input to system.

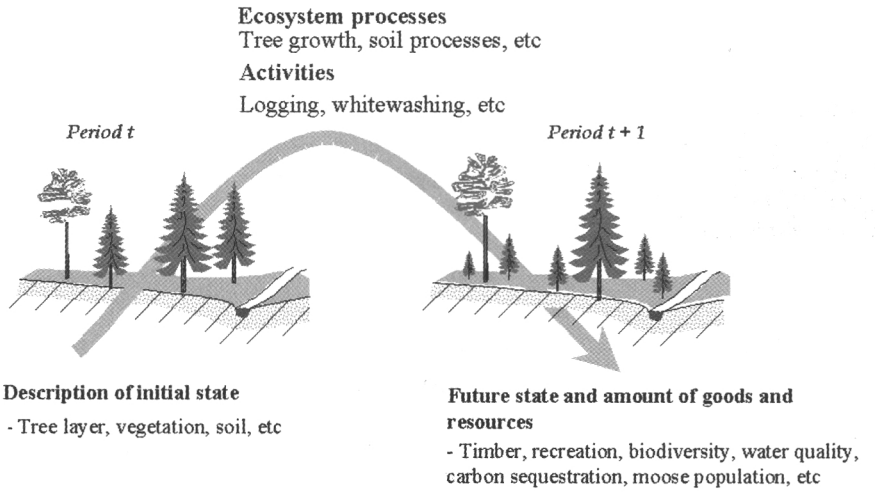


Fig. 3. Prognoses of state and output of goods and services predicted by models for ecosystem and activities.

2.2 Compilation of Initial State (Step 2)

The most important process in the system is the development of the tree layer. Growth of single trees will be estimated with dynamic models (Söderberg 1986, ProdMod 2001 1998) and most of the other processes are estimated as a result of the tree layer development (Fig. 3). Before the start of a calculation, an initial state of the forest must be available. The model base (Fig. 1) consist of functions calculating values of variables not available from step 1 and functions for simulating the future development of tree layer, division into assortments, costs and revenues from timber, biomass functions, etc. New functions not included in the present Hugin system will be included, such as functions calculating amount of carbon in soil and trees, volume and occurrence of dead wood (Kruys 2000), etc.

The concept of using raster elements as basic calculation units leads to large amounts of data and time consuming calculations. A way to reduce the amount of data and time for calculations is to sample a number of areas corresponding to forest estates inside the region for the calculations.

The reason for this, besides the reduction of data amount, is that half of the forest land in Sweden is owned by small non-industrial private forest owners. These owners are the actual decision-makers and the idea is to simulate or optimise their management within the system to analyse how changes in forest policy, legislation, prices etc. effect these owners' forest management behaviour. Another reason is that spatial restrictions connected to individual estates can be dealt with, such as maximum allowable size of clear-felled areas and proportion of young forest. Nature conservation is often also dealt with within individual estates.

2.3 Selection of Management Alternatives (Step 3)

Two basic principles for selection of management alternatives and four different approaches will probably be used:

1. Simulation of forest management activities according to rules based on silviculture management considerations.
2. Simulation of forest management based on forest owners' decisions.
3. Optimisation of forest management based on objectives of forest owners.
4. Optimisation of forest management based on society's objectives

In case 1 and 2, the results will be a consequence of initial state, prognoses of development of the forest ecosystem (Fig. 3) and the forest management applied based on rules or simulation of forest owners' decisions. The results of an optimisation, (case 3 and 4) will be the sum of the best management alternatives selected among generated alternatives that fulfil the objectives and restrictions.

2.4 Evaluation of Results (Step 4)

Step number four can be looked upon as an advanced report generator. The results from the calculations will be evaluated by looking at tables and maps. After evaluating the results reruns can be made, if required, with changes in step 3 and new evaluations in step 4. This iterativ process can continue until the calculations fulfil the goals of the analyses specified by the user of the system.

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The Finnish MELA System and On-going Research Projects

Tuula Nuutinen, Leena Kärkkäinen and Eero Muinonen

Finnish Forest Research Institute, Joensuu Research Centre
P.O. Box 68, FIN-80101 Joensuu, Finland
e-mail: tuula.nuutinen@metla.fi; leena.karkkainen@metla.fi; eero.muinonen@metla.fi

1 Background

The second round of regional forest programmes was finished in March 2001, as a follow-up to the first Finnish National Forest Programme (1999). Using the Finnish MELA system, a set of scenarios was produced. Their definition was an interactive process between the MELA Team and the regional forestry centres responsible for the preparation of programmes (Fig. 1). Three basic scenarios and an additional analysis to study the regional effects of some certification criteria were defined. In addition, a scenario for each region was defined to correspond to the chosen production program. The main results of the analysis were published in the Internet as tables and graphs (http://www.metla.fi/metinfo/mela).

In this paper the MELA system refers to the information system built and used by the MELA Team for regional and national timber production analyses. The MELA system contains the MELA software, tools for processing forest resource data into regional MELA data sets, applications for updating forest resource data and analyses of timber production possibilities, and tools for producing the graphs. The applications are here defined by scenario parameters such as the silvicultural instructions and economic information used in the simulation, and the problem description for the optimisation. The system has been used since the 1980s for several rounds of national and regional timber production analyses.

The revision and updating of programmes should be possible whenever the decision or policy environment changes. Therefore, the information system should have always up-to-date data sets covering the area of interest. The system should support interactive definition of scenarios and provide visualisation and interpretation of the numerical results and their sensitivity. As a part of participatory process, impact analyses have become a standard routine. Therefore, information needs on other forest products and services than timber are increasing. In addition, there is increasing pressure to transfer the strategic plans to operational district level goals.

In the future the emphasis of the research and development around the MELA system is laid on the development of background scenarios on demand and supply of timber – as well as other forest products and services, and the related sensitivity analyses. There are on-going projects to study the most effective combination of models

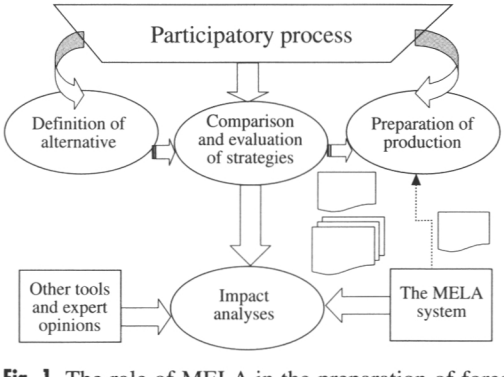


Fig. 1. The role of MELA in the preparation of forest programmes.

and data in updating forest resource information, and to develop tools to support participatory process. The most recent projects focus on developing methods for impact analyses and integrating data sources for district level calculations.

2 Methods for Impact Analyses

In the project "Climate change impacts on the dynamics of functioning and structure of boreal forests with implications for the sustainability of forest production and carbon sequestration" (2000–02), models for biomass, carbon and climate change are incorporated into the MELA software to be used in impact analyses.

In the first phase the existing biomass and carbon models are explored and the preliminary testing of the models is made. Permanent sample plot data sets are used for the testing of the models. The test material includes also biomass sample plot data of Finnish Forest Research Institute. The results of different biomass models are compared to each other and to previous research results both at the tree and forest level. The sensitivity of the models when the values of the variables are changed is also analysed.

Then the most representative models are integrated to the MELA system for the regional forestry analyses based on the NFI data. The aim of the analyses is to study how the amount of carbon sequestrated by trees varies under different management strategies and production goals (Nuutinen & Kellomäki 2001).

Finally, the variables describing the effects of climate change are transfered from the process-based FinnFor model (Kellomäki & Väisänen 1997) to the MELA system and simulations using different climate change scenarios are made.

As a part of the MELA system the new models can be used to take into account the effects of climate change in regional and national forestry analyses. The feasibility of the MELA system for producing the annual carbon balance as a part of forest statistics will be tested. When integrated with the stand information systems the software tools make it also possible to study the carbon flows caused by enterprises (environmental impact assessment).

3 Integrating Data Sources for District Level Analyses

In the project "Methods for statistical integration of satellite imagery and GIS data for spatial analysis in forest planning" (2000–2003, financed by the Ministry of Agriculture and Forestry) a new method to utilise GIS and remote sensing data for district level forestry analyses is tested. The starting point for the methods is presented by Lappi (2001). The study material consist of sample plot data from the 9th Finnish National Forest Inventory from Eastern Finland, digital map data and Landsat 7 ETM+ satellite image data.

In the project, calibration estimation is applied and tested in computing area weighting for the sample plot material. This area weighting forms an input to the MELA system for forest planning and analyses. The prior information can be used to define the area of interest and the reference area whose sample plot data are utilised. Further aspects to be taken into account in the project come from defining the interface between sample plot data definitions and the MELA system, and processing the effects of possible map errors in the digital map data.

Because the method does not straight produce a map, the further steps of the project focus on experimenting with the map production together with the MELA analysis.

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On Risk and Uncertainty in Forest Management Planning Systems

Peter Lohmander

Swedish University of Agricultural Sciences, Department of Forest Economics
S-901 83 Umeå, Sweden.
e-mail: plohmander@hotmail.com
www.Lohmander.com and www.sekon.SLU.se/~PLO

Abstract

The research area is primarily defined as "optimization of decisions under risk". This includes solution methods and definitions of problems and objectives. The optimal decisions are usually not the same under risk and certainty. This is true when we discuss forest plantation planning, thinning programs, final fellings and many other forest management decision problems. As new information concerning prices, costs, growth, physical damages etc. appears over time, which is typically the case in forest management decision problems, it is valuable to be able to adapt the management decisions to the latest information. Hence, it is important to create the optimal set of future options. These options are options to make optimal adaptive decisions based on the latest revealed state of the forest stands and of the world in general. Optimal decision rules and expected present values from harvesting when there are economies of scale and stochastic prices will be reported. More information including web software is found here: www.Lohmander.com and www.sekon.SLU.se/~PLO.

1 Introduction and the Links to the HEUREKA Program

The research area is primarily defined as "optimization of decisions under risk". This includes solution methods and definitions of problems and objectives.

Within the research area, we find:

- General methods to handle stochastic processes in forest management.
- Optimization methods for very large problems (with very large numbers of decision variables).
- Methods for optimization of large problems with linked sub problems.

It is very important that the complete problems are considered. Hence, too restricted problem definitions should be avoided. The solutions (and solution methods) should be as general as possible.

The ambition is that, after the project, the best possible algorithms for optimization of multi-objective decision problems under risk should be available. The algorithms should be possible to implement in computerized forest management systems.

The Swedish forest act and the HEUREKA research program stress the objectives "timber production" and "environmental objectives" (targets). Explicit formulations and transformations of these and related objectives are necessary and will be an important part of the research. In several cases, it is expected that other objectives and constraints also have to be considered.

These may, for instance, concern round wood

logistics and road investments.

Forest industrial planning in saw mills, pulp and paper mills and labour market considerations should perhaps be directly linked to the planning of forest management in some cases.

2 The Tree Species in the Forest Stands

In very large parts of the forest areas, it is possible to select different species. In most areas in Sweden, it is possible to grow pine, spruce or birch and, in many cases, other species. You can also let these species grow in different combinations in the same stands. A common opinion in traditional forest management is that the properties of the site determine the "best" species for the site. You can hear some older forest managers say: "This is a spruce site." As a basis for such evaluations, the traditional view is that the average volume growth per hectare with different species on the site is sufficient information. Selection criteria such as present values, based on the rates of interest in the capital market, have usually been ignored. A slightly more modern version of the traditional approach is to apply "site adapted forestry".

Of course, it is clever and necessary to take the properties of the site into account when forest management activities are planned. On the other hand, several very important parameters in the forest management planning problem are not functions of the site in isolation.

In order to be more adapted to the relevant situation, we should not only be "site adapted". The activities in the forest stand should be adapted to the site, to the market prices, to the financial market, to the cost functions of harvesting and plantation activities, to the local labour market, to the environmental regulations and so on.

If we do not adapt the forest management activities to those things, we do not care about the consequences of forestry to firms, individuals and the society.

3 Risk and Uncertainty in Forestry and General Perspectives

We do not know the exact future developments of prices, biological growth, the climate, the acidity of soils, insect damages, moose damages, rodent damages, fungi damages, windthrow damages and so on.

More reliable information concerning all of these things will appear later. In most cases, we can not be perfectly sure about anything before it has really happened.

One perspective on this situation, sometimes put forward by traditional forest managers, is the following: "Since the growth in the forest can be well predicted several decades ahead and since the markets are random, we should not care about the markets. We should just make the forest grow as well as possible."

According to such a view, the purpose of forestry is not to contribute as much as possible to the wealth of individuals, firms or the society. Costs, time preferences and revenues of the society, of individuals and of firms are simply ignored. Forest management decisions are taken without the ambition to coordinate the activities in the forest to the activities in the rest of the world in the best possible way.

The rational solution to the problem is the following:

We should accept the fact that all relevant information is not available in advance. This means that we should accept that it probably turns out to be optimal to deviate from long term plans.

Hence, we should not just make detailed long term plans and ignore the true structure of information.

We should explicitly take the fact into account that information sequentially appears over time and that the best decisions have to be conditional on the true and not yet known outcomes.

One example: If prices fall dramatically 4 years from now, it is very likely that the optimal harvest level at that point in time is lower than what you expected it to be. Of course, you should adapt harvesting to the true development of prices if you care about the surplus generated from the forest sector. This surplus covers profits to firms, wages

to individuals and taxes to society, environmental costs etc.

As a consequence of the modified harvest activity 4 years from now, the stock level in the forest 5 years from now is higher than expected. This in turn affects future growth. Hence, growth predictions based on the assumption of a predictable world also turn out to be wrong, even if the growth function in isolation is quite correct. (From the global and public debate on climatic changes, green house gases, acid rains etc. we can also expect that the forest growth has to be regarded as stochastic.)

We should also explicitly take the fact into account that the optimal activities at the present are affected by the desire to be able to adapt future decisions to future outcomes.

One example of this is the following: If you assume that the forest roads will have average quality during a particular year and your mission is to plan the cost minimizing logistics (transport and stocks) solution of your forest company, you probably suggest the lowest possible roundwood stocks. Stocks represent costs and costs should be avoided. But, since most years deviate from the average year, heavy rains and melting snow lower the quality of the forest roads very much during some years. This means that, perhaps 50% of the years, the roads are worse than expected. Then, if you have roundwood stocks that are sufficient only during a "standard year", then you have to close the mill for some time. That may be *very* costly.

In this case, it is obvious that the optimal stock policy has to be based on the probabilities of different road quality outcomes and the costs and revenues of different activities in the firm, including the mills. A traditional transport cost minimization approach simply is irrelevant.

4 Risk and Uncertainty in Forestry and Some Specific Cases

In some cases, it is possible to estimate probability distributions (or probability density functions) of future outcomes (conditions). In several cases, such probability distributions are functions of the present state, which in turn partly is possible to control. A description of the theory and tools of optimal sequential forestry decisions under risk is reported by Lohmander (2000).

Case 1

One example of such a case is when the probability of windthrow in a particular forest stand can be estimated as a function of the average tree height, the average tree diameter, the tree species, the degree of wind protection from neighbour stands and so on. Compare Lohmander and Helles (1987). Assuming that the general weather conditions in the region are stationary, we should be able to calculate the probabilities of different windthrow outcomes in a forest area based on such functions. Such analyses have been performed and optimal harvest decisions have been determined for spatially connected stands. In such cases, it is not possible to determine the optimal decisions in one stand without considering the activities in the neighbour stands. The spatial structure of stands and the sequential possible windthrows have to be considered if the best solution is needed. More information concerning these issues is found in Lohmander (1987) and Lohmander (1988a).

Case 2

In other cases, we may have estimated the probability of moose damage in young plantations of pine (and other species) as a function of the moose density in the region, the size and density of the plantation, the availability of other tree species in different age groups etc. With such a function, it should be possible to estimate the probabilities of different moose damage outcomes.

With such information, it should be possible to determine the best combination of species and the best proportions of different species in the plantation.

In case the moose destroys most of the pine plants, then it may be very good to have a number of spruce plants too. The spruce can be selected to be the species in the older forest.

This means that the option to sequentially adjust the species frequences in the forest is important. One reason, just mentioned, is that species specific damages may take place. In advance, we

do not know if a particular damage will occur. We may however be able to estimate probability distrubutions of different possible outcomes. We may with this information determine the best initial mix of species. The decision problem is at least a two stage problem: First you determine the initial species proportions. Then you observe the damages. When you have that information, you determine which species to select for future production. In Sweden, where the moose damages are frequent and strong, this type of two stage decision problem is clearly relevant.

There is a very large number of reasons for this type of multi stage decision structure in forestry. Here we find a few:

Case 3

Climatic changes represent major concerns in the global environmental debate. Different groups have different opinions about the true development of the climate. Clearly, since different species and species proveniences will grow and survive under different possible climates to different degrees, and since the future climatic outcomes are not yet known, one way to create future options is to place plants of different species and proveniences in the same stand. If the climate turns out to become too hot for one species, you can select to keep the other species in the forest. You usually have to make at least one thinning during the life of the stand in any case.

Case 4

The acidity of soils is another environmental concern of global interest. We do not know to what extent future emissions will be reduced. Some species may grow better and some species may grow worse if the acidity increases within some intervals. Some species may not survive and some species will at least survive. Clearly, if we have at least two species with different reactions to acidity in the plantation, we have options to select species several decades from now, based on better future acidity information. Studies of this type have been reported by Lohmander (1990b) and Lohmander (1993a).

Case 5

In the same way, we can adapt future harvesting to future prices and technological inventions, if we start with several species in the young stand. Future inventions are per definition not predictable. If, at some point in time, a new pulp industry process is invented, this will almost surely affect the relative prices of different species which can be used as inputs in the process. Such events have been reported in the past. The birch pulpwood prices increased in relation to pine and spruce pulpwood prices around 1975 because of new processes in the pulp industry. We can be convinced that inventions will take place also in the future. Those inventions will almost surely affect the relative prices. Today, we can not say anything about the direction or the degree of change. We can just say that relative price changes should be expected, which in turn means that there is a positive option value of some level associated with having several species available in the same stands. Only in such situations, it is possible to sequentially change the species proportions and rapidly increase the frequency of some species in the older stands. Compare the study by Lohmander (1992a).

Case 6

Optimal "continuous" harvesting with economies of scale and stochastic prices is one of the most recent areas under analysis. The "continuous" cover and harvesting problem in forestry is defined and analyzed over an infinite horizon. Prices are described as a stochastic Markov process and the optimal harvesting policy is calculated as a function of the entering stock, the price state, the harvesting set up cost, and the rate of interest in the capital market.

When the harvesting set up cost is strictly positive, which is always the case in real applications, you have economies of scale in harvesting operations. If the harvesting set up cost increases, the optimal stock level becomes less "continuous" (when timber prices are constant). The optimal stock is however affected not only by economies of scale in harvesting operations but also by stochastic timber prices. When there are no economies of scale in harvesting operations, the optimal harvest response to price changes (for a given entering stock level) is "almost continuous".

When there are economies of scale in harvesting operations, the optimal harvest level (for a given entering stock level) changes discontinuously if the price changes. The problem is solved as a true price adaptive optimization problem. The solution to the stochastic dynamic programming problem in a Markov chain is calculated via linear programming.

Case 7
Optimal "pulse" harvesting with economies of scale and stochastic prices is another area under analysis. Economic harvest decisions in forestry under the influence of stochastic prices have earlier been optimized for individual stands. However, in most harvesting operations, there are economies of scale which implies that the optimal decisions in different stands are not independent. If you harvest many stands in the neighbourhood simultaneously, you do not have to undertake long range transport of harvesters, forwarders and labour as often as if you harvest small areas more frequently. Furthermore, the administrative costs are reduced.

In an analysis, the optimal harvest decisions and optimal expected present values are determined in a forest area with two neighbour stands as a function of the economies of scale in harvesting operations and stochastic prices. The developed model, with minor modifications, can be used for 1–20 stands or stand classes. The stands have properties typical to northern Sweden. A t=0, Stand 1 is 50 years old and Stand 2 is 70 years old.

If there are no economies of scale in harvesting operations, then the youngest stand ages at which instant harvests are optimal (if the prices are at the average levels) are 75 years in Stand 1 and 85 years in Stand 2. However, if there are economies of scale of a typical magnitude, then the youngest stand ages when instant harvests are optimal (if the prices are at the average levels) is 70 years in Stand 1 and 90 years in Stand 2. In this case, the optimal harvest ages occur earlier in the younger stand and later in the older stand, when there are economies of scale, compared to when there are no economies of scale.

Thanks to these harvest age adjustments, both stands can be harvested simultaneously and the economies of scale are taken into consideration in the optimal way.

5 Risk and Uncertainty: Some Observations

The optimal decisions are usually not the same under risk and certainty. This is true when we discuss forest plantation planning, thinning programs, final harvests and many other forest management decision problems. As new information (concerning prices, costs, growth, physical damages etc.) appears over time, which is typically the case in forest management decision problems, it is valuable to be able to adapt the management decisions to the latest information.

Hence, it is important to create the optimal set of future options. These options are options to make optimal adaptive decisions based on the latest revealed state of the forest stands and of the world in general. The examples in this text have shown that risk and decisions adapted to sequential information completely changes the structure of the decision problems.

Traditional long-term optimization is often based on multi-period linear programming models. With such models you can often handle hundreds of thousands of decisions simultaneously. However, in situations with sequential information concerning prices, costs, damages etc., which are typical in forestry, traditional long-term planning models simply become irrelevant.

If you want to handle adaptive decisions in a consistent manner with stochastic transitions over time, then the full proof solution is to apply stochastic dynamic programming. You know that the obtained solution really is a global optimum. On the other hand, in most cases, you can not treat the state and decision spaces with the same high resolution as you could with standard linear programming formulations.

However, there are options to use adaptive but approximately optimal decisions. You can determine adaptive control functions via quasi gradient optimization and stochastic simulation of the objective function. Such studies can be found here: Lohmander (1992b, 1993b, 1995b and 1997a).

Hence, decision-makers and modellers must choose. Should you prefer detailed but obviously irrelevant planning to more relevant adaptive planning? The price you usually have

to pay for the relevant adaptive optimization of decisions is that you can not keep the very high state and decision resolution, which is possible with deterministic planning models. On the other hand, the details in the long-term models will be wrong in any case, as we have seen in this text. It has been shown by a large number of researchers that the expected economic results from adaptive decisions in forestry and elsewhere are much higher than the expected results from optimization models in which you ignore the sequential structure of information. For these reasons, the author strongly advocates the use of adaptive optimization in most forestry decision problems, even if the degree of detail is strongly reduced.

Presently, models for the web are under construction covering the topics of typical decision problems in forestry. Some adaptive Java-models, which right now may be used directly over the INTERNET, are found in the reference list. More adaptive models are under development. They will be found via links from the Java library site.

Right now, these areas are investigated within the project:

1. Continuous harvesting, economies of scale and stochastic prices
2. Pulse harvesting, economies of scale and stochastic prices
3. Mixed stands, adaptive thinnings and stochastic prices
4. Mixed stands, adaptive thinnings and stochastic environmental changes
5. Pulse harvesting and stochastic fungi processes
6. Pulse harvesting and spatial stochastic damages
7. Thinning, pulse harvesting and stochastic prices
8. Optimal forestry decisions under risk when there are global constraints

The author wants to express a strong interest in cooperation with all those who find the adaptive approach interesting and relevant.

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Web Publications and Web Software:

Lohmander, P. Economic risk management in forestry and forest industry and environmental effects in a turbulent world economy (Abstract). Paper invited

to and presented at the session: OR/MS in Forestry (Operations Research and Management Science) of the INFORMS meeting in Salt Lake City, USA, May 7–10, 2000, http://www.sekon.SLU.se/~plo/abstr/SaltLC1.htm

Lohmander, P. Alternative versions of the Faustmann problem and corresponding optimal solutions. Paper presented at the International Symposium: 150 Years of the Faustmann Formula: The Consequences for Forestry and Economics in the Past, Present, and Future, October 3–6, 1999, at The Hunting Castle of Kranichstein in Darmstadt, Germany. 16 p. (Forthcoming in the proceedings from the conference) http://www.sekon.SLU.se/~PLO/Fausymp/AltFau10.htm

Lohmander, P. Economic Risk Management in Forestry and Forest Industry and Environmental Effects in a Turbulent World Economy – A project family. http://www.sekon.SLU.se/~plo/ERM/proj99.htm

Graphical illustrations to central ideas and references to results in the area: http://www.sekon.SLU.se/~PLO/heureka/hgraphs/RiskInt1.html

Java – Library: http://www.sekon.slu.se/~plo/javakod/Jlib1.htm

Market Adaptive Harvesting: http://www.sekon.SLU.se/~plo/javakod/D2.htm

Optimal market adapted stumpage sales: http://www.sekon.SLU.se/~plo/Stump00/Stump00.htm

Strategic Planning – Production Possibilities of Broadleaves

Terje Gobakken

Agricultural University of Norway, Department of Forest Sciences
P.O. Box 5044, N-1432 Ås, Norway
e-mail: terje.gobakken@isf.nlh.no

1 Introduction

The increasing concern for the preservation of biodiversity of forest ecosystems has become a great challenge for forest management all around the world. Based on present knowledge, broadleaves seem an important aspect (e.g. Angelstam 1997, Fries & Lämås 1996). Thus, the probability of important species becoming extinct may be assessed by the proportion of broadleaves among the growing stock. This may be considered a "coarse filter" approach (cf. Hunter et. al 1988), i.e. a strategy focusing on preserving communities or ecosystems. Broadleaved forest or mixtures of broadleaves and conifers do also have other favourable effects.

The appropriate total amount of broadleaves and the amount of old broadleaves have been discussed. The Norwegian regulation about pre-commercial thinning subsidies requires a 10% proportion of broadleaves in conifer forest stands (Anon. 1994). According to the Norwegian "Living Forest Standards" the general rule must be a 10% broadleaved amount on any individual property (Anon. 1999). However, requirements of 20% broadleaves were discussed during the "Living Forest Standards" development process (Anon. 1998).

The objective of this study was to examine the impact in terms of economic value and growing stock of broadleaves by applying management practices affecting the broadleaf component at stand and forest level. Thus, restricted timber management practices were adopted promoting the preservation of biodiversity.

2 Material and Methods

The study was conducted in a 4260 ha forest area in southeast Norway. The growing stock was estimated to 392900 m^3 according to the 1991 inventory. The recorded tree species in the study area were Norway spruce, Scots pine, and broadleaves, which comprised 56.3%, 38.1%, and 5.6% of total standing volume, respectively. The broadleaves in the study area were mainly birch (*Betula pendula* Roth, *B. pubescens* Ehrh.). The total number of treatment units was 7032. A treatment unit is an identifiable polygon with respect to stand and vegetation characteristics.

Numerous treatment schedules with different thinning programmes, rotation periods, etc., were simulated for each treatment unit (stand) using the GAYA stand simulator (Hoen & Eid 1990). The growth functions for mixed and single species stands developed by Agestam (1985) were used. The planning horizon was 100 years, divided into 10 periods of equal length. The silvicultural options used in the current study were mainly defined as described by Hoen et al. (1998). In addition, broadleaved oriented treatment options for regeneration by planting and pre-commercial thinning were developed. They were specified with different levels of broadleaves left in the residual stand, i.e. 0, 5, 10, 20, 35, 50, 65, 80, and 100% broadleaves of the total number of trees.

Timber values were calculated using price functions (Blingsmo & Veidahl 1992, Gobakken 2000) and current timber prices were used. The

net present value (NPV) including the value of the ending inventory was calculated for all treatment schedules. Ending inventory valuation, based on predetermined treatment schedules given for each dominating species and varying with site index, was applied.

The objective functions were maximizing of the net present value of the forest area with different constraints regarding broadleaves considered important from a biodiversity viewpoint. The biodiversity-relevant growing stock of broadleaves was defined in four different ways according to the required rate of mixture of broadleaves of total volume of all species at stand level. The four definitions of growing stock of broadleaves were: *prob. 1*) all broadleaved volume, *prob. 2*) only broadleaves in stands with more than 10% broadleaves of total volume, *prob. 3*) only broadleaves in stands with more than 30% broadleaves of total volume, *prob. 4*) only broadleaves in stands with more than 50% broadleaves of total volume. More dispersed broadleaves than the mentioned proportions were not part of the considered growing stock of broadleaves, only as part of the total growing stock.

A transition period of 50 years to establish a non-decreasing growing stock of broadleaves was applied. However, in the meantime the volume of broadleaves should not be less than current levels according to the 1991 inventory. The initial levels were 21 700, 15 400, 5800, and 3500 m^3 growing stock of broadleaves for *prob. 1–4*, respectively. The restrictions were kept for the periods 1 to 10; thereafter, no restrictions were applied. The management problems were specified as linear programming problems. A reference alternative without the constraints was also calculated.

3 Results

The objective value of the reference problem was 17 085 NOK ha^{-1} using $\bar{p}_r$ of 2.5%. Even for the reference alternative, the proportion of broadleaves increased during the planning period of 100 years. In period 5 the total growing stock, i.e. 317 000 m^3, consisted of 10.8% broadleaves. The growing stock of all species over periods 1–10 is shown in Fig. 1. However, the average proportion of broadleaves out of the total standing volume in stands with broadleaves present (1180 ha or 27.7% of total forest area) was 27.3% in period 5.

Forests change naturally over time and it takes time to change the forest structure by silviculture. The new requirements demanding increased broadleaved proportion cannot be fulfilled within only a few years. Thus, in this study a transition period of 5 periods (i.e. 45 years) to increase the broadleaved volume was applied. Different management regimes aiming at different levels of timber production and maintenance of biodiversity were applied to the study area. The production possibility frontiers or the joint production possibility curves in Fig. 2 give estimates of the considered broadleaved volume that exists and could be maintained from period 5 to the end of the planning horizon for different percentages of maximum net present value according to the reference alternative. The different curves show the frontiers if all broadleaved volume is considered (*prob. 1*), or if only broadleaved volume in stands where broadleaves comprise more than 10, 30, or 50% of the total volume (*prob. 2–4*), respectively. The curves may cross since requirements for the initial volumes of broadleaves corresponding to the 1991 inventory differ for *prob. 1–4*.

A 32 500 m^3 growing stock of broadleaves, i.e. approximately 10% of the total growing stock of all species, reduced the NPV from 0.0 to 0.4% for the different problems. The reduction in NPV was somewhat higher when all broadleaved volume was considered (*prob. 1*) compared to when only volume in stands with at least 10% broadleaves of total volume was required (*prob. 2*). The high initial volume for *prob. 1* required a large amount of forest to be saved to satisfy a non-declining broadleaved volume compared to initial volume. When all broadleaves were considered (*prob. 1*),

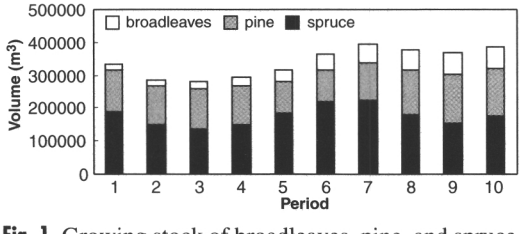


Fig. 1. Growing stock of broadleaves, pine, and spruce over periods for the reference alternative.

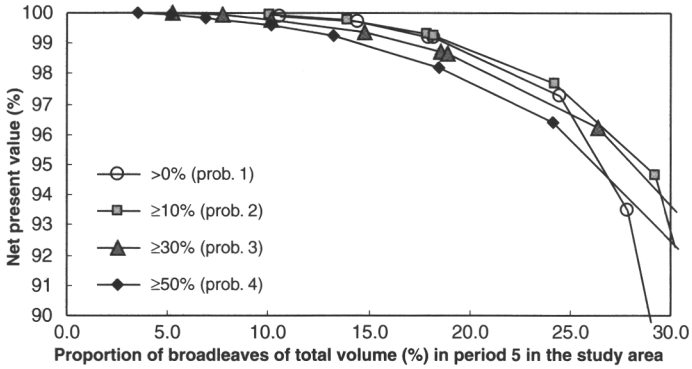


Fig. 2. Production possibility frontiers for different definitions of growing stock of broadleaves (*prob. 1–4*). The definitions were: all broadleaved volume considered (*prob. 1*), only broadleaved volume in stand where broadleaves comprise more than 10% (*prob. 2*), 30% (*prob. 3*), or 50% (*prob. 4*) of the total growing stock considered.

it was optimal to produce more than 32 500 m^3 broadleaves in period 5. The forest areas allocated to different proportions of broadleaves were changing according to how considered broadleaves were defined. For example, in period 5, the area covered with more than 50% broadleaves was more than 31% larger when broadleaves in stands with more than 50% broadleaves were considered (*prob. 4*), compared to when all broadleaves were evaluated (*prob. 1*).

If 65 000 m^3 growing stock of broadleaves, i.e. approximately 20% of the total, is required, the reductions in net present values compared to the reference alternative were approximately 0.8%, 0.7%, 1.3%, and 1.8% for *prob. 1–4*, respectively. Compared to the reference alternative the total growing stock was lower in the first periods, when a high proportion of broadleaves at stand level was required (*prob. 3–4*).

4 Discussion

This case study takes both timber production and the non-market commodity biodiversity into account. The study shows how net present value was related to the amount of broadleaves with different properties and requirements. In making the choice one has to strive to achieve a balance between indicators, cf. the required rate of mixture of broadleaves at stand and forest level, and objectives. If its better for the biodiversity to have a high proportion of broadleaves in the stands will, according to the current study, almost the same net present value be obtained as keeping the same forest level of broadleaves in stands with a smaller proportion.

The diversity indictor used in this study is not proposed to represent the best possible knowledge. Alternative or additional indicators should also be evaluated. However, the aim of this study was to analyse the increase of broadleaves and to evaluate how additional requirements favouring biodiversity may affect commercial forestry. The potential for preserving biodiversity was assessed based on the certain indicator of forest conditions. The success of the approach depends on how well biodiversity can be evaluated using indicators. The coarse filter approach used in this study must, however, sometimes be extended by a "fine filter", i.e. actions directed towards a particular species or groups of species.

For a more detailed observation of biodiversity connected to broadleaves, broadleaves can be broken down to specific tree species. In particular, old aspen trees are important for the survival of many threatened species of both flora and fauna (Kangas & Pukkala 1996). The stand-based approach carried out in this study differs from traditional strategic planning with aggregated stratum-based data. However, from a biodiversity

point of view, a singletree approach considering uneven aged forests or important single trees, e.g. nesting trees, would be more suitable.

The analyses showed that the effects in terms of reduced NPV of a higher proportion of broadleaves were quite small. Even for the reference alternative the proportion of broadleaves increased, which is in keeping with the trends observed for the whole country (Anon. 2000b).

The largest uncertainties were related to the assumptions for regeneration and to the modelling of tree mortality. Among the set of assumptions defining regeneration options, establishment of new forest based on natural regeneration was particularly laden with uncertainty. Possible biases also influence the estimates of growing stock and harvesting potentials in a more distant future. Mortality was modelled as a fixed proportion of the number of trees (Braastad 1982). Since the analyses were restricted to a certain area, one should be cautious in generalising conclusions. However, the study area was carefully selected in order to include a large area with a wide range of initial states of the forests.

Imperfect knowledge of the ecology of most species and their response to habitat changes due to forestry is evident. The lack of knowledge for developing habitat functions, which can be included in planning systems developed for timber productions under more varying conditions, is also an obvious shortcoming. Finally, even if complete knowledge were available for multiple-purpose planning of forestry, it would ultimately be up to the decision-maker to balance the different forest products against each other.

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MCDS Methods in Strategic Forest Management – Alternatives for the AHP

Annika Kangas[1] and Jyrki Kangas[2]

[1]University of Helsinki, Dept. of Forest Resource Management,
P.O. Box 27, FIN-00014 University of Helsinki, Finland
[2]Finnish Forest Research Institute, Joensuu Research Station
P.O. Box 68, FIN-80101 Joensuu, Finland
e-mail: annika.kangas@helsinki.fi and jyrki.kangas@metla.fi

Abstract

The Analytic Hierarchy Process (AHP) is so far the most commonly used multicriteria decision support (MCDS) method in forest management. With the AHP, in addition to objective information, subjective preferences and expert knowledge can be utilised in decision-making. It is also possible to utilise uncertain preference information by using interval or fuzzy AHP. The AHP can be utilised in group decision-making or participatory planning, e.g. by including an additional hierarchy level to describe the utility of participants. However, the AHP demands quite much information from the decision-makers. In several occasions less demanding methods would be useful. In recent years, several MCDS methods have been tested for forestry applications. In this paper, three outranking methods, ELECTRE III, PROMETHEE I and II, and a method based on voting theory, called multicriteria approval, are presented. They are less demanding than the AHP what comes to the information needs. These methods are able to deal with ordinal and more or less descriptive information on the alternative plans to be evaluated. In outranking methods, the uncertainty concerning the values of the criterion variables can be taken into account using fuzzy relations, determined by indifference and preference thresholds. These methods have been applied in two case studies, which are briefly presented. According to results obtained from case studies, all the presented methods are potentially useful for certain applications. However, they have a common drawback: if high quality information were available, these methods may waste information. Therefore in the future, methods that utilise all kinds of information to its full power and explicitly account for the uncertainty, are needed.

Key words: fuzzy relations, multicriteria decision support, multiple-use planning, uncertainty

1 Introduction

Nowadays, natural resources are more and more often managed for multiple uses. Both economic, ecological and socio-cultural sustainability are required, which calls for multi-objective natural resources management planning and decision support. In addition, there is more and more often a need to take into account aims of multiple decision-makers or participants in natural resources decision-making. This, in turn, calls for group decision support and participatory planning.

Typically, forest information is fairly accurate when compared to information concerning ecological or social aspects. For example, the ecological risks to watercourse due to ditch maintenance or clear cutting may be hard to assess accurately. Other examples are the effects of forest management on the viability of threatened species. In such cases, the information available for planning may have very low quality. All the information available should be able to be dealt with – no matter were the information descriptive or numerical.

So far, the Analytic Hierarchy Process (AHP), developed by T.L. Saaty (1980), has been the most commonly used multicriteria decision support method in natural resources planning in Finland and elsewhere. Many applications and extensions of the AHP exist (see, e.g., Kangas 1999). It has been widely applied in other fields, too. From the viewpoints of multiple use and participatory planning, the AHP has several advantages. Both objective value information, expert knowledge and subjective preferences can be utilised when using it. Also, qualitative criteria can be applied in the evaluation of alternative plans when the AHP is used. The AHP is based on a theory of ratio scale estimation (Saaty 1977), and by using it, pair-wise comparisons of qualitatively expressed measures can be transferred into a ratio scale. Other related methods, such as SMART, usually require values of the criteria to be measured directly in ratio scale and quantitatively.

There are, however, some problems in the AHP method. As the alternatives are pair-wisely compared with respect to each criterion, the number of comparisons needed increases rapidly as the number of alternatives increases. This may be too costly and too tedious for participatory planning problems, for example. Furthermore, in natural resources management, a great share of information gathered or produced during any planning process is uncertain. Thus, problems with the AHP also include handling of uncertain or fuzzy information. The AHP has been further developed in order to meet the needs of analysing uncertainties (e.g. Alho & Kangas 1997, Leskinen & Kangas 1998, Leung & Cao 2000). Also the number of comparisons can be reduced utilising regression techniques instead of eigenvalue technique in estimating preferences (Alho et al. 2001). However, there still is need for decision support tools with low information requirements, and more efficient handling of ordinal or qualitative information.

In this paper, three outranking methods, ELECTRE III, PROMETHEE I and II and one voting-theory -based method called multicriteria approval are briefly presented. These methods were tested in two case studies: the first was a public participation case of state owned forests and the other one a group decision-making case of a forest holding owned by a union. More detailed descriptions of the methods and applications can be found in original articles, to which references are provided.

2 Methods

2.1 Outranking

Outranking methods serve as one alternative for approaching complex choice problems with multiple criteria and multiple participants. In outranking methods, strong assumptions concerning the "true" preference structure of the decision-maker are avoided. It is not necessary to assume that a utility function exists, nor that it can be described with some certain function form. Outranking indicates the degree of dominance of one alternative over another. Outranking methods enable the utilisation of incomplete value information and, for example, judgements on ordinal measurement scale. They provide the (partial) preference rank-

ing of the alternatives, not any cardinal measures of the preference relations.

In PROMETHEE and ELECTRE outranking methods, the criteria are treated as pseudo-criteria (Brans et al. 1986, Roy 1991, see e.g. Salminen et al. 1998). This means that two thresholds, namely indifference and preference thresholds, are applied to the original criterion values. The indifference threshold for a criterion is a difference between two management alternatives beneath which the decision-maker is indifferent with respect to the criterion in question. The preference threshold for a criterion is a difference above which the decision-maker strongly prefers one management alternative to another. Between these two thresholds there is a zone where the decision-maker hesitates between indifference and strong preference, i.e. the zone of weak preference. In ELECTRE III method, there is an additional threshold, a veto threshold. If the difference between two alternatives is larger than the veto threshold, the worse one of the alternatives is discarded with respect to the criterion in question. Therefore, ELECTRE III can be considered as a non-compensatory model (Rogers & Bruen 1998a).

The criterion values may contain uncertainty, which can be described either by probability distributions (random variation) or fuzzy zones (uncertainty due to ignorance etc.) (Miettinen & Salminen 1999). The indifference threshold can be defined either with respect to the uncertainty of the criterion values or as a threshold at which the differences become perceptible to decision-makers (Rogers & Bruen 1998b). Maystre et al. (1994) defined the indifference threshold as the minimum margin of uncertainty and the preference threshold as the maximum margin of uncertainty with respect to the criterion considered.

Outranking methods are often applied to group decision-making situations. In group decision-making, the analyst typically chooses values for the thresholds, on grounds of the uncertainties in criterion values and the decision-makers' preferences. The decision-makers only determine the weights for the criteria. Usually, each decision-maker gives his/her own weights, and, in the analysis the median or mean values for the weights are used (Roy 1991). However, it is also important to study the effect of the extreme values to the weights in a sensitivity analysis.

In each of these methods, the final rankings are calculated in a different way. In ELECTRE, the 'Min' procedure can be utilised (Pirlot 1995). The dominance of one alternative over another is described with an outranking degree. Then, the alternative having the highest value for the worst of these outranking degrees is chosen. In PROMETHEE I, two partial rankings are combined to produce the final ranking (Brans et al. 1986). One of these is the degree by which one alternative outranks the others, and the other one is the degree by which the other alternatives outrank the alternative considered. One alternative is deemed better than another, if it is better by both these criteria, otherwise the alternatives are imcomparable. In PROMETHEE II, a difference of these two degrees is used to form the ranking (Brans et al. 1986). For more details, see also Kangas et al. (2001).

2.2 Multicriteria Approval

The ideas of approval voting theory can be utilised also in multicriteria decision support. Fraser and Hauge (1998) presented an application of approval voting, called multicriteria approval, which can be used in multicriteria decision support. In multicriteria approval, the alternatives and the criteria under which the alternatives are to be compared are first determined. Secondly, the decision-maker ranks the criteria by their importance. In the case of multiple decision-makers, a common rank for the criteria is required.

Next step is to determine which of the alternatives are approved regarding to each criterion. Fraser and Hauge (1998) defined the border between approval and disapproval as the average evaluation of the alternatives with respect to the criterion considered. The average value have been chosen as the borderline because, in approval voting theory, it can be proved that the optimal strategy for a voter is to vote all the candidates that are above average (e.g. Kim & Roush 1980).

The determination of the voting result begins after defining the dichotomous preferences. There are five possible classes of voting result: unanimous, majority, ordinally dominant, deadlocked

and indeterminate. The classification is presented in Fraser and Hauge (1998), see also Laukkanen et al. (2001a,b). In a unanimous result, one alternative is approved with respect to all the criteria, while any other alternative is not. In a majority result, one alternative is approved by the majority of criteria that are determined to be the most important, while any other alternative is not. For example, if the problem involves five criteria, the three most important of these are needed for majority result. In an ordinally dominant result, one alternative is approved with respect to more criteria, which are of greater importance than does any other alternative. In a deadlocked result, there may be several alternatives that are classified to one of the above mentioned categories. In an indeterminate case, more information is needed in the choice of the best alternative. For example, one alternative may be approved with respect to more criteria than any other, but some other alternative is approved with respect to more important criteria.

3 Applications

3.1 Public Participation in Strategic Planning of State Forests

Pykäläinen et al. (1999) used the HIPRE program developed by Hämäläinen and Lauri (1995) in an application of interactive decision analysis (IDA) on strategic planning of state-owned natural resources. Initially, four strategies following different scenarios were formulated in the planning project of Kainuu. The impacts of the strategies were measured by numeric criterion variables and they were estimated through planning calculations. So called 'Basic strategy' included the current principles of land use allocation. The 'Business strategy' emphasised the economical goals of the Finnish Forest and Park Service (FPS) in Kainuu area. The 'Forest recreation' and 'Nature conservation' strategies emphasised the related goals, respectively. However, the Finnish conservation program of old forests constructed simultaneously increased the area of forests to be conserved. As a consequence of this, all the initial strategies were not feasible any more. Therefore, two new strategies were constructed: 'Mixed 1' strategy and 'Mixed 2' strategy. 'Mixed 1' was

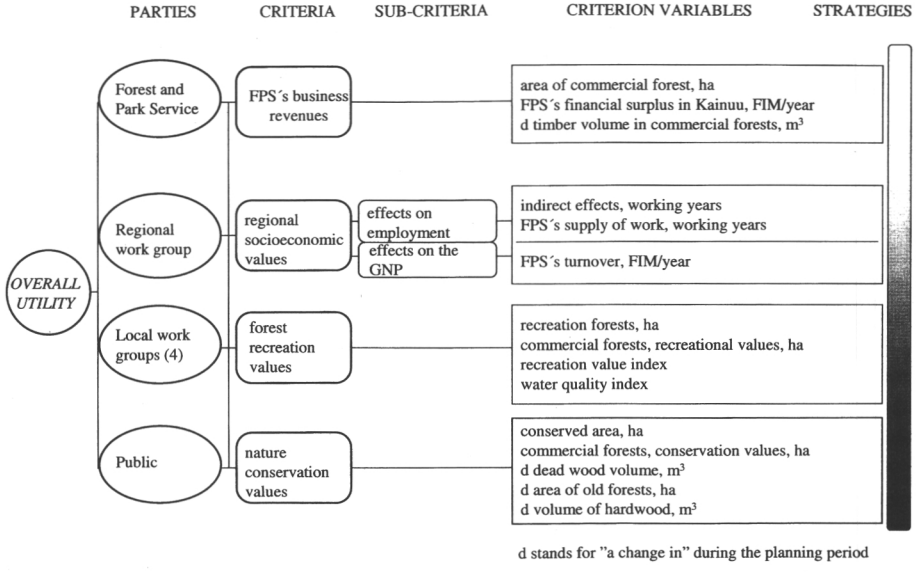


Fig. 1. Decision hierarchy applied by the FPS in Kainuu region.

Table 1. The public participation case ranks. Veto threshold applied for ELECTRE III for worst alternative (see Kangas et al. 2001).

Strategy	HIPRE	Promethee II	ELECTRE III
Business	1	1	6
Basic	2	3	1
Forest recreation	3	2	3
Mixed 2	4	4	4
Mixed 1	5	5	2
Nature conservation	6	6	5

the 'Basic' strategy including the new nature conservation criteria. The 'Mixed 2' strategy was a modified version of the 'Business' strategy.

The IDA was started with the decision hierarchy formulation (Fig. 1). The hierarchy consisted of six levels: the total utility, the parties, the four main criteria for forest management, the subcriteria, the criterion variables, and the alternative forest strategies. The parties involved were FPS, one regional and four local working groups including 10–12 interest groups each, and the public. The main criteria were FPS's business revenues, regional socio-economic values, forest recreation values and nature conservation values. These main criteria were measured with 17 subcriteria (see Fig. 1).

In Kangas et al. (2001), the material of this case study was reanalysed with two outranking methods, PROMETHEE II and ELECTRE III. Fortran programs written by the authors were utilised the analysis. In order to produce a problem formulation as close as possible to the original HIPRE formulation, the weights for the 17 criteria considered in the outranking process were those obtained with HIPRE analysis. Also, the used threshold values were related to the range of variation in the alternatives, to resemble the scaling in HIPRE.

In PROMETHEE II analysis, the best alternative in the analysis proved to be the Business strategy, as was in the original HIPRE analysis (Table 1). The only difference between these methods was that the Forest Recreation and Basic strategies changed places. The results of ELECTRE III, however, differed from the other methods. If veto threshold was not utilised, the order was quite similar to the initial analysis (see Kangas et al. 2001). A veto threshold, defined as the difference between the worst and best alternative with respect to each criterion, was also tested. When such veto threshold was applied, the rank of the Business strategy fell to the last place, and the compromise strategies, e.g. the Mixed 1 strategy, rose (Table 2). Thus, the veto threshold is a very powerful tool.

3.2 Group Decision-Making Case in a Forest Holding Owned by a Union

AHP, PROMETHEE I and II methods and the multicriteria approval method were used in a group decision-making situation (Laukkanen et al. 2001, 2002). The problem was to choose a forest plan for a forest holding owned by a union. There are three owners in the union, each having different kinds of objectives for forest utilisation. All the owners have a 1/3 share of the forest holding. One of them aimed at timber production, the beauty of forest landscape, and berry yield. The second one aimed at timber production, biodiversity of the forest, the beauty of forest landscape, and saving habitats for capercaillie (*Tetrao urogallus*), a valued game bird. The third one mainly preferred timber production.

The forest holding is 30 hectares large consisting of three separate blocks and 13 forest stands. Planning period consisted of two 10 years periods, for which 20 alternative forest plans were produced. The timber production criteria, as well as blueberry yield and the biodiversity criteria were obtained using mathematical models in MONSU planning package (Pukkala 1998). The capercaillie criterion was excluded from the final analysis: it was noted that the biodiversity criterion corresponds closely enough with the capercaillie criterion. The capercaillie criterion was accounted for by increasing the weight of biodiversity criterion. Landscape beauty was assessed using subjective weights for the predicted landscape beauty indices of the three blocks.

In the case study, the preference information was gathered from the three owners in two different ways. The pair-wise comparisons between the criteria were applied for AHP analysis. For PROMETHEE analyses, all decision-makers defined the weights that describe the importance

Table 2. Rankings of the 20 alternatives according to different methods (see Laukkanen et al. 2001, 2002).

Alternative	AHP	Promethee I	Promethee II	Promethee II with AHP weights	Multicriteria Approval
S1	5.	1.	2.	7.	
S2	4.	1.	1.	4.	
S3	11.	1.	7.	3.	1.
S4	1.	8.	18.	10.	
S5	8.	15.	14.	12.	
S6	3.	1.	4.	5.	
S7	19.	8.	8.	19.	
S8	7.	15.	19.	20.	
S9	13.	1.	5.	9.	
S10	2.	15.	20.	18.	
S11	14.	11.	10.	14.	
S12	6.	12.	17.	2.	
S13	9.	1.	3.	8.	
S14	18.	15.	12.	16.	
S15	12.	1.	6.	6.	
S16	10.	12.	13.	1.	
S17	15.	12.	16.	11.	
S18	20.	8.	9.	20.	
S19	16.	15.	15.	13.	
S20	17.	15.	11.	15.	

of the criteria using values 1–7. For multicriteria approval, the importance order of the criteria was obtained from PROMETHEE inquiry, on the basis of the average values of the decision-makers' weightings. This procedure was approved by all decision-makers. The order of the criteria from the most important to the least important was: net incomes, biodiversity, monetary value of the future timber production, scenic beauty of forest landscape, and berry yield. As the approval border, the average criterion value of the alternatives was used.

The results obtained with these decision support tools were different in each case (Table 2). In AHP case, the two alternatives with highest incomes got the best rankings. In PROMETHEE II, the alternative with lowest incomes and highest values for other criteria was chosen, implying less weight given to the net income than in the AHP analysis. In PROMETHEE I, seven alternatives were selected among the best ones, which were mutually incomparable (Fig 2.). They included the seven best alternatives in PROMETHEE II analysis. Multicriteria approval chose one compromise solution. These results indicated both that the decision models in these methods are different but also that they utilise different amount of information, which also was of different quality.

4 Discussion

All the methods applied in the two planning cases described above gave somewhat different results with respect to the rank of the alternatives. Similar results were also obtained by Zanakis et al. (1998) in their comparative study. The inconsistencies in the results of different methods were due to several reasons: the level of information used varied, the choice problem formulations did not reflect exactly the same preference structures, there were differences in the calculation techniques, and the interpretation of the criteria weights is different in the methods. The problem is that there is really no way to say which is the correct preference structure.

In the public participation example, results concerning the ELECTRE III method differed from the others, partly due to the 'min' procedure used,

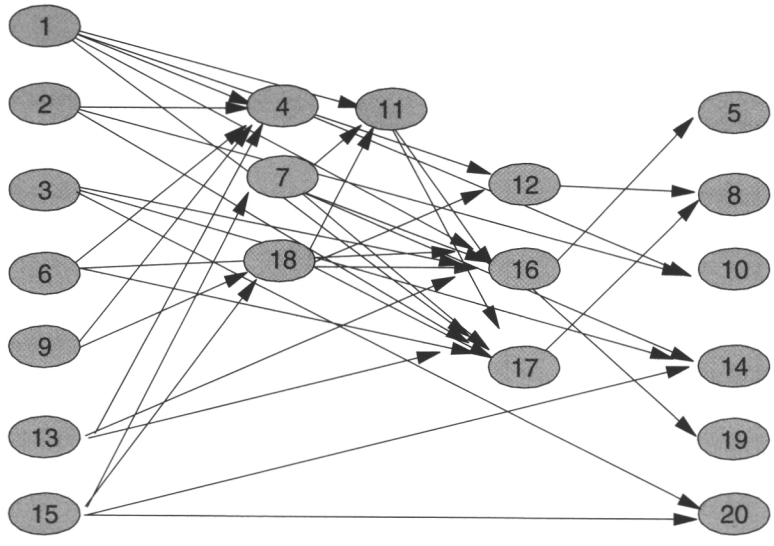


Fig. 2. The outranking relations obtained with PROMETHEE I.

which favours compromise alternatives, partly they were due to the use of veto thresholds. However, the weights of the criteria used in these calculations were the same, so that the AHP and PROMETHEE results as well as the ELECTRE results without the veto threshold coincided fairly well (Kangas et al. 2001).

In the group decision-making example, all the methods considered gave different results. In the AHP analysis, the economical aspects were emphasised more than in other analyses. One reason for this was that separate inquiries were made to estimate the weights of the criteria in the AHP and PROMETHEE analyses. However, even using the AHP weights in PROMETHEE II analysis did not give the same results, although these weights emphasised the economical aspects somewhat more than the original PROMETHEE analysis (Laukkanen et al. 2001). One reason for the AHP emphasising economical values more than the other methods is the way the preferences are elicited in the original method as applied in the case study: the smallest difference between any two alternatives is 1:2, i.e. the better alternative being twice as good as the other. The problem can be avoided by using a continuous comparison scale (e.g. Pukkala & Kangas 1993).

In the group decision-making case, differences between the alternatives were smaller than in the public participation case, which partly explains the differences in rankings. There may be several alternatives that are almost equally good. Given the uncertainties in preferences and criterion values, the truly best alternative may not obtain the first rank in the analysis. Indeed, it would be wise to present several alternatives to the decision-makers, and the facts that support each of them. Then, the final decision is left to the decision-makers, like it should.

Ability to deal with uncertain and fuzzy information is an indisputable advantage of outranking methods. However, taking the uncertainty explicitly into account in the calculations would be even more useful (see e.g. d'Avignon & Vincke 1988). The ability to deal with ordinal and other informal preference statements is also an advantage. For example, one main reason for criticism in the public participation case (Pykäläinen at al. 1999) by the participants was that the biodiversity and other ecological aspects were accounted for using numerical indices. Ordinal information might have been more natural to the participants and decision-makers. Generally taken, outranking methods do not require as much preference information as the AHP. Furthermore, theoretical assumptions for the information usable

in calculations are not so demanding as is usual with methods of MultiAttribute Utility Theory (MAUT) (Vincke 1992). However, the interpretation of the outranking results and analyses may be a problem.

Multicriteria approval has not been applied to forest planning before. It seems to satisfy many requirements of multicriteria forestry decision support, because its main aim is to find an alternative that is widely satisfactory among the multiple criteria. It is well suitable for situations where information that other methods demand is difficult or expensive to achieve, or the available information is of low quality. Due to minimal information requirements multicriteria approval does not demand much time; thus, costs of using this method remain low. Since multicriteria approval is so easy for decision-makers, queries can be carried out using post inquiry or, for example, via the Internet. Therefore, it could also be used for unions with plenty of owners, who may live scattered across the country.

However, applying dichotomous preferences means loss of information in cases where, e.g., cardinal weighting of criteria and cardinal preference orderings of the alternatives with respect to single criterion is available (e.g. Niemi 1984). If there is more information available, other methods such as outranking or the AHP provide readily available solutions. Also the outranking methods may waste information: if the decision-maker knows that alternative giving twice as much money as another is twice as good as the other, it means waste of information to state only that it is better. Then, methods utilising also the intensities of preferences may be more recommendable.

Applications for all different MCDS methods with different qualities can inevitably be found in the field of natural resources decision support. No method is the best one in all the decision support processes. The tool to be used should be case-wisely chosen in such a way that the information available is used to its full power: exact information is used for criteria with exact values, ordinal or dichotomous information is used for criteria with low quality data. In our on-going studies, methods which allow utilising mixed quality information in the same problem are being studied for making better use of all the information available, and thus, for enabling more complete decision support.

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Interactive Use of Multi-Criteria Decision Analysis in Forest Planning

Jouni Pykäläinen

Forestry Center of Kainuu
P.O Box 213, FIN-87101 Kajaani, Finland
e-mail: jouni.pykalainen@metsakeskus.fi

1 Planning Method

The paper reviews a method of interactive forest planning. The method has been developed by Kangas et al. (1996) and Pykäläinen (2000). The paper also reviews forest owners' feedback collected in North Karelia, eastern Finland. More information about the case study is given in Pykäläinen (2000).

The planning process consisted of the following steps:

(1) field inventory,
(2) simulation of alternative treatment schedules for individual forest stands,
(3) defining the forest owner's goals, and
(4) producing a forest plan which fulfils the goals defined in the step (3).

Defining the goals and producing the plan are the main focuses of this paper.

The goals were first defined qualitatively. A method called thematic interview (Hirsjärvi 1991) was selected for this purpose because it has several psychological and communicational advantages as a method for defining the forest owner's forest management goals. It possess the appropriate psychological background for forest planning, it is a familiar way of communication and easy to adapt by forest owners. It offers also a framework for discussion between the forest owner and the planning consultant: the interviewee and the interviewer can learn from each other.

The functional idea of the thematic interview application was to define the forest owner's goals by asking and answering questions. A specific interview guide was used for this task (Fig. 1). The main problems to be solved were. (1) What are the forest owner's forest-management goals? (2) Does the forest owner have time preferences or spatial specifications for the goals? (3) What is the relative importance of each goal?

Each theme was first discussed separately. In this process the forest owner and the planning consultant learned to know the forest owner's goals related to each theme. At the end of the interview, the planning consultant summarised the goals related to the different themes, and asked the forest owner to specify the goals when necessary. After that, the consultant asked the forest owner to describe the mutual importance of the goals. If the interviewee was unable or unwilling to describe the importance, the goals were assumed to be equally important.

Open and closed questions were used in the interviews. Closed questions limited or restricted possible answers while open questions did not. The planning consultant's influence on answers was minimised by using as much open questions as possible. The questions were typically sequenced so that general questions gave way to more restricted ones as the interviewer moved through a topic.

The goals were made operational by defining the owner's utility model following the principles of the HERO method (Pukkala & Kangas 1993). The utility that the forest owner expected from

PROBLEMS	CATEGORIES	THEMES	OBJECTIVE VARIABLES	OTHER MEANS
OBJECTIVES	Economy	Timber sales income	Net income	
		Economic value of forest	Value and volume of timber Value growth of timber	
		Domestic timber	Saw log harvest	
TIME PREFERENCES AND SPATIAL SPECIFICATIONS	Scenic values	Far view landscapes	Area of clearcuttings	Landscape visualisations Treatment limitations
		Close view lanscapes	Close view score Volumes of different tree species Area of clearcuttings	Landscape visualisations Treatment limitations
	Game habitats	Capercaillie	Area of old forest	Treatment limitations
		Black grouse	Volume of birch	Treatment limitations
MUTUAL IMPORTANCE OF OBJECTIVES	Berries and mushrooms	Cowberry	Estimated yield	
		Blueberry	Estimated yield	
		Mushrooms	Estimated yield	
	Nature protection	Certain species		Treatment limitations
		Overall biodiversity	Biodiversity index Area of old forest Volumes of dead wood and hard wood	
	GUIDE OF INTERVIEW		OPERATIONALIZATION OF THE OBJECTIVES	

Fig. 1. The guide of interview, and the means of including the various forest management goals in the planning.

the plan was computed from an additive utility function:

$$u = \sum_{i=1}^{m} a_i u_i \qquad (1)$$

where m is the number of goal variables, a_i is the importance of goal variable i, and u_i is the sub-utility obtained through the goal variable i. The sub-utility is defined through a sub-utility function (Fig. 2.).

The planning consultant and the forest owner selected the goal variables, gave an approximate relative importance to them (a_i in Equation 1), and formed a sub-utility function for every goal variable (Fig. 2.). The sub-utility function was determined through the smallest possible, target level and largest possible values of the goal variable.

The forest owner's time preferences for the goals were taken into account through utility function formulation, and through interactive optimisation. Spatial goal specifications were taken into account by limiting the treatment alternatives in certain parts of the planning area (Fig. 1, "Other means").

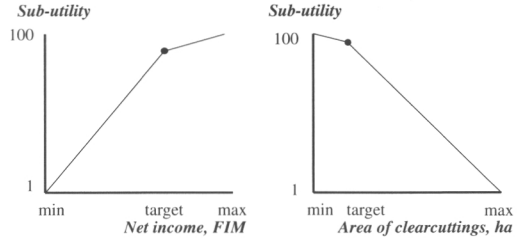


Fig. 2. Examples of sub-utility functions.

The initial solution was produced by means of a heuristic optimisation algorithm. This solution was presented to the forest owner. After that, the owner could change the current values of a_i. The problem was re-solved after every change, and the new solution was presented to the owner. Interactive search of the best plan was continued until the owner became satisfied with the result.

2 Feedback

The planning method was used in two planning projects and localities, Polvijärvi and Pyhäselkä, in eastern Finland. Most of the forest owners involved were mainly people of middle age or older, had typically some tens of hectares of forest, and lived near their forest holdings. Forestry was an important source of income for them. The planning sessions were arranged at the forest owners' homes.

An inquiry was used to collect information about the forest owner's initial knowledge in forestry, about learning in planning, and about the owner's opinions regarding interactive planning. The inquiry was done in Polvijärvi (12 forest owners) and in Pyhäselkä (7 forest owners). The main results of the inquiry were as follows. (1) Before planning the forest owners knew their forest management goals quite accurately. However, 79% of the owners thought that the thematic interview made their forest management goals clearer. (2) The connections between the qualitatively defined goals and interactive optimisation were well understood. (3) The use of computer in planning was quite easily adapted by the forest owners. (4) The qualitatively defined goals could be included in planning. (5) Planning made many forest owners more interested in forestry, and many owners learned something new about forestry. (6) 89% of the forest owners would like to take part in planning in the same way also the next time. (7) The majority of the forest owners preferred the method applied in the study over the current forest planning method (this question was asked only in Polvijärvi). (8) The planning process made the owners goals for forestry remarkably clearer.

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Modelling Volume, Growth and Mortality

Efficient Modelling of Stem Curves

Jouko Laasasenaho[1], Mark-Leo Waite and Heikki Karttunen

[1]University of Helsinki, Department of Forest Resource Management
P.O. Box 27, FIN-00014 Helsinki, Finland
e-mail: jouko.laasasenaho@helsinki.fi, Mark-Leo.Waite@tietoenator.com
and heikki_karttunen@hotmail.com

Abstract

The purpose of this paper is to introduce a highly efficient technique for deriving accurate and versatile stem curve models. The technique in question is based on relative stem diameters and relative stem heights and is subsequently called the relative stem curve method. The paper focuses on the following three main issues

(i) the uniformity and variability of relative stem curves,
(ii) the volume and commercial height estimation accuracy of relative stem curve models, and
(iii) the number of sample trees required to derive relative stem curve models.

It is shown, by an extensive set of stems measured in the field and comprising 1964 stems, that average relative stem curves of different sized trees are highly similar and that the variability of relative stem curves is also quite modest. Consequently the volume and commercial and saw-wood height estimation accuracies are high and the required number of field sample trees low. Standard errors varied from 10% to 7% for volume and the required number of sample trees from 1 to 15. It is proposed that a worldwide effort is launched in order to derive and utilize relative stem curve models for all commercially important tree species.

Generalisation of Sample Tree Data – Case Permanent Sample Plots

Kari T. Korhonen

Finnish Forest Research Institute, Joensuu Research Station
P.O.Box 68, FIN-80101 Joensuu, Finland
e-mail: kari.t.korhonen@metla.fi

1 Introduction

Two-phase sampling is widely applied in large area forest inventories. E.g. in the national forest inventory (NFI) of Finland, the first phase sample (later referred to as tally trees) consists of a large number of trees for which only diameter at breast height (d) is measured and some other descriptive variables are recorded (Tomppo et al. 1997). The second phase sample (sample trees) consists of trees for which some additional variables, necessary for accurate volume estimation, are measured. These variables include height (h) and diameter at six meters height (d_6).

One of the most challenging tasks in NFI data processing is the generalisation of the volumes "measured" for the sample trees to the tally trees. The generalisation should be effective and unbiased (see e.g. Ranneby & Svensson 1991). With permanent sample plot data, another requirement might be added: volume estimates of a tally tree for the different measurement occasions should be harmonised. This means that if the diameter of a tally a tree has increased between two measurement occasions the volume estimates should show increment, also. If the volumes of tally trees are estimated independently at different measurement occasions, it is not obvious that this criterion is fulfilled.

The aim of this study was to develop a method for generalising sample tree data (stem volume) in the case of re-measured permanent sample plots.

2 Study Material

The data used in this study consisted of 3009 permanent sample plots established in 1985–86 and re-measured in 1995 (Mielikäinen & Gustavsen 1993). In the first measurement occasion, 20595 pine (*Pinus sylvestris*) tally trees were measured on these plots. For these trees, diameter at breast height and several variables describing the site and growing stock of the stand were recorded in the data. The number of pine sample trees (d_6 and h measured) in the first measurement occasion was 6444.

In the second measurement occasion, 23868 pine tally trees were measured, 15654 of these were measured also in the first measurement occasion and the rest were observed as new tally trees. The number of pine sample trees was 6606 in the second measurement occasion.

In addition to the above described permanent plot data, pine sample trees measured in the 8th NFI (1986–1994) were applied in estimating the parameters of the general volume function (1). The number of observations was more than 30000 in these data.

3 Methods

3.1 Selection of the Method for Generalising Sample Tree Data

Two approaches were considered when selecting the method for generalising sample tree data:

1. At the first measurement occasion, the volumes of tally trees are estimated with regression models estimated or calibrated with the measured sample tree data. Re-measured sample trees are used for estimating volume increment as a function of diameter increment and other observed variables. The estimate of volume for a re-measured tally tree (at the second measurement occasion) is the sum of the volume estimate at the first occasion and estimated volume increment.
2. A general regression model for stem volume as a function of diameter and other possible regressors is estimated with available tree wise data. The general regression model is calibrated at both measurement occasions with measured sample tree data.

The first approach (based on the estimation of volume increment with the re-measured sample tree data) has the advantage that it is easy to guarantee that the volume increment estimates are realistic (e.g., volume increment is positive if diameter increment is positive). A disadvantage is that the trees that are measured for the first time in the second measurement occasion would call for a different method for volume estimation. Further, it would be difficult to ensure that the volume estimates of 'old' and 'new' tally trees would harmonise since the method of volume estimation would be different. Another disadvantage of this procedure is that it would be difficult to ensure that volume estimates are unbiased because the volume estimates of tally trees consist of volume estimates at the first occasion and volume increment estimates. The correlation between diameter and volume increment is quite weak and both of these would contain quite large measurement error.

The second approach has the advantage that at each measurement occasion, volumes of tally trees are estimated with a similar method. Thus, the volume estimates within one measurement occasion are harmonised. A disadvantage is that the residual errors of the calibrated volume functions may cause illogical volume increment estimates.

In this study, the second approach was selected. A robust calibration method was applied to reduce the problem of illogical volume increment estimates.

3.2 Estimation of Volume Functions

Equation (1) was applied as a general volume function.

$$\frac{v}{d^2} = a_0 + a_1 d + a_2 \frac{1}{d} + a_3 \sqrt{d} \qquad (1)$$

The parameters of the model (1) were estimated the data from temporary NFI plots. The parameters were estimated by following soil type and site class groups:

- mineral soils with site productivity class 0 or 1,
- mineral soils with site productivity class 2,
- mineral soils with site productivity class 3,
- mineral soils with site productivity class 4,
- peatlands with site productivity class 0 or 1,
- peatlands soils with site productivity class 2,
- peatlands soils with site productivity class 3,
- peatlands soils with site productivity class 4, and
- poorly productive mineral soils or peatlands (scrub lands).

These parameter estimates (parameters and related cross product matrices (see estimator 2) were used as a priori data when estimating the final parameters of local volume functions.

3.3 Calibration of the General Volume Function for Permanent Plot Data

The final parameters of the general volume function (1) were re-estimated separately for the first and second measurement occasions of the permanent plots with mixed estimator (2):

$$\beta = (X'X + k\frac{n}{m}U'U)^{-1}(X'y + k\frac{n}{m}U's). \qquad (2)$$

where

X is the matrix of the independent variable values in the calibration data (either first or second measurement occasion),

y is the vector of dependent variable values in the calibration data,

U is the matrix of the independent variable values in the a priori data (NFI8 sample trees),

s is the vector of dependent variable values in the a priori data,

n is the number of observations in the calibration data,

m is the number of observations in the a priori data, and
k is a scaling parameter for the two data sets.

The final parameters of the volume function were estimated locally, i.e., for each tree only sample trees with geographic distance less than 10 km from the tree were accepted in the calibration data (X and y-matrices). Further, a maximum difference of 10 cm in the diameter of the tree and a sample tree in the calibration data was allowed. However, if less than 10 sample trees fulfilled these criteria, the 'neighbourhood' was widened iteratively until at least 10 sample trees were found. Different values for the scaling parameter were tested iteratively. Volume models for different site class groups were calibrated independently.

3.4 The Nearest Neighbour Method

The results obtained by local calibration of volume functions were compared to results obtained with the nearest neighbour method. In this method, the volume of a tally tree was estimated as the mean of volumes of five 'nearest neighbour' sample trees (see e.g. Korhonen & Kangas 1997). The nearest neighbours were selected with following criteria:

- diameter at breast height
- land use class
- soil type
- site class
- geographic location.

The nearest neighbours were selected independently at the both measuring occasions.

3.5 Studying the Success of Calibration

The success of the calibration of models was evaluated with 3 criteria:

1. Reliability of tree wise volume estimates
2. Residual maps
3. Consistency of the volume estimates in the first and second measurement occasion

The reliability of tree wise volume estimates was studied with the cross validation method using sample tree data from both the first and second measurement occasion of the permanent plots. The volume of each sample tree was estimated with volume model calibrated with the sample tree data excluding the sample tree it self. The standard deviation and mean of residuals, $v - \hat{v}$, and relative residuals, $(v - \hat{v}) / \hat{v}$, were calculated using the volume estimated with all measured sample tree variables (d, d_6, h) of a sample tree as 'true' volume, v.

Residual maps were produced with geographic smoothing of tree wise residuals.

The consistency of volume estimates in the first and second measurement occasion of the permanent plots was studied using all re-measured tally trees. For this purpose, graphs with estimates of volume increment versus measured diameter increment were produced and trees with negative volume increment estimate were checked.

4 Results

4.1 Reliability of Tree Wise Volume Estimates

The standard deviation and mean of residuals, $v - \hat{v}$, and relative residuals, $(v - \hat{v}) / \hat{v}$, of volume estimates are presented in Table 1. Results for both

Table 1. The standard deviation (std) and mean of residuals and relative residuals of volume estimates.

	Residuals, dm^3		Relative, residuals, %	
	std	Mean	std	Mean
General volume function	42.0	0.83	18.8	–1.41
Calibrated volume function	38.8	–0.31	16.3	–0.51
Nearest neighbour estimator	46.0	–3.7	17.8	–1.2

the general and calibrated volume models and for both measurement occasions are included.

4.2 Geographic Autocorrelation of Residuals

The plotted residuals showed that without calibration, the general volume function (1) tend to overestimate stem volumes in Northern Finland and areas near the coast of Finnish Gulf and Bothnia Gulf. Negative local biases were found also at some areas near the large lakes in Central Finland. Correspondingly, fairly large areas with positive local biases were found. The local calibration of the general volume function effectively removed this large-scale spatial correlation of residuals. No significant spatial correlation was found for the residuals of the nearest neighbour estimator, either.

4.3 Consistency of the Volume Estimates in the First and Second Measurement Occasion

Data from the first measurement occasion consisted of 20 595 tallied pines. 15 654 of these were re-measured in the second measurement occasion. Negative diameter increment was measured for 194 trees (1.2 %) of the 15 654 re-measured tally tree. When applying the local calibration method, negative volume increment was obtained for 52 trees (0.3 %) of the 15 460 re-measured tally trees with positive diameter increment. When the nearest neighbour estimator was applied, the number of re-measured trees with negative volume increment was 385 (2.5 %).

5 Preliminary Conclusions

Local calibration of a general volume function worked slightly better than the nearest neighbour estimator if the reliability of tree wise volume estimates is considered. It is obvious, that adjustment of the nearest neighbour estimator to reduce the so-called edge effects would slightly improve the results (see e.g. Korhonen & Kangas 1997).

Both the local calibration and the nearest neighbour method succeeded in eliminating the geographic correlation of residuals.

The local calibration worked clearly better than the nearest neighbour estimator in volume increment estimation. With this method, the number of tally trees with negative volume increment estimate was clearly less than the number of tally trees with measured negative diameter increment. In the respect, the measurement errors caused illogical volume estimates more frequently than the volume estimation method.

The preliminary results indicate that local calibration of volume functions can be recommended for generalising sample tree information in the case of permanent plot data.

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An Outline of a System of Individual Tree Growth Models for Ecological Applications in Multipurpose Forestry Planning

Ulf Söderberg and Kenneth Nyström

Swedish University of Agricultural Sciences,
Department of Forest Resource Management and Geomatics,
S-901 83 Umeå, Sweden
e-mail: ulf.soderberg@resgeom.slu.se and kenneth.nystrom@resgeom.slu.se

Abstract

Traditionally the models used in forest planning have been restricted to characteristics for forest production and timber value. In this study the tree layer will form the basis for making relevant ecological connections to the characteristics of the trees, since the flora and fauna in the forest ecosystem are strongly connected with the structure and status of the tree layer. The study will put special emphasis on tree species that are of little (no) interest for forest industry, but are important in the ecological context.

Different models are developed with the objective to forecast tree characteristics that are better connected to ecological conditions. The basic features of the models are distance dependent individual tree models. Simultaneous regression techniques for a system of functions for basal area, height and crown height/length as dependent variables are used. The competition situation of the trees will be modelled explicitly in the models. Methods are used that consider spatial and temporal relations in the data set.

The functions are based on data from permanent sample plots in the Swedish National Forest Inventory from 1983 and onwards. The data set is representative of forest conditions and forest management throughout Sweden.

Keywords: growth model, simultaneous regression, NFI permanent plots, distance dependent

1 Introduction

In the Swedish forest policy the objectives of environment are of equal importance as those of forest production. The objectives of forest production have been considered for along time and methods and systems developed for different planning purposes. In the field of growth modelling, which is a substantial component in the planning systems, the aspects of forest production part are fairly well developed. The environmental considerations in planning systems are so far not much developed. There is a need of basic ecological knowledge to be built in into the planning systems. This is valid for the overarching national planning as well as for the planning of individual forest enterprises.

However, the growth models developed so far

have aimed at forest production issues only. The functions developed here are aimed to be able to form the basis also for ecological models that are developed elsewhere.

The preservation of biological diversity is nowadays an obvious aspect of forestry. The ambition is that silviculture shall imitate the processes that affected the natural forests and different concepts for planning according to these lines have been proposed (Angelstam et al. 1993, Haila et el. 1994). At the same time as these principles are getting commonly accepted, it is obvious that the knowledge about the requirement of different species and species groups on habitat and landscape patterns is too insufficient, to guide the operational aims of forestry. Such knowledge should enable an integration of species conservation in forest planning to a degree that is not possible today (Lämås 1996).

At present few aspects of species requirement are taken into account in forest management. Emphasising species conservation should mean a higher ambition in forest management, where species requirement on life environment is explicitly taken into consideration. For forest planning this implies the need of, among other things, an increased knowledge of making forecasts of future states of different habitats, including substrate amount and quality.

The starting point for this study is that the trees constitute the organisms in the forest that to a great extent dictates the conditions for other species. The trees are also the organisms that are manipulated by forestry and by that in different ways regulating the living conditions for the trees through various silvicultural measures.

From an ecological perspective the growth of trees can form the framework around which other models could be built. Such models could be the dynamics of the field- or bush layer, the establishment and growth of epiphytes, the dynamics of dead wood etc. These models should then be related to the conditions of the surrounding stand and tree layer (cf. Pettersson et al. 1995, Renhorn et al. 1997)

The objective of the study is to develop ecological relevant functions to estimate growth of individual trees in established forests. Specific emphasis will be put on models for key species such as aspen, alder, beech, oak, rowan and sallow, which today are treated very rudimentary. The dependent variables are tree basal area, height and crown ratio.

2 Material and Methods

Data from the Swedish National Forest Inventory (NFI) permanent sample plots are used as a basis for the project. During the years 1983–87, around 18 500 permanent sample plots were established on forest land. All plots were re-measured a first time from 1988 to 1992 and about half of the plots a second time between 1993–97. The design of the inventory is systematic cluster sampling covering the entire country each year. The sampling intensity is increasing from north to south.

The plots are circular with 10 m radius on which trees are registered for tree species, coordinates and diameter for trees ≥10 cm at breast height. Smaller trees were registered on a smaller plot with the size of 20 m^2. Trees less than 1.3 m height are not registered at all. Of the callipered trees a small proportion are selected as sample trees. These are measured for height, crown height, damages and some other characteristics.

Stand description, as well as detailed site description, was also performed on the plots. The variables registered were among others estimated total age of the dominating tree strata, type of performed silvicultural treatments and when it was done, field vegetation type, texture, soil depth, soil moisture, latitude, altitude and slope inclination and aspect.

The data are representative for stand and site conditions as well as forest management regimes for the whole country.

Functions for increment of tree basal area, height and crown height are developed using the NFI sample trees. These dynamic functions will also be complemented with static functions for height and crown height or possibly by using existing functions (Söderberg 1992) and Petersson (1997). The reason is to be able to apply the dynamic functions on NFI data or similar data where only diameter of the tree is known.

There are several methods that are planned to be used in developing the models. One is using

seemingly unrelated regression models. The second is mixed linear models in which spatial and temporal correlations can be explicitly modelled. This will result in better accuracy than ordinary linear regression (Gregoire 1987) and also make it possible to better describe the internal dynamics within stands (Stage & Wykoff 1993). The last statement is considered to be of special interest for the ecological applications of the study.

One problem in using NFI data are the measurement errors. The material has to be cleaned from gross errors that originate from obvious incorrect measurements, e.g. mixed trees or trees that have disappeared or were added. This type of errors is comparatively easy to handle and also related to a very small proportion of the total data set. To clean the data from registration errors a simple preliminary function was estimated. Trees with a residual greater than 3.0*RMSE of a simple function, where considered as having registration errors and omitted in the analyses.

Application of the developed functions will be done by simultaneous estimation of a system with three equations (basal area, height and crown ratio), cf. Borders (1989). A comparison to traditional methods where only one dynamic function (e.g. basal area) is applied and the others are estimated by static functions will be done.

3 Results

So far only some very preliminary results are available. The registration errors represent a small proportion of the total data set, varying from 0.4–1.2 % for different species. The "normal" measurement errors have not been dealt with so far. They are, however, of great importance for the accuracy predictions over time, since the standard error of functions are overestimated, but does not influence the estimation of the function itself to a considerable degree.

The preliminary seemingly unrelated models indicate that there is no significant gain in using such models compared to multiple linear regression models. It was expected that the seemingly unrelated models would have been superior as there is correlation among the dependent variables as well as the independent variables. It might be so that the measurement errors disturb the true relationships.

Using ordinary multiple linear regression results in fairly low correlation coefficients (R^2) and are especially low for height increment and change in crown length (ratio), 0.1–0.2 for height increment and 0.05–0.1 for crown length change.

4 Discussion

So far only some preliminary analyses have been performed. It is therefore difficult to have a strong opinion about the study. It seems, however, that the measurement errors will have a strong impact on the result. Both the overall fit of the functions and the significance of model parameters are surprisingly low. This is judged to be due to that the measurement errors are big in comparison with the change of the measured variables during the relatively short observation time.

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Growth Models for Uneven-Aged Stands

Björn Elfving

Swedish University of Agricultural Sciences, Department of Silviculture
S-901 83 Umeå, Sweden
e-mail: bjorn.elfving@ssko.slu.se

Abstract

Concepts and status of growth modelling in the Heureka project are reported. The models will be used for prediction of long-term forest development in the context of management planning and are aiming at validity also for uneven-aged and mixed-species stands.

The idea is to have separate models for regeneration after clear-cut, in-growth in established stands, and growth and mortality for single trees.

The regeneration model is the same as that constructed within the Hugin project around 1980. Expected stocking, as measured at a regeneration survey, is calculated as a function of site conditions and specified treatments. Based on expected stocking, a corresponding plot is selected from a data base containing 4000 plots from 800 stands investigated in 1977–81 in the Hugin young stand survey. Mean height on these plots is about 3 m, and measured trees on selected plots form the new stands in the prediction of forest development.

All the other models are based on data from the about 18 500 permanent NFI-plots established in the period 1983–87 and re-measured after 5 years in 1988–92. Most plots have also been re-measured for the second time. Positions are registered for all trees ≥10 cm on plots with radius 10 m.

The in-growth model contains four functions:

1. The probability for existence of small trees on a plot
   [ps (0<ps<1) = f (site, stand)]
2. Number of small trees on plots with small tree
   [n = f (ps)]
3. Probability for in-growth of small trees in 5 year
   [pi = f (site, stand)]
4. Mean basal area of in-grown trees after 5 year
   [bai = f (site, stand)]

The construction of these functions is of course depending on available data. Small trees are defined as trees with dbh in the interval 1–39 mm. Such trees were measured on a plot with 5 m radius (79 m^2) at the installation of the permanent plots and on "the inner quartile" (20 m^2) at the re-measurements. Data from the 5 m-plots are used at step 1. In reality we want to know ps for 10 m-plots so we have to transform results from 5 m-plots to 10 m-plots on theoretical basis. Separate functions for different species are constructed. The co-variation between species is taken into account through inclusion of the dummy variable "occurrence of small spruces" as independent variable in the functions for other species. At application of these functions the judgement, whether a plot will contain small trees or not, is decided by a random number RN with rectangular distribution in the interval 0–1. If RN < ps, then the plot is classified as containing small trees. A special problem is, how repeated applications should be handled: how does the temporal correlation of small tree occurrence look like? In-growth functions are based on data from repeated measurements of small trees in the inner quartile.

The growth model also contains four functions:

1. Basal area growth functions for single trees
   [$id^2 = f$ (d, stand, site)]
2. Height functions for single trees
   [h = f (d, stand site)]
3. Height growth functions for single trees
   [ih = f (d, stand, site)]
4. Volume functions for single trees
   [v = f (d, h)]

The basal area growth functions are distance independent and express 5-year increase of $(dbh)^2$ as estimated by repeated callipering of all trees ≥ 10 cm on 10 m-plots and also some sample trees < 10 cm. In total 230 000 trees were included, and separate functions were developed for seven tree species. Since measurement errors are large and negative growth was often registered, a logarithmic transformation of the dependent variable was not possible. The solution was non-linearly weighted regression with weights reciprocally proportional to expected residual variance. The latter is composed by a biological component for growth variation, probably proportional to the growth and with a log-normal distribution, and the measurement error, proportional to the diameter and with a normal distribution. In a first step, a simple growth function was constructed with preliminary weights. The residual variance was modelled as a function of diameter and estimated growth, and the latter function was used for weighting in the final regression.

Observed values of the dependent variable were corrected for the measurement error, for growth period lengths deviating from exactly 5 years and for the climatic variation according to year ring indices. Age and site index were avoided as independent variables. The most important independent variables were: tree diameter, basal area of larger trees, stand mean diameter, total basal area and its deviation from surrounding stand, basal area proportion of other species, effects of ditching, thinning and fertilisation, temperature sum, soil type, depth, moisture and texture and vegetation type. Functions were developed both with and without vegetation type included. All functions will now be tested with data from long-term research plots. Two problems have already been recognised and remain to be solved:

- There is a residual trend over stand age. Stage (1973) and Monserud & Sterba (1996) used relative crown length as an expression for stage of development This variable is not available in our data.
- The effect of thinning is only included as an indicator variable. It should probably be related to the proportion of removed basal area. Also the temporal aspect should be considered.

The functions for height and height growth were based on data from sample trees. Since estimated tree height depends on stand basal area it decrease after thinning. To avoid this problem the height growth model will be applied for a certain period after thinning.

The volume functions used will be those presented by Brandel (1990).

The mortality model contains three functions:

1. Probability for mortality on a plot, indep. of specie
   [pmp = f (plot size, stand, site)]
2. Proportion mortality of initial basal area during 5 years on plots with mortality
3. Probability for mortality on tree level (species-specific) [pmt = f (d, stand, site)]

This model was presented by Fridman & Ståhl (2000). It can be applied both deterministically and stochastically. In the first case only the step 3-functions are applied. In stochastic applications mortality on tree level is distributed proportionally according to the step 3-values so they sum up to the mortality level given by the step 2-function.

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Application of Data from Permanent Experiments and Forest Inventories in the Development of Growth Models Applied in Forest Management Planning

Jari Hynynen

Finnish Forest Research Institute
P.O. Box 18, FIN-01301 Vantaa, Finland
e-mail: jari.hynynen@metla.fi

Abstract

An overview of the development process of the growth and yield models of MELA System is given in order to demonstrate the application of data from different sources in the development of models applied in forest management planning.

MELA System is widely applied in forest management at various planning levels with varying time span of planning, and in different parts of Finland. MELA System includes only one set of growth and yield models, which is employed in order to provide information for several purposes across the field of forest management planning. Thus, the development of models for this kind of system is demanding task that cannot be fulfilled without some compromises in model building.

The major requirements for models applied in MELA include

- capability to produce unbiased prediction of the development of the forest resources,
- compatibility with forest inventory data,
- logical behaviour in long-term simulations, and
- capability to predict the responses to silvicultural practices.

In the development of models, three kinds of data sources were used in the different stages of model building. Data from repeatedly measured growth and yield experiments provide enough variation in growth factors (e.g. stand densities) in order to study the growth patterns of stands and trees growing in different conditions. Further, the plot size in these experiments is large enough, and measurement periods long enough for modelling stand dynamics. However, these data were too limited and non-representative to be applicable in fitting of the models to be used in MELA. Permanent sample plot data were applied in construction of initial model structure, and in the evaluation of the performance of developed models.

In fitting the models, permanent sample plot data sets of INKA (Inventory growth plots), TINKA (Young forest inventory growth plots), and SINKA (Inventory growth plots on peatlands) were used. These data form sub-sample of the stands containing the sample plots of the 6^{th} and 7^{th} National Forest Inventories. These were regarded as the most representative material available for modelling purposes. The plot size is large enough for modelling stand dynamics, and data were geographically quite representative. However, there were limitations with respect to the variation in site types and tree species.

Data from temporary sample plots of NFI provide the most representative data of forest resources in Finland. Nevertheless, these data could not be used in model development, because of the unreliable stand information caused by small relascope plots, and unsuitable sample

tree selection for description of stand dynamics. Temporary sample plot data of the 8th National Forest Inventory were used in the evaluation and calibration of the models. The purpose of calibration was to

a) adjust the predicted growth to the same average level as that obtained from the growth measurements of the national forest inventory,
b) take into account the effect of climatic short-term variation on tree growth,
c) obtain the growth predictions for tree species not included in the modelling data, and
d) obtain the growth predictions for site types not represented in the modelling data.

The following procedure was applied in the calibration of the models:

1. Growth of every tree in the calibration data was predicted with the growth models.
2. The prediction bias was calculated as a difference between observed and predicted growth.
3. A model for bias was developed with the most important variables (site, species, location) as regressors.
4. The calibrated prediction was obtained by adding the predicted bias to the initial growth prediction.

Mixed Model for Height Prediction Based on Site Factors

Risto Ojansuu

Finnish Forest Research Institute
P.O. Box 18, FIN-01301 Vantaa, Finland
e-mail: risto.ojansuu@metla.fi

Abstract

Forest site type is a categorical variable, which is determined on the basis of ground vegetation. Site index predicts the growth potential of the site better than the forest site type does, but it can only be used on one third of Finnish forest area. In order to integrate the site descriptions based on forest site types and site index, a mixed model for height growth is presented.

The used data set was a sub-sample of those Scots pine, Norway spruce and birch stands, on which there was a sample plot of the 7th National Forest Inventory of Finland. In each stand, three circular permanent sample plots (altogether 1080), containing 3680 sample trees, were measured. The plots were measured three times with five years' intervals so that the final data consisted on 7841 height measurements of dominant trees.

In the model, the age-dependent height development of dominant trees was a fixed function of site factors, such as forest site type and some climatic and geographical site factors. In accordance with the data, which included stand, plot, tree, and measurement levels, the random part of the model had a hierarchical structure. The random part of the model can be used to calibrate the model for a specific site if one or more tree heights and the stand age are measured. By using the model developed here, the broad experience of Finnish foresters concerning forest site type system, can be utilized effectively to make more accurate local growth predictions and predictions for local site productivity.

Calibration of a Hybrid Model with Data from the National Forest Inventory in Norway

Nils L. Lexerød

Agricultural University of Norway, Department of Forest Sciences
P.O. Box 5044, N-1432 Ås, Norway
e-mail: nils.lexerod@isf.nlh.no

Abstract
To gain the advantages of both empirical growth models and process simulation models a hybrid model, FORECAST, is tested for Norway spruce. FORECAST is a stand level model, and growth is predicted from empirical growth data and modified by different ecological processes. The driving function is the nitrogen efficiency of the foliage. Empirical growth data for trees includes, among other variables, biomass of different tree components, stand density, mortality, height and diameter. Data from 623 permanent sample plots in the National Forest Inventory in Norway were used for calibrating FORECAST for these variables. Norway was divided into five different climatic regions, and a rather large number of plots were available in all regions except West-Norway. The calibration of FORECAST is an ongoing project, but preliminary tests have shown rather reasonable performances by the model. It can therefore be concluded that a possible approach when calibrating FORECAST is to use data from a large number of sample plots on national or regional level.

Key words: hybrid models, FORECAST, biomass, Norway spruce, National Forest Inventory.

1 Introduction

We can diverge between three main types of models. The most common are the empirical growth models. These models take data that define how the forest has grown in the past, and use them to define how the forest will grow in the future. The basic idea is that our experience of how the forest has grown in the past is the best predictor of how the forest will grow in the future. Avvirk 2000 (Eid and Hobbelstad 2000) and Gaya (Hoen and Eid 1990) are examples of Norwegian scenario models that use empirical growth models. The second types of models are process simulation models. Such models represent what the modellers believe are the key ecological processes determining forest growth. They attempt to explain growth in terms of the processes that are represented. These models can also be used as predictive models, but they have some disadvantages compared to empirical growth models. Firstly they are very complex, secondly they are often hard to understand, and simulations are often time consuming even on fast computers. To gain the advantages of both empirical growth models and process simulation models, but without their major drawbacks, a third type of model has been developed, hybrid

models (Feller et al. 1983, Kimmins 1990, 1993, Kimmins et al. 1990, Kimmins et al. 1999). The hybrid models are based on empirical growth models or growth data. Those ecological processes that are supposed to be the most important modify the predicted growth.

The need for a model that can estimate the effects on site productivity of different management regimes, such as fertilization, whole-tree harvests and input of nutrients from atmospheric pollution is increasing in Norway. Since no models is available for such analysis' in Norway, the appropriateness of FORECAST (Kimmins and Scoullar 1994) is tested for boreal forests of Norway spruce (*Picea abies*). FORECAST is also an excellent tool for closer understanding of forest ecology, and it is therefore considered used for educational purposes in Norway.

2 Material and Methods

2.1 Model

FORECAST is a stand level model, which works best for even-aged stands (Kimmins et al. 1999). It simulates competition between herbs, shrubs and trees for light, nutrients and moisture and can represent the role of mosses, or other bryophytes. The nitrogen efficiency of the foliage is the driving function of the model. FORECAST predicts the biomass of different tree components and several ecological variables like forest floor mass, amount of decaying wood and nitrogen capital of the ecosystem. The model can also estimate the cost and revenues, the net present value and the benefit/cost ratio for each stand management regimes. In addition the model can estimate energy benefit/cost ratios and carbon budgets.

FORECAST consists of four input files; TreeData, PlantData, data for Bryophytes and SoilData. The input files contain empirical data which is used by the setup programs; Treegrow, Plantgrow, Bryogrow and Soils. The output from these setup programs is a set of simulation rules and values for various process rates that are used in the ecosystem simulation program. In this paper it will be given a short description of how the TreeData file was calibrated for Norway spruce in Norway.

2.2 Data

Kimmins et al. (1999) gives a description of all variables in the TreeData file. The variables can be categorized into variables describing growth, photosynthesis and nutrient cycling. Empirical growth data includes biomass, in tons/hectare, for stem wood, stem bark, branches, foliage, stumps, medium roots, small roots and fruits. The last being rather insignificant. The stand density is described by number of trees, and mortality by the proportion of the mortality that is not due to competition between trees. The average top height, the height of shortest living canopy tree and the average height of canopy bottom ought to be given. Tree stem maximum diameter and data defining the proportion of trees in up to ten stem biomass classes should also be specified.

FORECAST should be calibrated for at least tree different site qualities. The growth is estimated from the empirical growth data, specified at ten different ages in the TreeData file, using an interpolation algorithm. The ten data pairs were estimated for each variable using sample plots of the National Forest Inventory (NFI) in Norway. The ten ages have to be the same for all site qualities.

Empirical data describing the decay of wood has to be given for each climatic region where FORECAST is to be used (Kimmins et al. 1999). Since different parts of Norway have different climate, Norway was divided into five regions (Table 1). The user can then select the input files appropriate for the purpose and run the setup programs.

Norway spruce is, from an economical point of view, the most important tree species in Norway. It was therefore decided to start with developing a dataset for Norway spruce, and only spruce dominated plots were therefore used for calibration. Spruce dominated means that more than 70% of standing volume is spruce. Only plots with even-aged structure were selected, and the plots had not been thinned for 25 years. A total of 623 plots were divided into the five regions as shown in Table 1.

A rather large number of plots were available in all regions except West Norway. The total numbers of trees at the plots were 8461.

Table 1. Number of sample plots available in different regions.

Region	Plots
South and east < 600 m a.s.l	295
South and east > 600 m a.s.l	112
West	37
Central and north < 250 m a.s.l	102
Central and north > 250 m a.s.l	77
Total	623

2.3 Calculation of Biomass

For each plot biomass of different tree components were predicted for each tree and then summed over all trees at the plot. In Norway we don't have suitable models for predicting the biomass of different tree components. For that reason Swedish and Finnish models were used (Marklund 1987, 1988, Mälkönen 1977). No models for prediction of small roots were available. In FORECAST small roots is defined as roots with diameter less than 5 mm (Kimmins et al. 1999). For estimating the biomass of small roots it was assumed that the amount of stumps and roots is 25 to 40% of the above ground biomass depending on age (Hakkila 1989, Kimmins 1997). The biomass of small roots was then estimated as the difference between this proportion and the biomass of stumps and roots predicted by the models (Marklund 1988, Mälkönen 1977).

To obtain data at stand level for the ten same ages at the three different site qualities, a linear regression model including age and site index was fitted to the data for each biomass component and for height variables and number of trees. The parameters of the model were estimated using least square method in PROC REG (SAS Institute Inc. 1988). The models fitted the data rather well, but they were not very well suited for extrapolations. The outputs from these models were then used for calibration of FORECAST.

4 Discussion

According to Kimmins et al. (1999) three different types of datasets can be used to provide the empirical growth data. The most common is to use yield tables directly, or combined with models for prediction of biomass, developed from long trial field experiments in which the only variable that differentiates the sites is time (Sachs and Trofymow 1991, Comeau and Sachs 1992 , Wang et al. 1995). The Norwegian Forest Research Institute has established long trial field experiments. Blingsmo (1992) calculated yield tables for biomass of different tree components based on these plots. The calculations were done by adding models for prediction of biomass (Marklund 1988) to the yield tables developed by Braastad (1975). These yield tables could, unfortunately, not be applied, because they do not cover long rotation lengths at the best sites. This is necessary, because the ages, where data is given, have to be the same for all site qualities. Data is therefore needed for ages equal to, for example 150 years at the highest site qualities. This is because 150 years is not an unusual rotation length at the lowest site qualities in Norway. The plots, from which the tables have been calculated, have also been treated more intensely than commonly practiced today, and very few are undisturbed. It was therefore concluded that the yield tables presented by Blingsmo (1992) was not particularly suitable for calibration of FORECAST.

The second possible approach is to use output from a well-calibrated and reliable empirical growth model, as shown by Grewal et al. (1990), Grewal (1991), Wei et al. (2000). The scenario models Bestprog (Blingsmo and Veidahl 1989) and Gaya predict biomass of different tree components. The growth projections in the scenario models are based on models developed from the long trial field experiments at the Norwegian Forest Research Institute. It is therefore doubtful if they have a satisfactory prediction of the biomass in stands on good sites that are grown for long rotations.

The third approach, which is described in this paper, is to use data from many plots of a particular site-quality. The permanent sample plots

of NFI offered such data, and were used for calibration of FORECAST. One of the advantages with NFI data was that it contained some plots that were older than the usual rotation length, but even for this dataset there were few plots with very high ages on the best sites. The division into five regions was possible when using data from the NFI. A disadvantage with the NFI data was that more parameters than time separated the plots for each site quality. The large number of plots should, however, reduce the effect of extreme plots. Another problem was the size of the plots, which in this case was 100 m^2. Strand (1983) points out that models derived from small sample plots can deviate significantly from corresponding models developed from larger plots.

Our aim was that the regression models should give predictions close to the highest possible level of biomass production at the different site qualities. To obtain this, plots that had been thinned the last 25 years were removed. Output from the TreeGrow program indicated, after all, that the regressions models gave to low biomass predictions. The reason was that several plots with low standing volume, which had not been thinned, were included in the estimation of the parameters. The influence of these plots on the parameter estimates of the regression models should therefore be analysed, and the plots removed if their influence is large. This will certainly reduce the number of plots available, but the models estimated from the remaining plots will most likely give biomass predictions closer to the highest possible level of biomass production.

The wood density depends on the diameter increment. A tree with small annual rings has higher wood density than a fast growing one. The biomass of a tree, at a given diameter, is therefore higher for trees with small annual rings. The diameter increment depends, among other factors, on the site quality. The models used for prediction of biomass in this paper contain no variable describing growth. Petersson (1999) found that models including a growth variable describe the effect of diameter increment on the biomass in a more reasonable manner than the models by Marklund. These models includes, unfortunately, variables not collected within the Norwegian NFI, and were for that reason not used.

Since the calibration of FORECAST is not finished, no results from ecosystem simulations can be presented, but preliminary tests have shown rather reasonable performance by the model (Pers.comm. Prof. Finn H. Brække, Dept. of Forest Sciences). It can therefore be concluded that a possible approach when calibrating FORECAST is to use data from a large number of sample plots at national or regional level.

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Modelling Individual Tree Mortality from Permanent National Forest Inventory Sample Plots in Norway

Tron Eid[1] and Erik Tuhus[2]

[1]Agricultural University of Norway, Department of Forest Sciences
P.O. Box 5044, NO-1432 Ås, Norway
[2]Accept Data Norge AS,
Strandveien 12, P.O. Box 258, NO-1324 Lysaker, Norway
e-mail: tron.eid@isf.nlh.no

1 Introduction

Recent developments with respect to practices in forestry involve increasing focus on selective cutting techniques. An appropriate description of the dynamics in a forest where selective cutting are applied, requires in-growth-, growth- and mortality models for individual trees. Until recently no such models had been developed in Norway. At the Norwegian Forest Research Institute there is an ongoing project that aims at developing in-growth and growth models for individual trees. The modelling has been based on permanent sample plots from the National Forest Inventory (NFI). A similar project, with focus on mortality, has been done at the Department of Forest Sciences, Agricultural University of Norway (Eid and Tuhus 2001). The aim of the present paper is to give a short description of this work.

Internationally, there is a wide range of mortality models adapted to individual tree growth predictions (e.g. Vanclay 1994). However, most models do not sufficiently meet the requirements of large-scale forestry scenario analyses applied to a country or to countrywide analyses on the property level. For nation-wide analyses the data should reflect the full range of variability with respect to treatments, sites, forest structures, and tree species. To use data from a NFI with permanent sample plots is probably the best way to meet these requirements. An example of such models is described by Monserud and Sterba (1999) for Austria.

The aim of the work carried out was therefore to develop models for individual tree mortality based on permanent sample plots from the Norwegian NFI. The models should also include regular mortality (mortality due to suppression and competition) and irregular mortality (mortality due to wind, snow, diseases, etc). The models should be applicable to even-aged and uneven-aged forest as well as forest with mixed and pure species composition. Since the models also should be applicable to analyses in practical management planning, the modelling was restricted to include explicatory variables that were available from practical inventories.

2 Material and Methods

The NFI established permanent sample plots from 1986 to 1993, and remeasured them from 1994 to 1998, i.e. data from one remeasurement were available. The sample plots cover the forest area of Norway (Finnmark county excluded) in a systematic 3×3 km grid (Norwegian Institute of Land Inventory 1998). Each plot had an area of 100 m^2. The time periods between the meas-

urements varied from one to 12 years, with an average of 5.6 years.

The data comprised 4506 sample plots with 46 107 individual trees. The data were divided into four groups according to tree species:

(i) Norway spruce (*Picea abies* (L.) Karst.),
(ii) Scots pine (*Pinus sylvestris* L.),
(iii) birch (*Betula* spp.) and
(iv) other broadleaved trees.

The numbers of trees in each of these groups were 17 250, 7802, 15 650 and 5405, respectively. Each tree was classified as "alive" or "dead" at the time of plot establishment as well as remeasurement. At remeasurement, all trees were alive at 3402 (24.5%) plots. Out of 46 107 living trees at the time of establishment, 1911 trees were dead when they were remeasured. When converted into annual mortality rates for number of trees, the 1911 dead trees corresponded to an overall annual mortality rate of 0.82%, and to 0.48%, 0.37%, 0.97% and 2.13% for Norway spruce, Scots pine, birch and other broadleaved trees, respectively.

The logistic function is the most widely used in modelling individual trees mortality (e.g. Monserud 1976, Buchman et al. 1983, Hamilton 1986, Vanclay 1991a, Tuhus 1997, Monserud and Sterba 1999). The following logistic model was selected for the present work:

$$PS = (1 + e^{-\beta' \mathbf{X}})^{-t} \quad (1)$$

where PS is the probability of survival (mortality is given by 1-PS) over a period of t years, $\beta' \mathbf{X}$ is a linear combination of parameters β and explicatory variables $\mathbf{X}$, and e is the base of the natural logarithm. Since the remeasurement intervals of the data were irregular, it was necessary to weight the logistic function to account for time. The use of the exponent –t rather than –1 in the function is one way to deal with this (Monserud 1976). The following survival model was hypothesised for all species:

$$PS = [1 + e^{-(\beta 0 + \beta 1 * t1 + \beta 2 * t2 + \beta 3 * S1 + \beta 4 * S2]^{-t}} \quad (2)$$

where t1 = individual tree size (d – diameter individual tree), t2 = competition (BAL – summarised basal area for all trees larger than subject tree), S1 = stand structure (PBA – proportion basal area), and S2 = stand productivity (S – site index). An alternative competition index d/D_{ba} (i.e. diameter individual tree/basal area mean diameter) was also tested, but was not found significant in the final model. The same pattern was settled for variables describing stand density (number of trees ha^{-1}, basal area ha^{-1}) when they were tested in the model. The significance of the parameter estimates was tested by means of $z = \beta/ASE$, where β is the parameter estimate and ASE is the asymptotic standard error (e.g. Agresti 1996).

Approximately 20% of the observations (9217) were used in a test data set for validations. Predicted and observed mortality were compared by visually studying deviations over the explicatory variables included in the models. The model development data set as well as the test data set was compared in this way. The test data set was also sorted according to certain attributes not included as explicatory variables in the mortality models, and then used for comparisons of predicted and observed mortality over different classes within the attributes. The deviations between predicted and observed values were tested by means of Pearson chi-squared statistics (e.g. Agresti 1996).

3 Results

For all species, except birch, d^{-1} was highly significant ($P < 0.001$) in predicting tree survival (Table 1). For birch the level of significance was lower ($P < 0.01$) for d^{-1}. The probability of survival for all species increased when diameter increased (negative parameter estimates), thus mortality rate decreased as diameter increased. For all species, except birch, the summarised basal area for all trees greater than the subject tree (BAL) was highly significant in predicting survival (i.e. the greater BAL, the larger the probability of mortality). Site index (S) was also significant in predicting mortality for Norway spruce ($P < 0.05$) and Scots pine ($P < 0.001$) (i.e. the greater S, the larger the probability of mortality). Norway spruce was the only tree species where the proportion basal area (PBA) of the respective species was found significant

Table 1. Estimated parameters and standard errors for survival model.

Variable	Norway spruce		Scots pine		Birch		Other broadleaved	
	Estimate	St. err.	Estimate	St. err.	Estimate	St. err.	Estimate	St. err.
Intercept	8.0599***	0.2933	8.4904***	0.3593	4.8923***	0.1225	5.1575***	0.1663
d^{-1} (cm)	–6.7020***	1.1823	–14.2660***	1.7790	–2.5280**	0.9494	–7.3544***	1.1335
BAL ($m^2\,ha^{-1}$)	–0.0281***	0.0038	–0.0462***	0.0071			–0.0199***	0.0040
S (m)	–0.0264*	0.0126	–0.0761***	0.0223				
PBA (%)	–0.0132***	0.0024						

Significance levels: *P<0.05; ** P<0.01; *** P<0.001

Table 2. Predicted and observed mortality over tree species. Test data set.

Tree species	Total no. of trees	Predicted		Observed		Deviation (%)	χ^2
		No.	(%)	No.	(%)		
Norway spruce	3426	93.2	2.72	78	2.28	19.5	2.47660 ns
Scots pine	1599	34.9	2.18	46	2.88	–24.1	3.54444 ns
Birch	3131	145.6	4.65	124	3.96	17.4	3.19539 ns
Other broadleaved	1061	108.9	10.26	123	11.59	–11.5	1.83019 ns

Significance levels: ns not significant, *P<0.05; ** P<0.01; *** P<0.001

in predicting survival (i.e. the larger PBA, the larger the probability of mortality).

The average deviations between predicted and observed mortality in the test data set varied from –24.1% to 19.5% (Table 2). No evidence of lack of fit was found. The same holds true when predicted and observed mortality were compared over different densities. Further tests indicated some problems related to certain regions and altitudes. Some of the occurrences of lack of fit may, however, well be accidental.

4 Discussion

Mortality of individual trees is a stochastic, rare, and irregular phenomenon. Many mortality models for individual trees include three or fewer explicatory variables (e.g. Monserud 1976, Buchman et al. 1983, Monserud and Sterba 1999). Also in this study most of the tested predictors were rejected from the final models (Table 1).

The data used in the present study was in general substantial. The number of observations was relatively large, the data were representative of the productive forest area in Norway, and comprised even-aged and uneven-aged forest structures as well as forests with mixed and pure tree species composition. The dispersion of practical forest treatments under different conditions was also included.

The small sample plot size was a main drawback to the data. A plot size of 100 m^2 means that a relatively large number of the trees are affected by the forest conditions outside the plot. This problem is particularly relevant for BAL and PBA, since these variables solely were based on the conditions inside the 100 m^2 plot. For S, this problem probably was of less importance because the determination of this parameter was based on a plot size of 0.1 ha.

The aim of the work was to create models applicable for forestry scenario models and analyses. Although stands are commonly used as basic calculation units in such analyses, the target levels with respect to accuracy of the predictions are usually at property, county or regional level. Detailed studies at the stand level are seldom an important part of such analyses. The uncertainties related to the models should be seen in this perspective.

The average deviations between predicted and observed mortality in the test data set varied from –24.1% to 19.5% (Table 2). An error of 20% is quite large if, for example, volume is considered. For mortality, an error of 20% is more acceptable. If the correct annual mortality rate is 0.5% and

the erroneous mortality rate is 0.4% (an underestimation of 20%), the number of stems 50 years from now would be 1549 ha^{-1} and 1630 ha^{-1}, respectively, if the initial number is 2000 ha^{-1} (i.e. an overestimation of 5.3%).

There are many sources of uncertainty related to large-scale forestry analyses in general. Examples of uncertainties are the input variables used as basis for the analyses (e.g. Eid 2000), model errors of the numerous functions used for predictions (e.g. Kangas 1996), the stochasticity of future growth (Pasanen 1998), and the stochasticity of future prices (Leskinen and Kangas 1998). Thus, as long as the mortality models are unbiased, they will not introduce any substantial change with respect to the final uncertainty of large-scale forestry analyses.

The mortality models can be used both stochastically and deterministically. With stochastic use, the probability of survival is calculated for each tree, and then a selected random number determines whether the tree survives or not. With deterministic use, the number of trees in, for example, a particular diameter class is directly reduced by the probability of survival predicted by the mortality model. As long as the mortality model is distance-independent, stochastic and deterministic use provide for nearly the same results at the stand level (Weber et al. 1986, Vanclay 1991b). The last concept reduces the required computer capacity considerably, which is important for analyses involving large amounts of data.

5 Conclusions

Logistic models for prediction of mortality for individual trees, designed for use in large-scale forestry scenario models and analyses, have been developed. Provided the many uncertainties of large-scale forestry scenario analyses in general, the presented models seem to hold an appropriate level of reliability. This does not mean that the models cannot be enhanced, however. With new rotations of NFI permanent sample plot measurements, the models should be evaluated and, if necessary, revised or calibrated.

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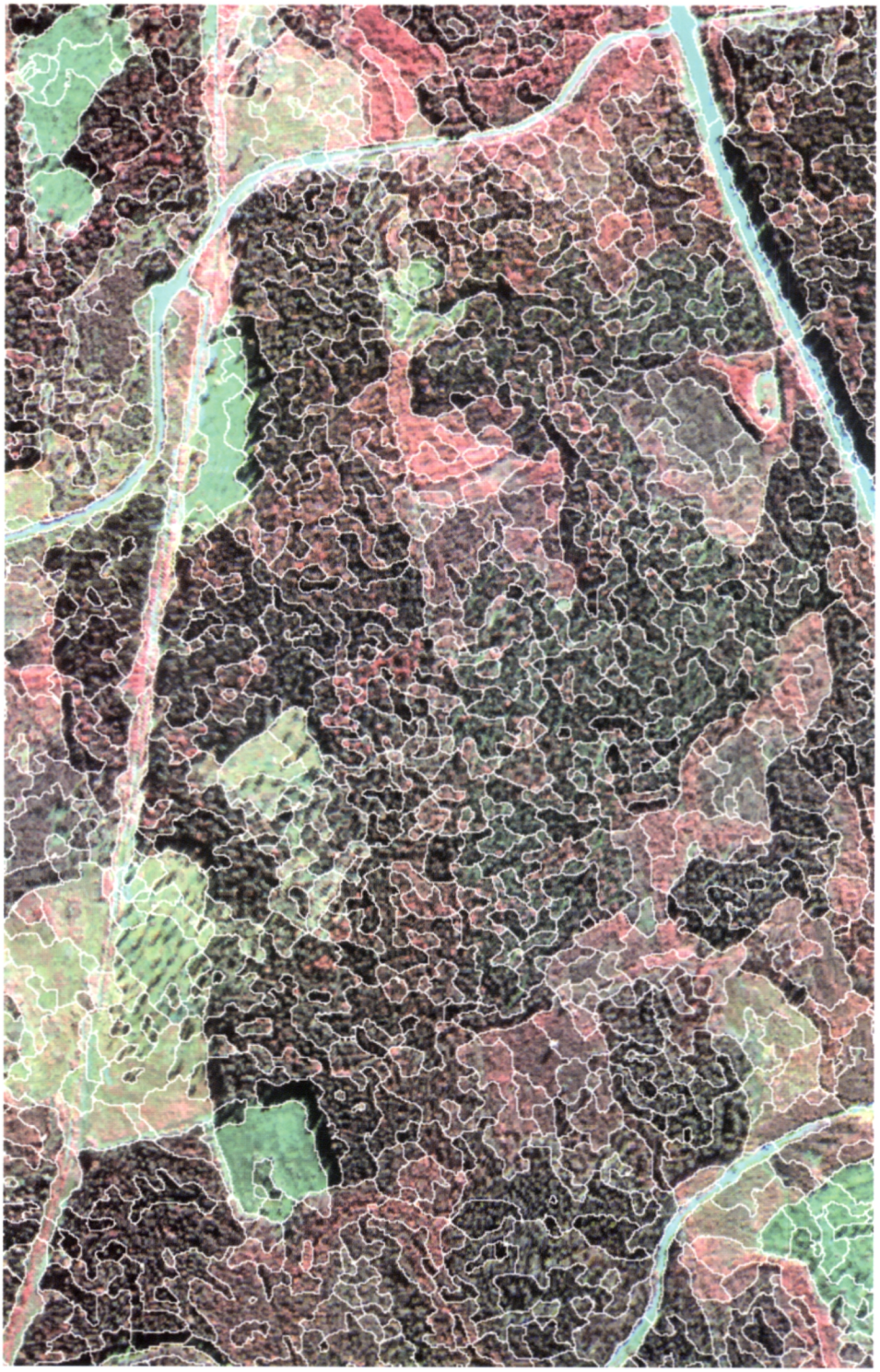
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