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Editors:
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D W Längin
M C Antonides

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Table of Contents

Preface 1

The precision forestry cooperative: it's genesis and future;
P. Schiess, D. Briggs 3

Estimating internal wood properties of logs based on real-time, NIR measurements of chainsaw wood chips from a harvester/processor;
G. Murphy, M. Acuna 5

The use of RFID technology in the timber supply chain;
S. Korten 19

Modern techniques in terramechanical measurements;
A. Suvinen, M. Saarilahti 21

Current state and potential of the IS-HS project - integration of in-situ data and hyperspectral remote sensing for plant production modeling;
J. van Aardt, P. Coppin 33

Developing a GIS-based flow-channel and wet-areas mapping framework for precision forestry planning; ***F. Meng et al*** 43

Small format digital photogrammetry for plantation forestry applications;
A. Kunneke 57

Determining areas of high weed growth using resolution satellite imagery;
M. Norris-Rogers 59

Reclassification method for the high-resolution satellite photograph by multi agents; ***T. Sakai*** 77

Segment-based forest volume-by-type modeling using small footprint LiDAR height distributions; ***J. van Aardt, R. Wynne*** 85

Forest resource assessment using stochastic geometry;
G. Perrin et al 105

Advanced techniques for measuring and mapping the impacts of harvesting operations on forest soils using high resolution scanning methodologies; ***A. Kunneke, W. de Clercq*** 117

The use of high resolution airborne imagery for the detection of forest canopy by *Sirex Noctilio*; ***R. Ismail, O. Mutanga, U. Bob*** 119

Automation of forest machines – an important piece in precision forestry;
B. Löfgren 135

Accuracy of GPS/GIS applied harvester skidding tracks;
A. Kopka, B. Reinhardt 149

Evaluation of forestry machinery performance in harvesting operations using GPS technology; ***R. Cordero, O. Mardones, M. Marticorena*** 163

Precision forestry and information - Information management a forgotten task? ***C. Kätsch*** 175

Forest operations management: towards mobile communication; ***E. Mikkonen*** 187

Remote sensing and current forestry information needs in South Africa; ***F. Ahmed*** 195

Simulating harvesting procedures to evaluate different working systems based on discrete single-tree events; ***M. Hemm, M. Ziesak, W. Warkotsch*** 205

Precision forestry and the Multiple Path Principle; ***K. von Gadow*** 221

Multi-criteria optimization of technologies based on forest growth simulation; ***A.Skoupý, J.Simon*** 237

Information requirements to fertilize plantations with greater precision in a dry country; ***B. du Toit*** 245

Automatic generation of treatment paths for mixed forest stands of spruce (*Picea abies*) and beech (*Fagus sylvatica*); ***L. Hinrichs*** 261

Defining planting windows for successful re-establishment of *Pinus patula* in Southern Africa; ***J.W. Crous , R.G. Mitchell*** 277

Identification of tree root system damage caused by heavy machinery using new measurement technology suitable for precision forestry; ***J. Čermák et al*** 291

Gaining precision in plantation forestry: building on soil information; ***A. Rozanov et al*** 305

Precision forestry and site sustainability; ***D. Matthies et al*** 307

Planning logging systems through site analysis; ***D. Lubello, S. Grigolato, R. Cavalli*** 319

Management of wood haulage through GIS/GPS tools in maritime pine forests (France); ***R. Emeyriat, M. Bigot*** 331

Integrating harvesting and sawmill operations using an optimized sawmill production planning system; ***B. Wessels et al*** 341

A new approach for woody resource monitoring in Namibia: field inventories and remote sensing; ***V.U. Kazapua, P.N. Haindongo*** 349

Using e-Cognition for improved forest management and monitoring systems in precision forestry; ***M. Shiba, A. Itaya*** 359

How much energy wood can our forests supply? - Development of a GIS-based decision support system for the assessment of the potential of energy wood from sustainable managed forests;
T. Cremer et al 361

Dynamic management of biomass inventories using GPS;
B. Talbot, W. Brink 371

The potential of site specific measurements (SSM) and modeling in agroforestry research & development; ***P. Chirwa, C. Black, C. Ong*** 383

Precision forestry in the Southeast U.S.;
S.E Taylor et al 397

Comparison of DEM resolution for forest road design with soil sediment evaluation; ***E.S. Miyata, J. Session, K. Aruga*** 415

High-end GPS vs. low-end GPS: Comparing GPS positional accuracy in the forest environment; ***T. Yoshimura, T. Sakai, M. Nose*** 429

A model for evaluating forest road load by forest operations;
J. Krč 437

Cost-competitiveness of harwarders in CTL-logging conditions in Finland - a discrete-even simulation study at the contractor level;
K. Väätäinen, H. Liiri, D. Röser 451

The precision of productivity models for the harvester – do we forget the human factor? ***T. Purfürst, J. Erler*** 465

Forest operations planning based on high-resolution wet-areas mapping: verifications; ***P. Murphy et al*** 477

GPS-based documentation of manual silvicultural operations;
T.P. McDonald et al 489

Robust optimization of forest transportation networks: A case study;
G. Murphy, H. Stander 503

Preface

On behalf of the Symposium Scientific Committee, I am honoured to provide the introduction to this volume of proceedings. These proceedings represent scientific contributions to this IUFRO Precision Forestry Symposium titled "Precision Forestry in plantations, semi-natural and natural forests" held in Stellenbosch, South Africa, from 5 to 10 March 2006. The symposium was jointly organized by Forest Engineering (FE), Stellenbosch University (the local host), the Chair of Forest Work Science and Applied Informatics, Technical University Munich (TUM) and IUFRO.

The objective of this symposium was to provide details of research results and promote communication and share information on precision applications in forest operations. It is vitally important to now entrench precision concepts in forest operation from sound research through the value chain. In this way the benefits of this work will be tangibly demonstrated.

This symposium was the culmination of a number of events and initiatives, not only in South Africa, but in Europe and North America. The initial idea of presenting the first South African Precision Forest Symposium in 2003 and the formation of the Precision Land-use and Management working group were sparked by events at Washington State's Precision Forestry Cooperative's initiative, and their presentation of the First International Precision Forestry Cooperative Symposium in 2001. In addition precision developments in agriculture and particularly in fields of Viticulture and Oenology here in South Africa made researchers at Forest Engineering take note of the enormous potential of precision based forest operations could offer in forestry. These occurrences in turn led to a close relationship between FE and Walter Warkostch and his team at TUM, and the joint presentation of the already mentioned 2003 symposium, plus a second symposium in 2004. Without this partnership much of what has happened would not have been possible.

I would like to thank all three organizations for their contributions to the success of the symposium. We are also indebted to the authors of the papers included in this volume, as well as all the symposium participants. This publication would also not have been possible without the significant financial support from Andreas Stihl, the Department of Water Affair and Forestry and other sponsors of the symposium. Lastly my appreciation to the members of the FE team - Dirk Laengin, Poppie Gordon, Carien Antonides and Sheila Henning, – and Martin Ziesak for their contributions towards the successful presentation of this event.

These proceeding are reproductions of abstracts and papers submitted to the symposium with editing to achieve consistent format. No attempt was made to review or verify results, although the abstracts were reviewed for suitability..

The following experts served as abstract reviewers for the International Precision Forestry Symposium 2006 in Stellenbosch, South Africa:

Pierre Ackerman, University of Stellenbosch, South Africa
Walter Warkotsch, TU München, Germany
Martin Ziesak, TU München, Germany
Peter Schiess, University of Washington, USA
Reino E. Pulkki, Lakehead University, Ontario. Canada
Glen Murphy, Oregon State University, USA
Robin N. Thwaites, Queensland University of Technology, Australia
Daniel Guimier, VP Eastern Region – FERIC, Canada
Staffan Berg, The Forestry Research Institute of Sweden, Sweden
Masami Shiba, Kyoto University, Japan
Esko Mikkonen, University of Helsinki, Finland

February 2006 Pierre Ackerman

THE PRECISION FORESTRY COOPERATIVE: IT'S GENESIS AND FUTURE

Peter Schiess and David Briggs
Precision Forestry Cooperative, University of Washington, USA
E-mail: schiess@u.washington.edu

Abstract

The Precision Forestry Cooperative at the University of Washington arose from a concern expressed originally by industry and academic leaders in the 1990's about the challenges facing the State at the dawn of the 21st century. Questions were asked about the need for new technologies that can transform traditional sectors of the State economy, such as agriculture, construction, and forest products, and how technology could create important new sectors. These concerns were shared by the legislature and out of this shared concern the concept of the "Advanced Technology Initiative (ATI)" was created. The ATI is seen as the conduit towards new knowledge generating cutting edge research that will generate new concepts for education (knowledge generation) and new economic activities (applications). The ATI represents a major new tool for stimulating business activity in the state of Washington. It draws on proven models of economic and research development from Washington's own history. In the 1950's visionary members of the Washington legislature invested in the expansion of the School of Medicine at the University of Washington. The School of Medicine has become a world leader in research and treatment. It has become a regional magnet for medical services. It has received hundreds of millions of dollars in out-of-state grants and contracts and has become a major generator of high paying jobs.

The concept of "expertise clusters" forms the core of successful ATI programs. Each expertise cluster consists of 3-5 faculty members and technical support staff, organized around a particular theme and nationally recognized research leaders. In the case of the University of Washington, four such clusters were advocated by the University administration and industry to the State legislature in areas of research that have unusual potential for economic impact in our region. One such cluster was termed "Precision Forestry" in the College of Forest Resources, the others being in the School of Medicine – "Infectious Diseases", Department of Computer Science and Engineering – "Computer Animation and Digital Media", and College of Engineering – "Construction". These were established in 1999 through an act by the Washington State Legislature.

The paper will discuss the Precision Forestry cluster, organized as the Precision Forestry Cooperative (PFC) at the UW and the process of developing and prioritizing research themes and initiatives, based on close interaction with its stakeholders, industry, the State, and the University. Research themes are as much driven by individual's expertise and interest as well as perceived needs by outside constituencies that provide additional funding sources beyond the base funding provided by the State Legislature. We will describe and discuss the development of the PFC from its inception, the processes by which current areas of emphasis were selected, and other, promising areas of research were not pursued, abandoned, and that may emerge in the future.

ESTIMATING INTERNAL WOOD PROPERTIES OF LOGS BASED ON REAL-TIME, NIR MEASUREMENTS OF CHAINSAW WOOD CHIPS FROM A HARVESTER/PROCESSOR

Glen Murphy and Mauricio Acuna
Forest Engineering Department, Oregon State University, USA
E-mail: glen.murphy@oregonstate.edu

Abstract

In many parts of the world log markets are becoming increasingly competitive and complex. Wood properties, such as stiffness, density, spiral grain, and extractives content, are now being considered by log buyers. Assessing these properties in real-time will be a challenge for log supply managers. The utility of near infrared (NIR) technology for predicting wood density in Douglas fir stems was examined. Wood disks were collected from 17 sites around Oregon. Each disk was cut with a chain saw, of similar gauge to that used on mechanized harvesters/processors, to provide saw chips. Near infrared spectra were then obtained for the chip samples. Multivariate techniques were used to correlate wood properties with the NIR spectra. The preliminary research results showed that NIR could be used to predict density. The density predictions should allow logs to be segregated into several density classes.

Keywords: log segregation, sensors, forest harvesting

Introduction

In many parts of the world log markets are becoming increasingly competitive and complex. Where at one time tree species, dimensions, and external quality characteristics (such as branch size, sweep, and scarring) may have been sufficient to specify a log-sort, consideration is now being given to specifying such wood properties as stiffness, density, spiral grain, and extractives content. Accurately assessing these properties in real-time can be a challenge for log supply managers wanting to segregate logs into different product classes based on wood properties. Variables such as stand age and height within a tree have been used in the past as substitutes for accurate measurements.

Worldwide there is a trend towards increased mechanization of forest harvesting operations. This has come about for a number of reasons; to reduce the impacts of smaller trees on productivity and costs, to improve worker safety, to reduce environmental impacts and to overcome the difficulties some regions face in attracting labor to work in their forests. Mechanized harvesting machines are frequently fitted with computer technology and rudimentary sensor systems for measuring external stem dimensions – usually diameters over bark along the stem and stem length. Research into technologies for measuring stem quality attributes is progressing on a number of fronts with varying levels of success; e.g. acoustics, optical and laser scanning, x-ray, microwave, ultrasound and near infrared (NIR) spectroscopy (Tian 1999, So *et al.* 2002, Carter *et al.* 2004). Some of these scanning technologies could be integrated into the design of mechanized harvesting systems.

One of the more promising technologies is NIR. Reflectance of near infrared light has been used quite successfully in measuring many wood properties. Hauksson *et al.* (2001), for example, have measured age, density and fiber length distributions. Others have measured wood fiber angle (Gindl & Teischinger 2002), cellulose content (Raymond & Schimleck 2002), microfibril angle (Schimleck *et al.* 2001), wood stiffness (Schimleck *et al.* 2002, Kludt 2003, Kelley *et al.* 2004a & 2004b), and pulp yield properties (Sefara *et al.* 2000). NIR spectroscopy has been applied in measuring components of lignin associated with decay (Kihara *et al.* 2002) and in measuring other structural characteristics. A number of authors have concluded that NIR reflectance could be used as a universal method for predicting a wide range of wood properties and applied in genetic selection and log grading (Schimleck *et al.* 2001, So *et al.* 2002).

A five-step process is required for using NIR technology (Kelley *et al.* 2001). First, a set of samples with known wood properties is required. Second, the NIR spectra are collected for the known samples. Third, the spectra and the property of interest are correlated using multivariate techniques. Fourth, the reliability of the correlations is validated. Fifth, the validated model can be used to predict the properties of interest for unknown samples. Collecting the spectra and predicting the properties of interest for unknown samples can be done in real-time.

NIR spectra only relate to wood properties up to a few millimeters of depth into the sample. Measurement of wood properties deep within a stem requires internal samples of the wood to be obtained. Chain saw chips, generated as a stem is cut up into logs by a harvester or processor, are a sample of wood through the stem. This leads to the question, "will chain saw chips, and in particular green chain saw chips, be a suitable sample for predicting wood properties based on NIR measurements"?

Kelley *et al.* (2001) reported that the strength and stiffness of dry poplar could be predicted from the spectra taken from green poplar. Sefara *et al.* (2000) found that good predictions of pulp yields in plantation eucalypts could be obtained by using NIR spectra gathered from wedge, chip or sawdust samples. Kludt (2003) found that solid wood samples gave similar results to powder samples for predicting modulus of rupture (MOR), and were more accurate than powder samples for predicting modulus of elasticity (MOE).

The objectives of the research reported in this paper were to determine whether NIR spectroscopy could be used to accurately predict Douglas-fir wood density based on three types of samples – green chain saw chips, dry rough chain saw chips, and dry ground chain saw chips.

Methods

Sites and trees selected

In mid-2003, 119 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) trees were felled at 17 forest sites located in the Coast Range and the Cascade Range of Oregon. The latitude and longitude of the sites ranged from 44° 13' to 45° 36' and from 122° 00' to 123° 35', respectively. The sites were chosen to cover a range of elevations (217 to 996 m) and aspects. Approximately 7 trees were felled at each site and these were selected to cover the range of diameters present. All stands contained second growth Douglas-fir and were of similar age class (45-55 years). The characteristics of each site under study are shown in Acuna and Murphy (in press).

After felling, disks approximately 100 mm thick were cut at regular intervals up each stem: at 0, 1.4, 5, 10, 20, and 30 metres above the base of the tree. The disks were labeled, placed in large bags, and stored in a cold room until they were ready to be used for the wood density determination. Close to 500 disks were collected.

Sample preparation for NIR spectroscopy

From the total number of disks collected, about 150 were used for NIR spectra measurements. Bark was removed from the edge of each disk. Each disk was then cut with a chain saw, of similar gauge to that used on mechanized harvesters/processors, to provide saw chip samples. Chip samples were collected between 5 and 10 cm from the outer edge of each disk. Samples were divided into three groups: green (100 samples), dry rough (47 samples) and dry ground (50 samples). Chips of the green group were processed just after being collected in the field and were taken from 100 randomly selected wood disks that came from various sites and heights above the base of the tree. Chips from the two dry groups came from 50 randomly selected breast height (1.4 m) disks which had been previously oven-dried. Approximately half of the dry rough chips were then ground into fine powder with a Wiley mill. Samples from the dry ground group were cleaned and their impurities removed.

Near-infrared measurements

NIR measurements were spread over a period of two years and involved the use of two pieces of equipment; an ASD Field Spec and an NIRSystems 6500.

The NIR measurements for samples in the green and dry rough groups were taken with an Analytical Spectral Devices (ASD) Field Spec (product specifications in www.asdi.com) at wavelengths between 400 nm and 2500 nm using the default parameters. This device uses a fiber optic probe oriented at a right angle to the sample surface to collect the reflectance. The chip samples thickly covered the bottom of a petri dish which was placed on top of a slowly rotating turntable. The samples were illuminated with a DC lamp oriented at 30 degrees above the samples. Thirty scans were collected and averaged into a single average spectrum. Two spectra were taken from each chip sample, which were averaged to have a single spectrum for each sample. The reflectance spectra were transferred from the ASD to an Unscrambler® file and converted to absorbance spectra. The spectra collected on each sample were averaged to provide a single spectrum that was used to predict the density of the sample. The next step was to reduce the averaging spectra that were collected at 1 nm intervals, to a spectral data set at 5 nm intervals. According to Kelley *et al.* (2004a), averaging the spectral data reduces the size of the spectra matrix and significantly reduces the time required to compute the multivariate models without decreasing the quality of the models.

The NIR measurements for samples in the dry ground group were taken with a Foss NIRSystems Model 6500 at wavelengths between 400 nm and 2500 nm using the default parameters. The powder from the dry ground samples was placed in a standard static ring cup with a sample area of approximately 11 cm^2. The detectors were sited at a 45 degree angle to the incident light. Thirty-two scans were collected and averaged into a single average spectrum. The reflectance spectra were converted to absorbance spectra. The spectra, collected at 2 nm intervals on each sample, were only used to predict the density of the sample.

Wood density measurement

Two slightly different procedures were followed for preparing samples for solid wood density measurements. The disks from which dry chip and dry ground chip samples were taken were first oven dried. Two solid wood samples (about 5 cm wide) were then randomly cut from each disk at about 4-5 cm from the outer edge. The volume of each of the samples was then measured using a water displacement method. Relative wood density (specific gravity) was then calculated as the ratio of dry wood weight to dry volume (Hughes 1967).

The alternate procedure, used with the disks from which green chip samples were taken, also involved cutting two solid wood samples 4-5 cm from the outer edge. These green solid wood samples were immediately placed in a cold store with an identification tag. The samples were later dried in an oven at 103 degrees C until their weight stabilized (24 to 72 hours). The volume and weight of each sample was then measured and relative wood density calculated. Data on the pith to bark density of each disk was not obtained.

Multivariate analysis of NIR spectra using Partial Least Square (PLS) procedures

The data sets were divided into calibration sets for developing discriminant models and into prediction sets for evaluating the classification performance of the computed models. The characteristics of the samples in each group, as well as the absorption bands used in the analysis were as follows:

- Green group: Calibration set (65 samples), Prediction set (35 samples), absorption band [502-2500], number of data points (401, every 5 nm of the spectra).
- Dry rough group: Calibration set (24 samples), Prediction set (23 samples), absorption band [355-2495], number of data points (429, every 5 nm of the spectra).
- Dry ground group: Calibration set (25 samples), Prediction set (25 samples), absorption band [400-2500], number of data points (1050, every 2 nm of the spectra).

The analysis to perform chemometric analysis of the spectroscopic data was made through the use of the SAS® partial least squares (PLS) software. As implemented, SAS® (version 9.1) can perform PLS regression type II only (Reeves & Delwiche 2003). While possessing several algorithms for PLSR analysis or for cross-validation and various options for determining the number of factors to use, SAS® does not possess any other spectral pretreatments routinely used in spectroscopy. A number of programs have been written using SAS® macro language to implement 1st and 2nd gap derivatives, Savitzky-Golay derivatives and smoothing, the ability to skip or average spectral data points, to correct spectra for scatter correction by either multiplicative scatter correction or standard normal variate correction with or without detrend, and finally, to mean centre all data prior to regression analysis. Despite the above and other preprocessing techniques such as orthogonal projections to latent structures, that can be used to improve the quality of the PLS models (Reeves & Delwiche 2003), very often they greatly complicate the ability to provide interpretation of the regression coefficients (Kelley *et al.* 2004a) or provide little to no improvement in predictions (Kludt 2003). Therefore, in this study no preprocessing techniques were used.

Following the recommendations given by Shao (1993), PLS regression was used to develop the calibrations with a cross validation method where every nine or ten observations were excluded. The test statistic used for the model comparison was PRESS, the predicted residual sum of squares. For the three groups analyzed, the cross-validation procedure indicated zero factors as the minimum number to be used, despite the dependent variables and model effects explained with that number of factors being very low. For that reason, it was decided to perform a series of analyses by using from one up to fifteen factors, and looking at the results of such runs in terms of the dependent variables explained by the model in the calibration set, but especially in the prediction set. As we were concerned with the predictive ability of the regression model, the number of factors that produced the highest coefficient of determination (R^2) in the prediction set was used and reported in this paper. A calibration model can have a very high coefficient of determination due to overfitting with a high number of latent variables. This can lead to a poor performance of prediction when the model is used with the prediction set.

The quality of the models in the calibration and prediction sets was evaluated with two common measures, R^2 and SEC (SEP for prediction set) (Martens & Naes 1991, Burns & Ciurzcak 2001). The R^2 value s a measure of the variation of the response variable (wood density) explained by the regression model. For a heterogeneous material such as wood, R^2 values of 0.75 and above are considered good (Kelly *et al.* 2004a). Likewise, the SEC is the standard error of calibration, a measure of the prediction error expressed in the units of the original measurement (Kludt 2003). This is given by the following equation:

$$[1] \qquad \text{SEC} = \sqrt{\frac{\sum_{i=1}^{SC}(\hat{y}_i - y_i)^2}{(SC - n - 1)}}$$

where $\hat{y}_i$ is the value of the wood property of interest for validation of sample i estimated using the calibration, y_i is the known value of the wood property for sample i (wood density), SC is the number of samples used to developed the calibration model, and n is the number of factors used to develop the calibration model.

On the other hand, the measure of how well the calibration predicts the wood property of interest for a set of unknown samples that are different from the calibration test set is given by the standard error of prediction (SEP) (Kludt 2003):

$$[2] \qquad \text{SEP} = \sqrt{\frac{\sum_{i=1}^{SP}(\hat{y}_i - y_i)^2}{(SP - 1)}}$$

where $\hat{y}_i$ is the value of the wood property of interest for sample *i* predicted by the calibration, y_i is the known value of the wood property (density) for sample *i* , and SP is the number of samples in the prediction set.

Results

Wood density

Table 1 gives a statistical summary of wood density for the calibration and prediction data sets for the three sample types – green, dry rough, and dry ground chain saw chips.

The minimum density for the calibration set corresponded to the green group (315 kg m^{-3}), while the maximum density was associated with the dry rough group (490 kg m^{-3}), which was very close to that of the green group (489 kg m^{-3}). Averages densities were higher in both dry ground and dry rough groups (436 and 433 kg m^{-3}, respectively) with more than 30 units of difference with the green group (399 kg m^{-3}). A similar tendency was found in the prediction set. The minimum density in this set corresponded to the green group (335 kg m^{-3}) and the maximum density is found in both the green and the dry rough group (509 kg m^{-3}). Also, standard deviations were considerably higher in the prediction set than in the calibration set. The green samples came from heights ranging between 0 and 30 m within selected trees while the dry samples were only taken from breast height disks.

Wood density tends to decrease with height in a tree, so it could be expected that the dry samples had higher average densities than the green samples.

Table 1. Range and standard deviation (SD) of wood density (kg m^{-3}) by sample type, for calibration and prediction data sets.

Sample type	Calibration set				Prediction set			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Green chain saw chip	315	489	399	41.7	335	509	414	43.8
Dry rough chip	371	490	433	29.8	359	509	441	40.4
Dry ground chip	381	476	436	26.5	359	499	432	40.3

Variation of NIR spectra

Peaks of absorbance for all three sample groups (green, dry rough, dry ground) were found at about 1500, 2000 and 2500 nm.

The spectral curves for the green chain saw chip group are shown in Figure 1. They illustrate the difference between the NIR spectra for three representative samples of low (315kg m^{-3}), average (407 kg m^{-3}), and high (509kg m^{-3}) densities in terms of their general absorbance.

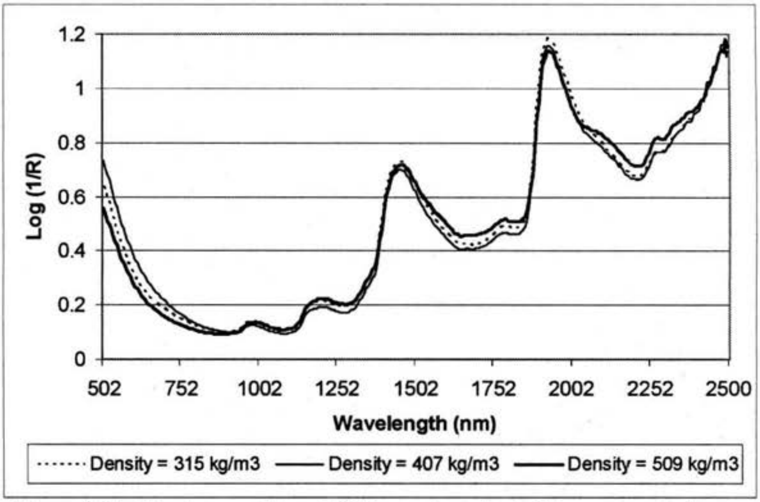

Figure 1. Variation in near infrared (NIR) spectra collected from green chain saw chip samples for different values of basic density.

Figure 1 shows that the high-density sample has slightly less absorbance than both the low and average density samples at wavelengths below 1000 nm. For the rest of the spectral range (1000-2500 nm) the high-density sample has the highest absorbance – most notably in the 1500-1850 nm and 2000-2350 nm ranges.

The spectral curves for the dry rough group show a lower absorbance for all spectra in comparison to the green chain saw chip group. This tendency is confirmed by previous reports (Schimleck *et al.* 2003); however in their studies the difference between green and dry samples is more notable than that found here. This may be due to the characteristics of the dry rough samples used. Other differences between the spectra for the dry rough group and the green group include: a possible reversal of absorbance trends (absorbance for high density samples being higher at wavelengths below 1000 nm and lower at wavelengths above 1900 nm), and the presence of more "noise" and irregularities in the dry rough spectra.

Absorbance values for the dry ground group were intermediate between those found in the green and the dry rough groups. When compared to the other two groups (green and dry rough), there appeared to be no differences among the high, average and low density samples. There also appeared to be no significant differences between the dry rough and dry ground groups over the 400-2500 nm spectral range.

Development and application of PLS regression calibrations

Summary statistics for the wood density calibrations are presented in Table 2. The calibration developed for wood density in each group of samples gave good results, with values of R^2 ranging from 0.89 to 0.95. Wood density calibrations developed using NIR spectra obtained from the dry rough group gave better results compared with the calibrations developed using spectra obtained from the green and the dry ground groups (Figure 2).

Table 2. Summary of calibrations with partial least squares regression developed for basic density using spectra collected from the samples.

Sample type	Calibration set			Prediction set	
	No. of factors	R^2	SEC	R^2	SEP
Green chain saw chip	12	0.89	15.2	0.74	22.7
Dry rough chip	3	0.95	6.9	0.56	27.4
Dry ground chip	12	0.90	11.8	0.85	15.7

Another interesting aspect of the calibration procedure is the difference observed in the number of factors in each group that gave the best results. While just three factors were necessary in the dry rough group to reach the best R^2 in the prediction set, twelve factors were necessary for the green and dry ground groups. Clearly, however, the R^2 in the prediction set was lower for the dry rough group than for the other two groups.

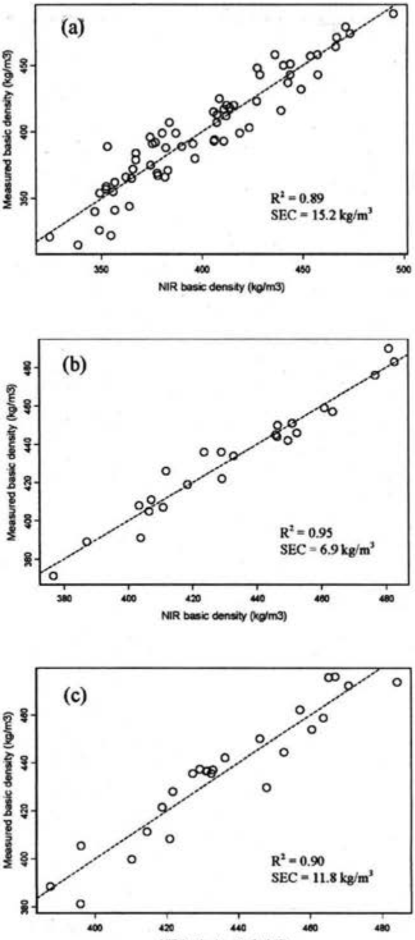

Figure 2. Relationships between measured values and values predicted with near infrared (NIR) spectroscopy for (a) green chain saw chip samples, (b) dry rough chip samples, and (c) dry ground chip samples. Results presented are those obtained for calibration.

When calibrations were used on a separate prediction set for each sample group it was found that calibrations developed using spectra collected from the dry ground group gave the strongest prediction statistic, with a R^2 of 0.85. Conversely, the weakest relation was found in the dry rough group with a R^2 of 0.56. The regression lines between measured and NIR-predicted values for the prediction set are shown in Figure 3. The prediction values of R^2 for these linear regressions are shown in Table 2, and they represent the proportion of variation in the independent prediction set that was explained by the calibration model.

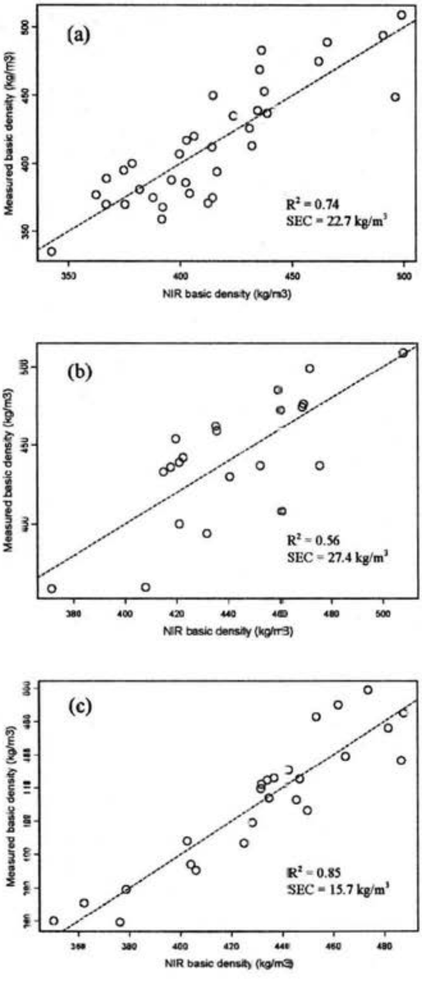

Figure 3. Relationships between measured values and values predicted with near infrared (NIR) spectroscopy for (a) green chain saw chip samples, (b) dry rough chip samples, and (c) dry ground chip samples. Results presented are those obtained for prediction.

In general, predictions of the density in each sample type were satisfactory, but the R^2 values were lower than the R^2 obtained for the calibration sets, with the greatest reduction occurring for the dry rough group. SEP values (15.7-27.4 kg m⁻

^{3}) were considerably higher than the SEC values (6.9-15.2 kg m^{-3}). The dry rough group showed the greatest difference between the SEP and SEC values. The presence of some outliers in the dry rough sample group did not permit a good fit of the data. As some references point out (Dryden 2003), these outliers may be associated with either some mechanical errors inherent to the NIR spectrometer measurements or to the measurement and calculation of the density of the wood samples. These outliers and sources of error may help to explain the high values of SEP found for the dry rough and green groups.

Discussion and Conclusions

The usefulness and potential of NIR spectroscopy for predicting wood density of Douglas-fir based on chain saw chip samples has been successfully demonstrated. Calibration models were found to perform best for both dry rough and dry ground samples; SEC's expressed as percentage of the mean were 1.6% and 2.7% respectively. On the other hand, prediction models performed best for both the green and dry ground samples; SEP's expressed as percentage of the mean were 5.5% and 3.6% respectively. The standard errors of the predictions using the dry rough samples were relatively large compared with the standard errors of the other two groups. We believe, however, that removing a couple of outliers would considerably improve the prediction capability in the dry rough group and reduce the standard errors observed.

R^2 values for NIR-predicted basic densities ranged from 0.56 for the dry rough Douglas-fir chip samples to 0.85 for the dry ground chip samples. The green chainsaw chip samples had an intermediate R^2 value of 0.74. These R^2 values are similar to those reported by So *et al.* (2002) and by Schimleck et al. (2003) for loblolly pine solid wood; R2 values of 0.67 and 0.74 respectively.

Kelley *et al.* (2001) have reported that NIR measurements of green solid wood samples can be used to accurately predict dry wood stiffness for poplar. Schimleck *et al.* (2003) found that NIR measurements of green wood can be used to predict air-dry wood density for loblolly pine. The results of our study confirm their work and reveal the possibility of using NIR spectroscopy of green chain saw chip samples to predict wood properties (such as density) in real time, negating the need to dry samples prior the analysis. These results open the doors to the use of this type of technology for log segregation by mechanized harvesting equipment (e.g. harvesters).

NIR spectra on the green chain saw chip group in this study were gathered from a loosely packed sample in a petri dish on a slowly revolving turntable. While it would be possible to collect "grab" samples of green chain saw chips for NIR measurement in this manner it would be preferable to undertake the measurements on green chips that are being ejected from the log as it is being cut. This would mean obtaining measurements on very, dispersed chips moving at high speeds. Axrup *et al.* (2000) have successfully used NIR spectroscopy to quantify the chemistry of packed pulpwood chips moving at speeds of 1 m s^{-1} on a conveyor belt. Further research will be required to determine whether reliable measurements of wood density can be made from green chips ejected from a log as it is being cut.

To operate in "real-time" NIR measurements would need to take only a few seconds. In this study both spectrometers were using an average of about 30 scans to produce the spectral curves for the 400-2500 nm range. Scan rates for one spectrometer were 10 scans per second and for the other spectrometer 1.8 scans per second, implying overall scan times ranging from 3 to 17 seconds. Kelley *et al.* (2004b) have demonstrated that some wood properties, such as strength and stiffness, can be predicted with only a slight decrease (~ 0.05) in the R value, when a reduced spectral range (650-1050 nm) is used. They comment that the reduced spectral range would allow the use of much smaller, faster, lighter and less expensive spectrometers.

Research by many others has highlighted the potential for measuring a wide range of wood properties using NIR spectroscopy. From this study we can conclude that:

1. Useful calibrations for Douglas-fir wood density can be developed using NIR spectroscopy of chain saw chip samples.
2. Green chain saw chip samples could provide NIR estimates of wood density that are only slightly degraded from those coming from dry ground chip samples.
3. Further work is required to determine whether the promise of real-time, cost effective measurements of wood density (and other wood properties) using NIR technology is valid.

Acknowledgements
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THE USE OF RFID TECHNOLOGY IN THE TIMBER SUPPLY CHAIN

Sven Korten
Forest Work Science and Applied Informatics, TU Munich, Germany
E-mail: korten@wzw.tum.de

Abstract

The goal of a current research project at the Technical University of Munich is to identify the feasibility and limits of using RFID (Radio Frequency Identification) technology in the timber supply chain.

Auto-ID (Automatic Identification) systems like RFID provide generally a better control of the material flow ("real time inventory") within supply chains. In the forestry sector an automatic log marking and identification system leads to traceability of logs from forest to sawmill, easy identification of the forest owner and shorter lead times which causes better product quality.

For this application a transponder must be tagged to each log. Each transponder has a unique number, the transponder-ID. This number is linked directly to a database, where further information can be 'attached' to it, like location, buyer, seller, tree species, length and diameter etc.

During the research project transponder technology was implemented into two different harvesting methods:

1. felling with chainsaw, skidder-based extraction (manual tagging and reading)
2. cut-to-length system using a single-grip harvester and forwarder (automatic tagging and reading)

Both methods caused different requirements on transponder design, tagging and reading techniques. The development of automatic tagging (harvester) and reading (forwarder, truck) devices were crucial challenges.
Real-time tracking and tracing the wood automatically can lead to substantial time and cost savings for every participant in the timber supply chain.

Keywords: RFID, Transponder, Timber Supply Chain

MODERN TECHNIQUES IN TERRAMECHANICAL MEASUREMENTS

Antti Suvinen, Martti Saarilahti
University of Helsinki, Finland
E-mail: antti.suvinen@helsinki.fi

Abstract

Use of a datalogger connected to the CAN bus of an 8-wheeled forwarder's hydrostatic transmission permits measurement of the gross power on the driveline. The ground velocity and the path of the forwarder are monitored by the GPS technique. These data allow the total resistance force to be determined under different terrain conditions. The measuring system was tested in practice on an even tarmac surface and a steep sloping hard earth road, the number of input variables in the first tests having been reduced. The other part of the tests was carried out on the forest floor. It was concluded that the measuring technique is accurate enough for terramechanical research of forest tractors.

Keywords: CAN bus, GPS, Mobility, Forwarder, Forest tractor, Resistance

Introduction

Terramechanical measurements of forest machine operations have traditionally been very costly and difficult to carry out. Modern techniques give new possibilities to develop more sophisticated, economical and accurate measuring systems to evaluate forest tractors' mobility and terrain trafficability parameters. In this study is tested how CAN (*Controller Area Network*) and GPS (*Global Positioning System*) techniques can be utilized for terramechanical measurements.

The CAN bus technique is initially developed for automotive applications. Nowadays CAN bus technique is also adopted for modern forest tractors, for regulating and monitoring engine and power train operations, and since modern forest tractors are equipped with GPS and CAN systems, the technique does not increase the costs substantially. Only an additional CAN datalogger is needed. Although, these techniques have been on hand, these have not been utilized for terramechanical research.

In this study, a datalogger connected to CAN bus of an 8-wheeled forwarder's hydrostatic transmission permits measurement of the gross power on the driveline and the rotational velocity of the drive axle. The ground velocity and trajectory of the forwarder is monitored by the GPS technique. These data allow the total resistance force to be determined under different terrain conditions.

Materials

Instrumented forwarder and tyres

The instrumented forwarder was an 8-wheeled Timberjack 1110 registered in 1997 with about 6000 engine hours logged. The engine is a six cylinder turbo-charged diesel engine, and the forwarder has a hydrostatic-mechanical power transmission system which can generate a maximum pull of 150 kN. The maximum engine power is 114 kW at 37 r/s and the maximum torque 620 Nm at 25 r/s. The dimensions of the forwarder are:

- Length: 9650 mm
- Width: 2820 mm
- Vehicle trend 2110 mm
- Height: 3700 mm (height of cabin 3300 mm)
- Ground clearance: 605 mm
- Wheelbase 5400 mm
- Mass (unloaded) 14 200 kg
- Carrying capacity 11 000 kg.

The tyres are Nokian Tyres 710/45-26.5 16 Forest King F SF (Nokian Tyres). The inflation pressure was 350 kPa in the front bogie tyres and 440 kPa in the rear ones.

Global Positioning System (GPS)

The GPS receiver in this study was a 12-channel Trimble GeoXT, with the external antenna placed on the top of the tractor's cabin. According to Bolstad et. al. (2005)

the mean error of Trimble GeoXT is about 1.6 metres and the standard deviation is about 1.4 metres below a forest canopy using post-processed differential correction. Naturally, the accuracy is better in open areas.

The data acquisition mode was line generic with a one second recording frequency. The post-processed differential correction (DGPS) for GPS data was performed using a base station located in Evo about 80 kilometres south of the test area.

CAN bus datalogging system

CAN (Controller Area Network) is a serial bus system originally developed for automotive applications (Lawrence, 1995). Nowadays, it is also utilized in modern forest tractors, in which it has mainly been used to control and adjust engine and driveline performance automatically. The collecting of data for terramechanical research is quite a new application.

The CAN bus is a multi-master bus, which means that every node in the network can send a message on its own initiative (Alanen, 2000). Each identifiable message is broadcasted into the communication network and every node which needs the information contained in the message can receive it simultaneously (Turski, 1994). If more than one node tries to send a message at the same time, the system has a priority ranking which defines the sending order (Alanen, 2000).

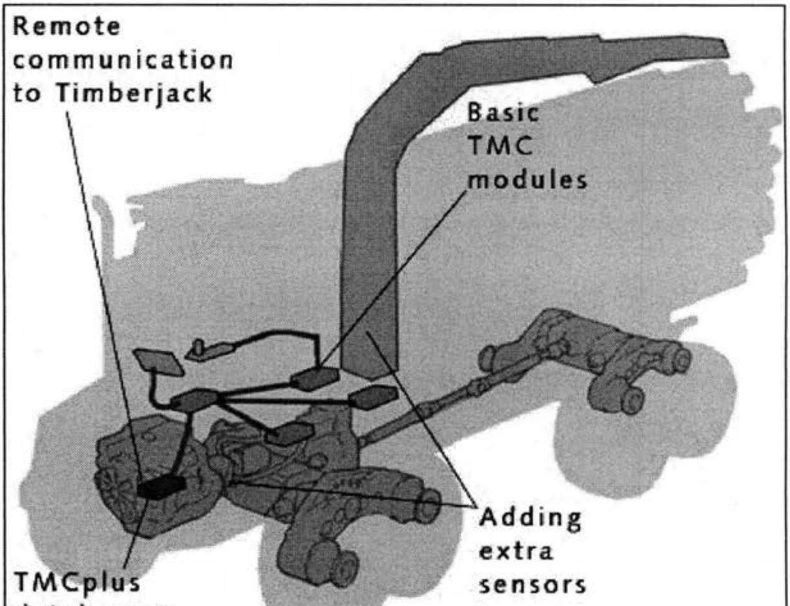

Figure 1. The CAN bus instrumentation of the test tractor (Plustech Ltd. 2002).

The CAN bus data logger used here was developed by Plustech Ltd (subsidiary of John Deere Forestry Ltd). The instrumentation of the tractor is presented in Figure 1. The system enables simultaneous measurement from three CAN buses, which are placed in the pressure sensors of the engine. Messages are recorded four times per second and are converted to engineering units.

The following information was collected for the present purpose:

- event time (recorded every 0.25 seconds), s
- input pressure in hydraulic circuit, bar
- counter pressure in hydraulic circuit, bar
- working pressure in hydraulic circuit (difference between the above two measurements), bar
- signal current of drive pump, mA
- volume of drive pump, cm^3
- torque of drive axle, Nm
- rotational speed of diesel pump, r/s
- rotational speed of drive motor, r/s
- signal current of drive motor, mA
- gross power on drive line, kW.

Much more information on the state of the tractor is also available using the CAN technique but would not be relevant for this purpose.

Data synchronizing

As the GPS data were been recorded once per second and the CAN bus data were been recorded four times per second, both data had to be modified to the same frequency. That was done by averaging every four consecutive CAN bus observations. GPS data and CAN bus data were recorded separately and the linkage were done afterwards. The synchronizing was done by matching the end of zero velocity from both data The GPS antenna is sited the on top of the tractors cabin, but tractor's centre of gravity is some 3 metres further back. Because of that the GPS data should be moved 3 metres backwards in co-ordinates.

Methods

In the earlier literature the terrain often contained only soil parameters (Baladi 1987), and in Wong's (1978) handbook only rolling resistance (F_R), slope resistance (F_S), drawbar pull (F_P), air resistance (F_A) and inertia ($a \cdot m$) are listed as resisting forces. In forest terrain the soil surface is rough and contain obstacles e.g. rocks and stumps, which cause obstacle resistance (F_O) (Saarilahti 1997). In addition, winding (F_W) increases the lateral forces (Crolla and El-Razaz, 1987; Schlotter et. al., 1999) and slip (F_I) causes deeper rutting (Myhrman, 1990) and hence an increase in the resisting forces. Snow resistance (F_L) must also be taken into account in winter conditions. Due to the low velocities attainable on the forest floor (< 2 m/s), air resistance (F_A) can be omitted and drawbar pull is zero in forwarding. The total resistance for forwarders is thus:

$$F_T = F_S + F_R + F_O + F_W + F_L + F_I + a \cdot m \qquad (1)$$

, in which:

F_T = total resistance, N
F_S = slope resistance, N
F_R = rolling resistance, N
F_O = obstacle resistance, N
F_W = winding resistance, N
F_L = snow resistance, N
F_I = slip resistance, N
a = acceleration, m/s^2
m = tractor mass, kg

Because the tests were carried out in summer conditions snow resistance (F_L) is irrelevant in this study. The first part of the tests were implemented on the tarmac yard and on the hard earth forest road, thus obstacle resistance (F_C) can be omitted. The analysis of slip resistance (F_I) is ignored and it is included in rolling resistance, i.e. rolling resistance is assessed in these cases at <15% slip. Tarmac yard test were implemented driving directly, so the winding resistance was in these cases zero (ignored also in forest road tests). Because the velocity of a forwarder was fairly constant during measurements, the inertia resistance can be ignored in this study. For the present purpose Eq. 1 can be reduced to the following form:

$$F_T = F_S + F_R. \qquad (2)$$

The latter part of tests was carried out on the forest floor. In this study rolling resistance (F_R), obstacle resistance (F_O), steering resistance (F_W) and slip resistance (F_I) in forest conditions are handled as one single resistance, which can be named as motion resistance (F_M). In these cases Eq. 1 can be reduced to the following form:

$$F_T = F_S + F_R + F_O + F_W + F_I, \qquad (3)$$

which is in this study simplified to the form below:

$$F_T = F_S + F_M. \qquad (4)$$

If the power on a driveline can be measured and the velocity of the tractor is known, the total resistance force (F_T) can be calculated. It can then be divided into factors, (which are in these cases slope resistance and rolling or motion resistances) provided that the slope is known. Meaningful sloping can be determined from geographical maps, and a GPS signal can be used to determine the macrotopography with adequate accuracy. If special accuracy is needed, levelling of the surface is the best approach.

Measurements

Field tests were carried out in the Central Finland near the Jämsänkoski Forest Machine School in August and October, 2004. The driver was an experienced forwarder operator. The weather during all tests was dry.

The rolling resistance on a hard surface was determined by driving 70 metres long straight line on the tarmac yard. It should be noted that this also includes the internal friction of the drive line and therefore differs slightly from the official concept of rolling resistance.

The sensitivity and accuracy of the measuring system were verified by driving uphill on a hard earth forest road, which was sloping quite steeply. The slope was recorded by levelling the road section. As the rolling resistance on a flat, hard surface had been established at the beginning of the tests, the surplus total resistance was assumed to be the slope resistance. The measured total resistance less the observed rolling resistance on a flat, hard surface should correspond to the theoretical slope resistance based on the inclined plane equation.

The latter part of the tests was carried out on the forest floor. The off-road track was 190 metres long, typical Finnish forest terrain, which bearing capacity was high. Four special parts were been able to recognize from the path:

- uphill slope, about 7%
- two curves, about 90 degrees
- soft terrain , about 15 metres.

The total resistance coefficient was recorded during the unloaded and loaded drives. The load size was 7.6 tons, which is about 70 percentages of the forwarder's carrying capacity. Behaviour of the total resistance coefficient was studied, particularly in the four special track parts.

Results

The rolling resistance coefficient on the tarmac yard

When determining the rolling resistance force on a tarmac yard, the 70 meters straight line was tried to drive at as constant a velocity as possible. In practice, the velocity varied slightly during the driving, although the driver tried to keep it constant. If we assume the velocity to be constant during the 70 meters lane which does not contain the acceleration and deceleration parts, however, we can also assume that both velocity measured by the GPS method and the gross power on the drive line measured by the CAN bus method are constant. The rolling resistance coefficient on the tarmac yard based on this assumption, was 0.056. The standard deviation of rolling resistance coefficient was little over 10%. Later, this rolling resistance coefficient, 0.056, is used as the minimum rolling resistance coefficient. The surplus total resistance compared to this minimum rolling resistance coefficient means that e.g. winding or slope causes extra resistance. More detailed results of measuring rolling resistance coefficient on the tarmac yard can be found from the report: "*Measuring the Mobility Parameters of Forwarders Using GPS and CAN Bus Techniques*" (Suvinen and Saarilahti, 2006)

Slope resistance coefficient

The sensitivity of the measuring system to changes in the resisting forces has been analysed in the report: "*Measuring the Mobility Parameters of Forwarders Using GPS and CAN Bus Techniques*" (Suvinen and Saarilahti, 2006). Suvinen and Saarilahti (2006) separated the surplus resistance from the total resistance on gently sloping hard earth forest road using CAN and GPS techniques. This surplus resistance was considered to be slope resistance in that case. The measured surplus resistance or slope resistance was compared to the levelled slope angle. If the slope angle is given in percentages it should be the same as the slope resistance coefficient. Suvinen and Saarilahti (2006) reported that the root mean square error of that measuring system was about 0.6. The measuring system was reported to give slight overestimations.

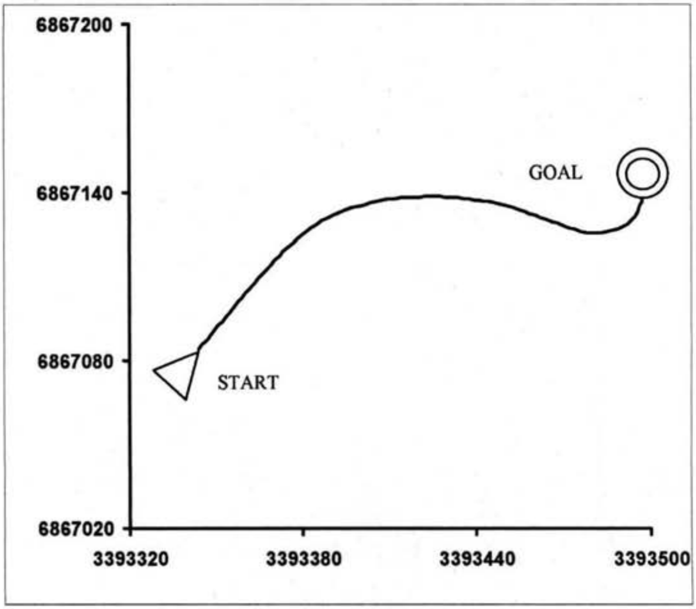

Figure 2. The trajectory of the forwarder on the hard earth forest road.

In this study was done a similar test, which has been described above. The test lane was 182 metres quite steeply sloping hard earth forest road. The trajectory of the tractor is presented in the Figure 2. The route was driven so that it does not contain acceleration or deceleration portions. The slope resistance coefficient was calculated using Eq. 5. The rolling resistance coefficient (μ_R) 0.056 measured on a hard surface was used.

$$\mu_S = \frac{P}{W \cdot v} - \mu_R \qquad (5)$$

,in which

μ_S = slope resistance coefficient
P = power, recorded gross power on driveline, kW
W = total weight of the forwarder, kN
v = velocity, m/s
μ_R = rolling resistance coefficient (= 0.056).

The slope resistance coefficients were as plotted in Figure 3. The solid line in Figure 3 describes the slope percentages obtained by levelling. It can be seen that the measuring system reacts quite well to changes in road inclination. Because the winding resistance was not analysed and the route was curved, the precision of the result was worse than reported in the paper "*Measuring the Mobility Parameters of Forwarders Using GPS and CAN Bus Techniques*" (Suvinen and Saarilahti, 2006).

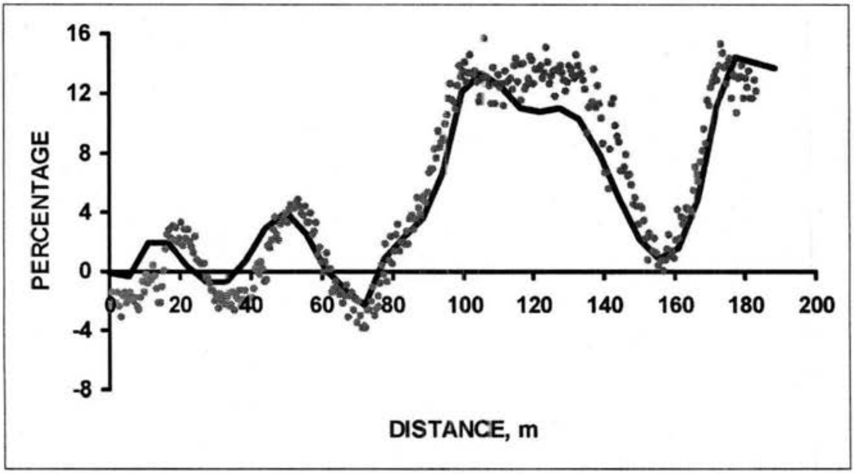

Figure 3. Measured slope resistance coefficient*100 relative to road slope.

Total resistance coefficient on the forest floor

Forest track was 190 meters long and it was been driven with loaded and unloaded tractor. The average total resistance coefficient for unloaded drive was 0.209 and for loaded drive 0.201. The margin between these average total resistance coefficients was only about 4%. The average total resistance coefficient on the forest floor was about four times bigger than the total resistance coefficient on the tarmac yard. Measured rolling resistance coefficients for both forest track drives are presented in the Figure 4. The acceleration in the very beginning of the track raises the total resistance coefficient. The 7% uphill slope causes the next top for the curve. It is remarkable that both curves in the path (about 90 degrees) resist the motion of the forwarder more than this uphill slope and the soft terrain section.

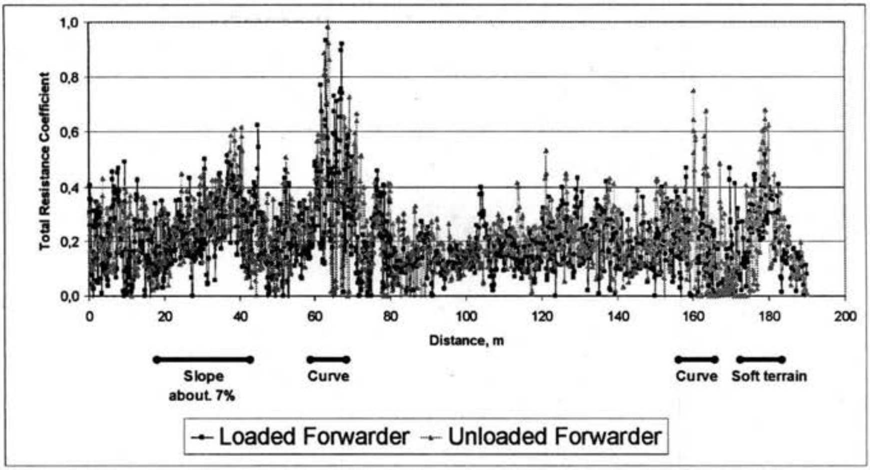

Figure 4. Total rolling resistance coefficients for loaded and unloaded forwarder on the forest floor.

Discussion

In this study is introduced a new technique for determining the mobility parameters of forest tractors. The validity and reliability of the technique was examined by carrying out tests on a tarmac yard and a hard forest road, with the number of input variables reduced to a minimum. For the most part the method utilizes the tractor's own data transmission technique, and only one additional datalogger is needed.

The observed rolling resistance coefficient on an even, hard tarmac surface, 0.056, is little bit higher than the values without internal friction found in the literature for hard surfaces (Saarilahti, 2002). It should be noted that this study's rolling resistance also includes some internal friction in the drive line.

Tests on a steep sloping forest road showed that the measuring system reacts well to changes in road inclination, although the accuracy was little bit worse than Suvinen and Saarilahti (2006) reported on the gentle sloping forest road. That is caused mainly, because the route was not straight line in this case and the winding resistance was not analyzed. However, even this result can be considered accurate enough for measuring the resistances of off-road vehicles. The technique proved to be practicable also in the forest conditions. In addition, tests on the forest floor proved that the turning of the 8-wheeled forwarder causes significant resistance for the motion of the forwarder.

The proposed technique permits the recording of instantaneous power on the driveline with a fairly high accuracy, and the drive axle rotational velocity and the momentum are also obtained as output signals. The data collected to detect changes in ground velocity, based on GPS data, and power and rotational velocity, can be used for analyzing the mobility of the forwarder and the trafficability of the terrain.

The total resistance force can be calculated from the CAN bus measurements and the GPS derived velocity. Furthermore, the total resistance force can be divided into its component forces. The slope resistance coefficient (tanα, in which α = slope angle, degrees) can be defined based on levelling, maps or GPS. The variable for winding resistance can be calculated based on changes in the travel path (Suvinen and Saarilahti, 2006). The validity of soil surface roughness or obstacle resistance needed to be studied further.

The slip can be defined by comparing the velocity measured by GPS with the circumferential velocity of the wheel, based on the rotational velocity of the driveline. As the inertia and air resistance are insignificant for forest tractors, all the resistance forces in Eq. 1 except for the rolling and snow resistances are known. The rolling resistance (and snow resistance) can be regarded as a residual force on the basis of which the terramechanical attributes of the soil and terrain-vehicle interaction can be defined. The rolling resistance consists of soil deformation and tyre deflection.

The proposed technique allows quick, easy and economical possibilities for obtaining more accurate information about terrain conditions and parameters for the purpose of off-road mobility. These parameters can be linked to digital maps and used to solve off-road routing problems, for example Suvinen (2006). Another example of an application of forest tractor terrain parameter collations would be some kind of terrain data bank, which could be used in a similar manner to stem databases in harvesters (Malinen et. al., 2001). Based on digital map information and/or simple terrain measurements (e.g. cone penetrometer tests), the planning software would search for previous forest stands in which the terrain conditions were closest to those in the forest stand in question. Such a solution would improve the planning of logging substantially. More accurate soil parameters can also be used to solve forest regeneration problems (e.g. tree species selection and forest regeneration methods).

It has been shown that modern techniques can open a lot of new possibilities for terramechanical research. The proposed technique is useful not only for research but also e.g. for development work of forest tractors and tyres.

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CURRENT STATE AND POTENTIAL OF THE IS-HS PROJECT - *INTEGRATION OF IN SITU DATA AND HYPERSPECTRAL REMOTE SENSING FOR PLANT PRODUCTION* MODELLING

Jan A.N. van Aardt, Pol R. Coppin
Department Biosystems (M3-BIORES), Faculty of Bioscience Engineering, Katholieke Universiteit Leuven, Belgium
E-mail: jan.vanaardt@biw.kuleuven.be

Abstract

The second generation SUNSAT satellite (ZASat II), to be launched in 2008, will incorporate a hyperspectral sensor, sponsored by Flemish Regional Government of Belgium. The hyperspectral sensor will have 200 wavelength bands between 400 nm and 2350 nm, a spectral resolution of 10 nm, and a spatial resolution of 15 m. This sensor will play a pivotal role in the IS-HS project which was developed to study vegetation production systems by jointly using in situ and hyperspectral data as model inputs, as opposed to traditional process-level attempts. The objectives are to deepen our system understanding and to develop production-oriented steering for capital-intensive vegetation scenarios. Real-time steering in a 10-15 year timeframe is envisaged, where current system state is monitored, modeled, and steered towards an ideal state in terms of production quantity and quality. An overview of the system-concept, the current status, and future project potential are presented here.

Keywords: Hyperspectral, in situ, system modelling, system physiology mini-satellite

INTRODUCTION

The Flemish Regional Government of Belgium has sponsored the development of a hyperspectral sensor for incorporation in the South African Multi-Sensor Microsatellite Imager (MSMI) which will form part of the payload of the second generation SUNSAT satellite (ZASat II). This South African mini-satellite, which is being developed by SUNSPACE, has an expected launch date of end-2008. The hyperspectral sensor nominally will have 200 wavelength bands between 400 and 2350 nm, a spectral resolution of 10 nm, a radiometric resolution of 10 bits, a spatial resolution of 15 m, and on-board processing capabilities. A swath of 15 km is envisaged, with a storage capacity of 18 square cubes of hyperspectral imagery. The hyperspectral image processing component of the MSMI will be managed exclusively by the M3-BIORES Division (Geomatics Engineering group) at the Katholieke Universiteit Leuven (K.U.Leuven), Belgium, which is headed by Prof. Pol Coppin and assisted by Dr. Jan van Aardt. This hyperspectral sensor will form the pivot of the "integration of *in situ* data and hyperspectral remote sensing for plant production modelling" project (IS-HS).

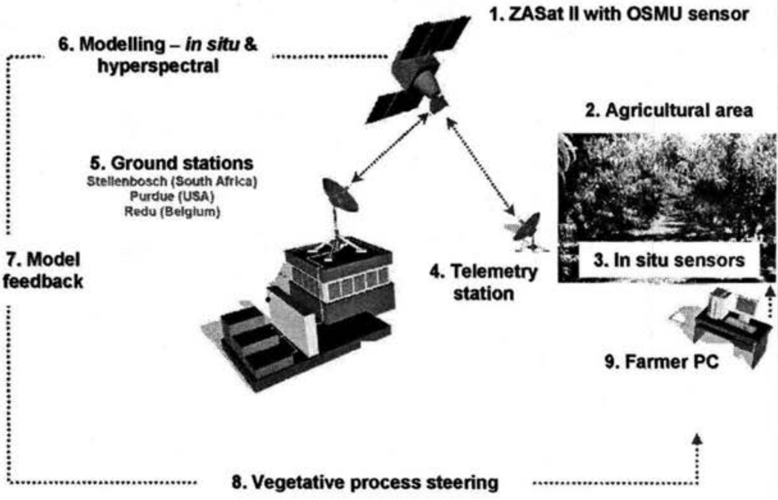
The IS-HS project was developed to study vegetative production systems by jointly using *in situ* and hyperspectral data as model inputs. Such an approach will not only deepen our understanding of such systems, but also will aid in their management. Accurate modelling has significant implications especially for production-oriented systems, given the potential to monitor abiotic and biotic stresses, vegetative accretion, and current system state. The goal is to provide resource managers with up to date information to pro-actively manage vegetative systems. A system overview and component breakdowns are shown in Figure 1.

SYSTEM COMPONENTS

The hardware component of the IS-HS project consists of two phases, namely (I) the construction of the hyperspectral sensor by OIP Systems (Belgium) and (II) the development of ground and satellite telemetry components by Orban Microwave Products (OMP) (Belgium). The timeline and details of Phases I and II are shown in Figure 2.

Hyperspectral sensor construction (Phase I) will be completed in January 2006, while Phase II will commence at the same time. The TELEMIC research team of Prof. Guy Vandenbosch at the K.U.Leuven and OMP will be responsible for Phase II: The development of radio frequency (RF) antennas for ground- and satellite units, construction of satellite hardware, a telecommunication system study, software development, and quality control. These two partners ultimately will develop methods and materials for the collection and transmission of *in situ* data from biosensors to local satellite links. This *in situ* component of the IS-HS project is unique, since such a satellite-driven data acquisition system is at present non-existent. Major challenges in the *in situ* project component include development of (i) the collector for ground-biosensor data, (ii) the transmitter/receiver (wireless modem) for connection with ZAsat II, (iii) antennas, and (iv) the software needed for down- and upload tasks.

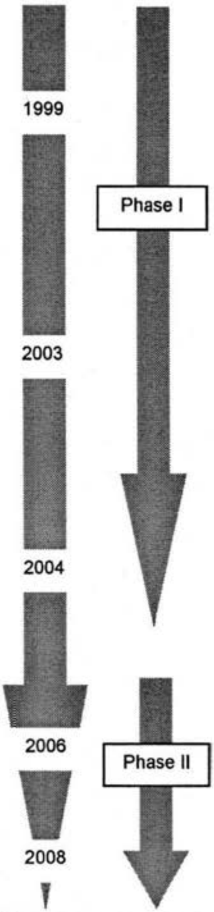
Ensuring flight readiness of all satellite-hardware on a limited budget remains a general challenge, but all partners have proven track records in this aspect. The timeline likely will span three years, with a budget of € 1 300 000.



1. ZASat II (OSMU) sensor – revisit time of 28 days (nadir), with 4 day revisit (off-nadir) temporal resolution; future satellite constellation will allow for daily nadir image acquisition
2. Agricultural area – *in situ* and hyperspectral process monitoring, modelling, and steering of forest stands, fruit orchards, and vineyards
3. *In situ* sensors – for collection of inexpensive, yet crucial model parameters, e.g., temperature, precipitation, and soil moisture
4. Telemetry station – local collection of *in situ* data for transmission to ZASat II satellite
5. Ground stations – for collection and pre-processing of complete hyperspectral imagery
6. Modelling (*in situ* and hyperspectral inputs) – onboard processing capabilities allow model programming and execution at satellite-level
7. Model feedback – regional model feedback via ground stations; local feedback via local telemetry stations
8. Vegetative process steering – real-time process steering and adaptation based on model outputs
9. User computer system – collects model outputs and adapts/steers vegetative production system, e.g., drip irrigation, soluble fertilisation, and early warning systems (abiotic and biotic stress)

Image courtesy of www.internet-par-satellite.com

Figure 1. Schematic presentation of the IS-HS project concept and associated components



IS-HS PROJECT PHASE I: DEVELOPMENT AND TESTING OF SPACEBORNE HYPERSPECTRAL SENSOR

February 1999	-	Launch of SUNSAT satellite (Engineering Faculty; University of Stellenbosch, South Africa)
February 2001	-	SUNSAT´s last contact with the ground station
Start-2003	-	Initiation of ZASat II project with Multi-Sensor Microsatellite Imager (MSMI) sensor (€ 39 million budget)
July 10, 2003	-	Flemish Minister Dirk van Mechelen (Science, Technology, and Innovation) signs IS-HS project contract, authorising Flemish involvement of € 1 million for development of hyperspectral sensor component
End-2003	-	Flemish company OIP Sensor Systems starts development of Optical SpectroMeter Unit (OSMU) hyperspectral imager; delivery end-2005

IS-HS PROJECT PHASE II: DEVELOPMENT AND TESTING OF GROUND AND SATELLITE TELEMETRY COMPONENTS

2006-2008	-	Development of *in situ* and telemetry (communication) project components (Flemish industrial and academic partners)
End-2008	-	ZASat II foreseen launch date

Figure 2. Diagram of the IS-HS project time-frame. Operational system implementation only is foreseen in approximately 2015-2020, given full system development and a constellation of ZASat II satellites, allowing daily image acquisition and subsequent process steering

PERIPHERAL RESEARCH

Present research efforts at the K.U.Leuven are geared towards the development of crop-specific models and applications, which include process description and analyses. These models use *in situ* sensors and portable hyperspectral spectroradiometers. Eventually, these model-based applications will be scaled to satellite sensor-level to lay the foundation for continuous and relevant satellite sensor output data for natural resource managers. Bi-directional reflectance distribution function (BRDF) modelling also is underway to provide information regarding the operational aspects of image acquisition.

Early detection of abiotic and biotic stress in apple orchards (Stephanie Delalieux)

The potential yield of capital-intensive multi-annual crops, e.g., forest and fruit sectors, is seldom realised. A targeted monitoring and modelling of the production system could enable an early detection and treatment of production limiting factors, thereby optimising yield. The objectives of this study were (i) to determine if *Venturia inaequalis* leaf infections could be differentiated from healthy leaves in both resistant and susceptible apple cultivars using hyperspectral spectroradiometer data, (ii) to gauge at which developmental stage *Venturia inaequalis* infections could be detected, and (iii) to identify wavelengths or spectral regions that best differentiate between infected and healthy leaf material. Partial Least Squares Discriminant Analysis (PLSDA) was used to distinguish between infected and healthy plant material. Results suggested that good predictability could be achieved when classifying infected plants based on hyperspectral data using PLSDA. A band reduction technique, which is based on logistic regression, was used to select the hyperspectral bands that best define differences among treatments. This study showed that the spectral domains centred at 1500 nm (early infection stage) and the visible region (well-developed infection stage) were best suited to differentiate between infected and healthy plants (Figure 3).

Studies such as these have implications for all perennial vegetation production systems. Both the crop and the biotic stress discussed above only serve as proxies for other crops and potential deviations from an ideal growth system. The same principles apply to abiotic - (e.g., water) and biotic (e.g., various fungi) stress conditions in forests.

Bi-directional reflectance distribution function (BRDF) **modelling** *(Dimitrios Biliouris)*

A hyperspectral virtual forest scene of a *Fagus sylvatica* stand has been developed based on accurate structural and spectral inputs. Off-the-shelf tree architectural software (Bionatics) was used to generate a biologically accurate *Fagus* tree, while leaf BRDF data were acquired with the use of a hyperspectral Compact Laboratory Spectro-Goniometer (CLabSpeG; Figure 4). The goal behind the virtual forest scene is to create a Virtual Imaging System using measured BRDF data of vegetative material in order to improve existing canopy reflectance models. This imaging system is the first step towards the creation of a hyperspectral virtual laboratory that will be used to research and better understand earth solar interaction principles.

This research has significant implications for the IS-HS project in terms of satellite operational parameters and output. Knowledge gained during the BRDF project will be used to determine which off-nadir satellite look-angles are useful for vegetation studies and also will provide information related to the normalization of off-nadir imagery to at-nadir reflectance.

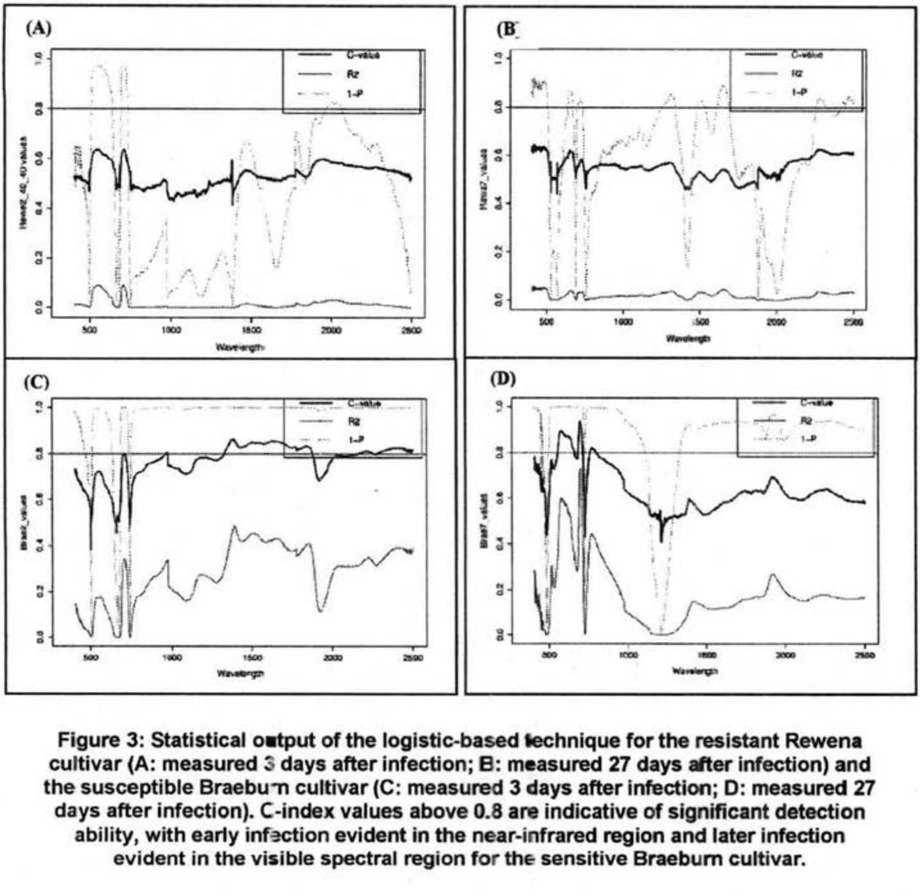


Figure 3: Statistical output of the logistic-based technique for the resistant Rewena cultivar (A: measured 3 days after infection; B: measured 27 days after infection) and the susceptible Braeburn cultivar (C: measured 3 days after infection; D: measured 27 days after infection). C-index values above 0.8 are indicative of significant detection ability, with early infection evident in the near-infrared region and later infection evident in the visible spectral region for the sensitive Braeburn cultivar.

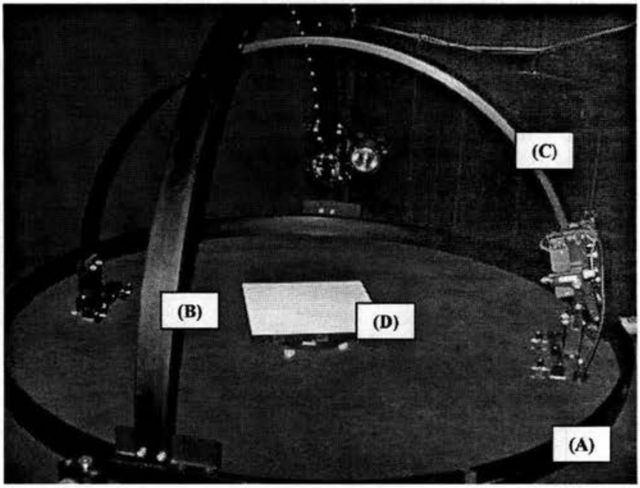


Figure 4: Physical system setup of CLabSpeG, with horizontal aluminum rail (A), supporting a light source arm (B) which rotates anti-clock wise with a resolution of 30°. The stationary arm (C) supports the imaging sensor which is capable of movement with a resolution of 15° in zenith. The sample holder in the centre (D), with a spectralon reference panel on top, rotates clock-wise with a resolution of 30°. This instrument is capable of collecting 4 356 hemispherical reflectance measurements at various light-source-sensor combinations in approximately two and a half hours.

Future research

Further research is needed to advance a combination of *in situ* and hyperspectral data towards a better understanding and modelling of vegetative production systems. Envisaged research projects include:

- Development of robust hyperspectral indicators at the leaf -, canopy -, and airborne/spaceborne sensor levels with focus on process and physiological description
- Citrus production modelling using *in situ* and hyperspectral model inputs, eventually allowing real-time steering towards optimal production outputs
- Mechanistic forest carbon and water modelling based on the IS-HS approach
- Temporally dynamic hyperspectral pixel unmixing with focus on extraction of the vegetative spectral response, as well as spectral fractions
- Geometric and radiometric pre-processing chain development
- Atmospheric correction algorithm development and/or adaptation
- Identification of existing and development of novel *in situ* sensors that will contribute in terms of non-remote sensing model parameters to increase model accuracy and applicability

The research listed can be regarded as peripheral project components, all being crucial to the eventual operational use of the complete IS-HS system.

BENEFITS AND EXPECTATIONS

The long-term goal of the IS-HS project is the development and testing, in an operational environment, of *in situ*-hyperspectral vegetative production models. This goal realistically only can be achieved after sustained basic research over a time-frame of approximately 10-15 years. The concrete benefit at that stage most likely will revolve around operational, real-time modelling at the orchard-level to detect growth process anomalies and to steer the system through adjusted inputs to realise optimal production quantity and quality. Short-term benefits, however, are related more to the distinct research topics as defined above:

- Mechanistic, input-output-based production models that incorporate *in situ* and hyperspectral data to determine the necessary process adaptations for optimal yield of fruit, crops, and forests
- Cost-effective hyperspectral sensor components and telemetry technology
- Pre-processing chain research related to efficient extraction of radiometrically and geometrically accurate imagery
- Novel algorithms in terms of pixel unmixing of vegetative signals *and* fractions, satellite on-board processing, off-nadir-to-nadir image reflectance correction, and crop-specific mechanistic models.

Expectations of potential collaborators:

- *Academic/research institutions*

  Academic institutions are needed for expertise in all project components. Partners will be expected to provide academic and logistic support, and study sites (where applicable). Tangible benefits include co-authorship on research papers, access to satellite imagery and *in situ* data, and academic benefits such as workshops, training, conferences, etc. Research funding for this project is provided almost entirely by the Flemish Regional Government of Belgium for concept development, with limited funds available for personnel and working costs. Peripheral projects are funded through competitive grant money from K.U.Leuven, Belgium Science Policy Office, and the Flemish Fund for Scientific Research (FWO). It therefore is expected of collaborators to provide funds for their researchers through similar means, while data and knowledge sharing are the main trade commodities.

- *Industrial partners*

  Industrial partners should provide study areas (e.g., orchards or forest stands), logistic support (e.g., housing, transport, manpower), and crop-specific data (e.g., fertilisation, irrigation, and production specifics) for research. Concrete financial support, other than that implied in the stated contributions is not required. The benefits for such partners include, among others: (i) Crop-specific production models that can be adapted to steer vegetative processes towards optimal production in a given regional scenario; (ii) orchard specific models that can be used to predict production quantities; and (iii) increased knowledge of the crop- and orchard-specific physiology as it pertains to production. Production models are developed as part of the project concept and can be implemented by partners using off-the-shelf technology. This implies that models will not be inherently satellite-dependent. It could, for instance, implement spectroradiometers to provide spectral data inputs, while *in situ* model inputs are acquired from existing or developed ground-based sensors. Farmers therefore could implement developed models in an operational context without being dependent on project fruition.

The IS-HS project has the potential to significantly contribute to the precision-farming revolution, especially in terms of real-time monitoring and steering of growth processes, as opposed to post-harvest steering. Managers of vegetative growth systems therefore will have access to information regarding the current and goal states of their crops, and have the ability to adapt management practices to realise full crop potential.

CONTACT

Interested parties can contact the project leader, Dr. Jan van Aardt, at the K.U.Leuven. A broad range of processing and vegetative system research will be considered for inclusion in the IS-HS project.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the partners in the IS-HS project, namely the University of Stellenbosch (Prof. Arnold Schoonwinkel), OIP sensor systems (Belgium), and OMP (Belgium). We also would like to acknowledge the work of two Ph.D. researchers, ir. Dimitrios Biliouris and ir. Stephanie Delalieux, included in this paper.

DEVELOPING A GIS-BASED FLOW-CHANNEL AND WET-AREAS MAPPING FRAMEWORK FOR PRECISION FORESTRY PLANNING

Fan-Rui Meng, Mark Castonguay, Jae Ogilvie, Paul Murphy, Paul Arp
Faculty of Forestry and Environmental Management, University of New Brunswick, Canada
E-mail: arp2@unb.ca

Abstract

Digital elevation models (DEMs), when forced to comply with already mapped hydrographic features (streams, lakes, shorelines), can produce realistic delineations of small-scale catchment areas, flow channels, depressions, and wet areas, at 5 to 10 m resolution: predicted wetland borders and road-stream crossings were found to occur within distances smaller than twice the average DEM grid spacing (*i.e.* <70 m). The resulting quality of the wet-areas is useful for surprise-free operations planning process. Thus far, greater efficiencies have been demonstrated for office-field communications, cutblock lay-out and harvesting, road and trail construction, tree planting, productivity assessment, wetland delineation, source-sink pathway identification, timber cruising, and off-road navigation. The map resolution is much enhanced using LiDAR-generated DEMs, but at increased data acquisition and computer processing costs. LiDAR-generated DEMs, however, are not free of artefacts, especially for densely wooded forest areas. Removing these artefacts would enable high-precision tree-by-tree operations planning for forestlands, parks and urban areas.

Keywords: Digital elevation modelling, hydrographic features, mapped and unmapped flow channels, soil wetness, depth to surface water, coarse-fine grid comparison, operations planning.

Introduction

High-resolution flow channel and wet-areas mapping is in the process of becoming a precision tool for improved forest management operations planning across the landscape, from uplands to wetlands (Gessler et al. 2000, Underwood and Crystal 2002, Andison 2003, Clarke and Burnett 2003, Pulkki 2003, Case et al. 2005).Typically, two components are needed for this type of mapping: a local digital elevation model (DEM), and the local hydrographic features map (depicting all lakes, streams, shorelines, etc.). Appropriate processing of these produces:

- a seamless network for mapping all already mapped and unmapped flow accumulation
- a means to automatically draw watershed areas above any point along a stream
- a way to locate most as yet unmapped depressions and wetlands
- an approximate depth-to-water surface, at high and low water marks
- a high-resolution means to display soil drainage conditions
- a framework for adding additional data layers and surface images, which – in turn - are useful for refining and updating the original maps that may have been drawn from coarse-gridded DEMs and incomplete digitization of hydrographic features
- ways and means to verify the mapped information

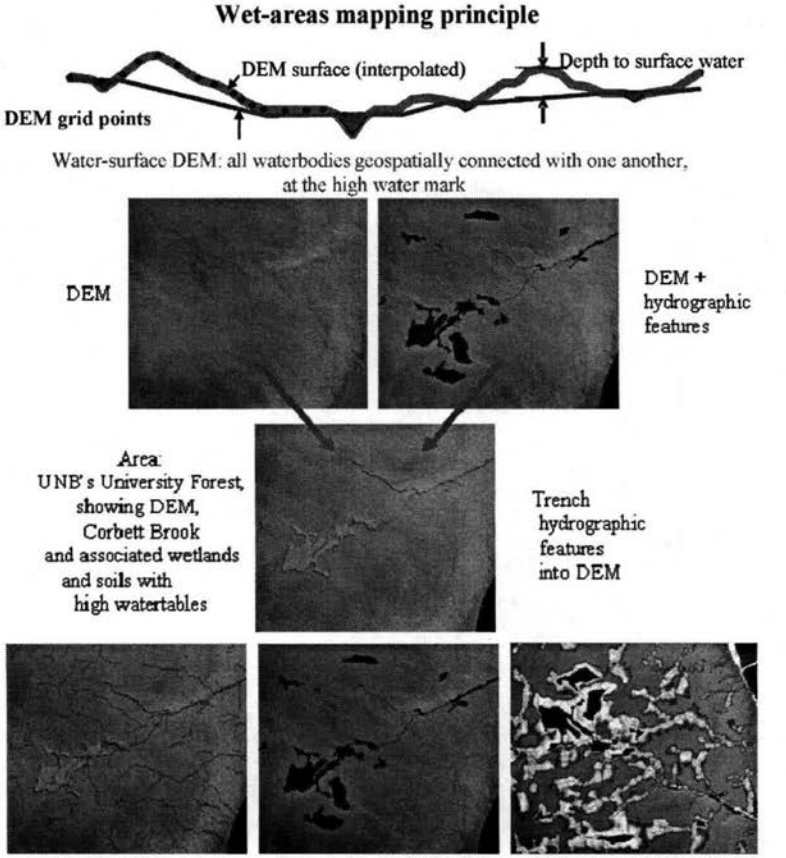
The principal stages in this process are illustrated in Figure 1.

Wet-areas mapping challenges

There are many challenges regarding detailed flow-channel and wet-areas mapping. These vary with hydrological region, and with the agency that provides DEMs and hydrographic maps or atlases for specific regions through data-sharing agreements. Here are a few issues that need to be resolved:

- The DEM and hydrographic layers need to be positioned correctly within the geographic projection system of choice; otherwise, there will be misalignments
- Even with correct geographic positioning, there needs to be conformity between all already mapped water features (lakes, streams, rivers, shorelines, islands) and the DEM grid; when this does not occur, there may be inadvertent distortions in the DEM, or there may have been inconsistent attention given to detail in the hydrographic digitization process. For example, there is often a lack of systematic connectedness or continuity between the various stream and lake segments that are part of the hydrographic database. Lack of connections may only become apparent through pixel-to-pixel examination of the digitization work (see Figure 2).
- DEM grids (xyz) may contain holes, spikes, bands, etc. All these artefacts need to be eliminated systematically to avoid problems in the projection of watershed boundaries and flow channels. For example, banding leads to artificial straight-line flow features. Spikes can produce ripple effects within the geo-spatial interpolation process. Holes simply mean no xyz data for an area.

- High-resolution DEMs are better than coarse-gridded DEMs, but even coarse-gridded DEMs (e.g., 70 to 100 m spacings) can lead to useful applications, provided the coarse-gridded DEMs are free of artefacts.



Delineate predicted flow accumulation towards trenches

Reintroduce hydrographic features, colour new flow features red

Determine predicted depth to water (white 0, red 1 m) next to all mapped flow features

Figure 1. Principal stages involved in deriving mapped and unmapped flow channels from local DEMs, using already existing hydrographic information to force the digitally derived flow channels and surface water bodies to comply with this information.

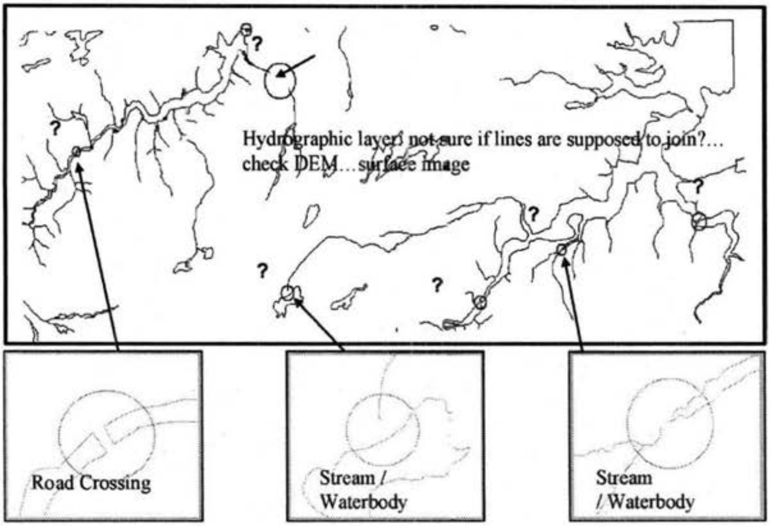


Figure 2. Example of improving the quality of already digitized hydrographic features: all flow needs to be seamless from ridges to coast, to avoid the possibility of artificial flow barriers in the resulting flow channel and wet areas map.

Wet-areas mapping benefits

In New Brunswick, we merged the current provincial DEM (35 m) grid data with the provincial hydrographic data layer, to produce a base map for practical applications in forestry and forest engineering. These data layers were inspected, all obvious artefacts inherent in these data layers were removed, and a map was produced province-wide, at 5 to 10 m resolution. The map was then inspected by forest operations planners, and these planners developed a number of applications that facilitated their daily routines, made communications with field staff more efficient and directed, and enhanced overall operational efficiencies regarding:

- Road layout, design and construction
- Cutblock layout and design, including harvest patterns, access trails to and within cutblocks, and layout of wood landing locations
- Site preparation for planting, and distribution of tree seedlings by type, depending on site wetness within blocks
- Delineating areas with unique conservation value (e.g., vernal pools, riparian zones)
- General reconnaissance, using the flow-channel and wet areas map as guide to identify and affirm locations with operational risks
- On- and off-road navigation, to avoid entering areas that pose risks and enhanced down-time potential under wet weather conditions.

The resulting wet-areas map has become part of the day-to-day planning protocol of eastern forest companies, notably JD Irving (JDI), and has been adopted by the provincial Department of Natural Resources in New Brunswick as a recommended base layer for forest operations planning, to be used within the current 5-year forest operations planning cycle. Within JDI, the wet-areas map has encouraged the conceptualization of "surprise-free operations planning", and "flag-free operations". At this stage, company employees are demonstrating greater efficiencies and cost-savings in terms of cutblock lay-out and harvesting, road construction, tree planting, silvicultural operations, productivity assessment, wetland delineation, and source-sink pollutant pathway identification.

Figure 3. The change from traditional forest operations planning to "surprise-free" operations planning, using the wet-areas map as means to enhance effectiveness and efficiency of the communications and implementation phase of the operations process.

Map reliability

The same GIS framework that allows for the automatic derivation of all mapped and unmapped flow channels and wet areas facilitates the reliability checking of the data and of the processes that are used to produce these maps.

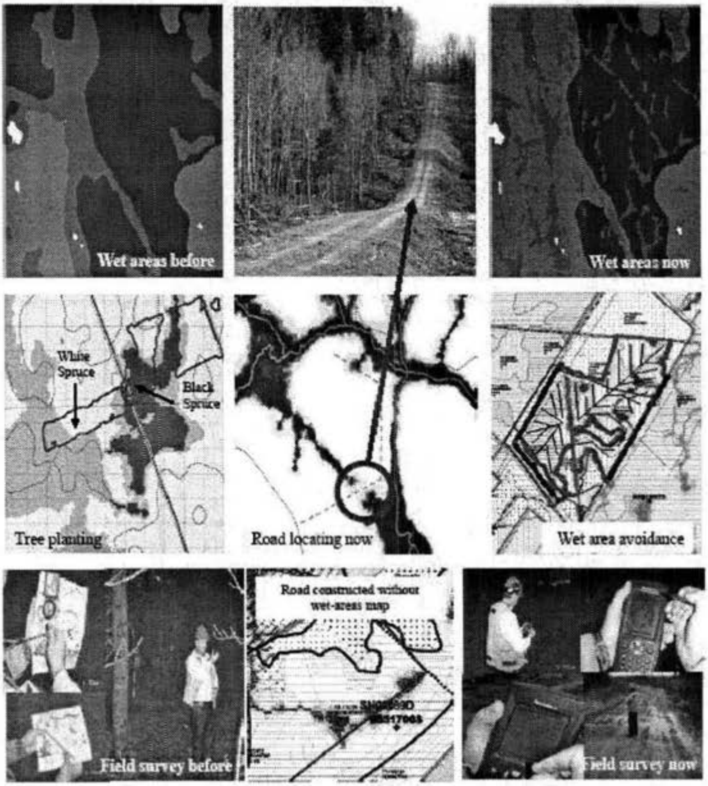


Figure 4. A composite illustrating wet-areas mapping applications: redrawing of the soil drainage map (compare top left with top right, with green referring to wet soils, orange and blue referring to two upland soil types); improved decision making regarding within-block harvest operations (middle right), and tree planting (wet areas are shown as blue to light blue shaded areas); optimized road locations (middle column: top and middle show how a road was constructed to pass through an unmapped saddle point while staying clear of a mapped stream (line feature within in dark blue shading are mapped streams); mid-bottom shows an existing road that lines up with an unmapped but field-confirmed wet area. Photographs bottom left and right illustrate the change in the field operations of the planning process: maps, compass and rulers on the left; hand-held devices on the right showing wet area map, with GPS markers and screen-editing tools used to enter and to outline features such as actual locations of flow channels and wet ground.

This is done by aligning other information that sheds light on the veracity of what has been napped. The following summarizes a number of items that proved to be useful:

- Post-harvest ortho-rectified surface images reveal much detail about local flow channels and wet areas; overlaying these images on top of the wet-areas map generally showed good alignment.
- Overlaying GPS-ed culvert locations (e.g. stream road crossings) indicated an average agreement of location within 70 m or more (Figure 5). This agreement increased with increasing slope (Figure 6), and with increasing DEM resolution (Figure 5).
- Assessing frequency of tree blow-down along the cutting edge of cutovers revealed a preponderance of tree blowdown in areas where the cutting edge traversed wet ground, as mapped (Figures 7, 8).
- GPS-tracing transitions from wetland to upland vegetation using, e.g., the border of bogs, marshes, and overlaying these traces on top of the wet-areas map. For the New Brunswick wet-areas map, mapped and field-traced transitions between wetlands and uplands were typically within 35 m of each other.

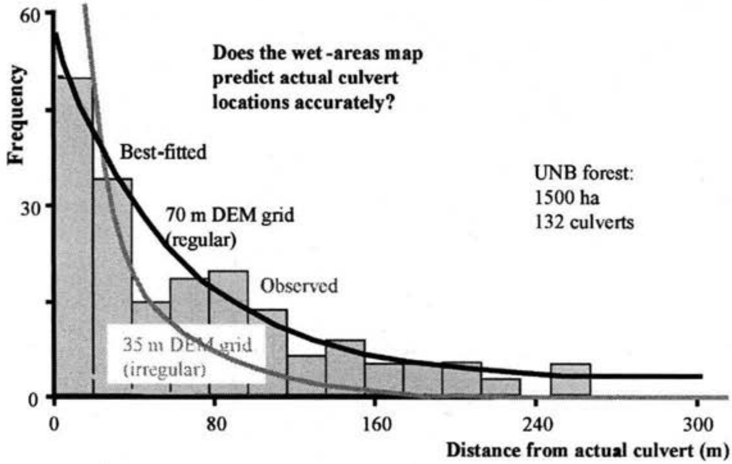
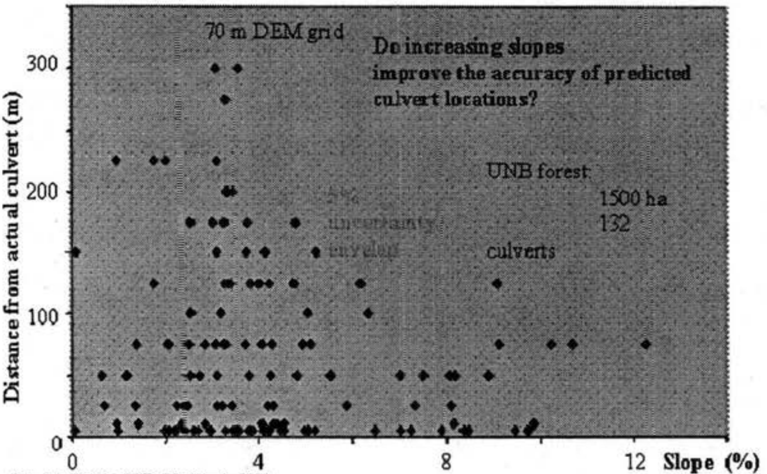


Figure 5. Frequency plot of distances between actual and mapped culvert location (stream-road crossing) for the University of New Brunswick Forest. Dark blue line is a best-fitted model of the distribution. Light blue line shows an improvement that was afforded by an irregular (random) re-sampling the original New Brunswick 70 m DEM grid, at doubled resolution, to overcome / resolve the original banding problem.



Data: M. Noddin, UNB BScF thesis, 2000

Figure 6. Diagram showing that locating culverts via flow-channel and wet-areas mapping becomes more precise when the slope of the terrain increases.

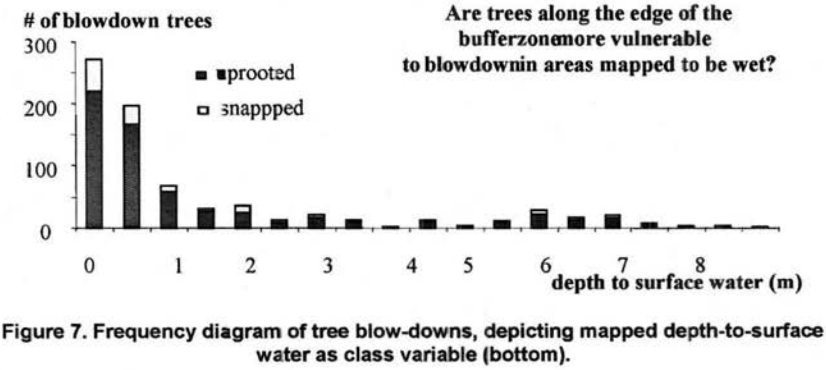


Figure 7. Frequency diagram of tree blow-downs, depicting mapped depth-to-surface water as class variable (bottom).

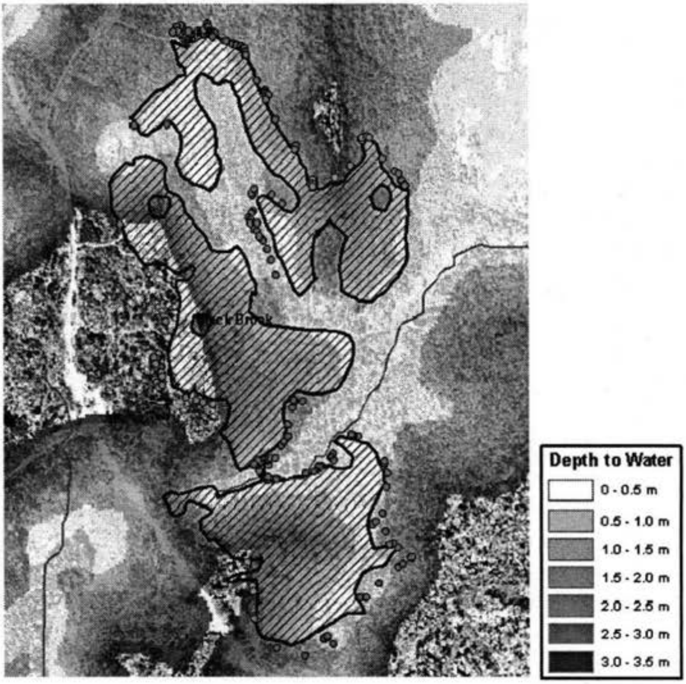


Figure 8. Air photo showing roads, access trails, unmapped flow channels(blue), cut-over boundaries (black), depth-to-water feature (grading white to red), with locations of tree blow-down overlayed (green dots). For frequency distribution of tree blow-down, see Figure 7.

Enhancing DEM resolution, with LiDAR

Digital elevation maps have become available with a wide range of resolution from very fine (< 1 m) for small areas, to coarse (e.g., 35 to 100 m) grid point spacings for large areas (provinces, states, countries). For large-scale wet-areas mapping, coarse-gridded DEMs are more useful than the fine-gridded DEMs. LiDAR-derived DEMs have advantages and disadvantages associated with them. For example, the higher resolution will lead to a much improved delineation of small-scale features such as tree tops, boulders, rocks, logs, ditches, and berms. Ordinary top-end desk-top computers, however, are still quite limited to process very finely-gridded DEM data, even for small areas: it takes several days to process each mapping step for an area of a few 100 ha. In contrast, coarse-gridded data produce results for an entire province, within about the same computational time frame. Shown in Figure 9 is an overlay of a high-resolution DEM on top of a low-resolution DEM (New Brunswick grid). Overlain on both are the local roads, and the 10-m wet-areas map derived from the coarse grid. Note that this wet-areas map conforms quite well with the highly detailed LiDAR DEM. Differences, however, do occur, but mainly at the small scale only.

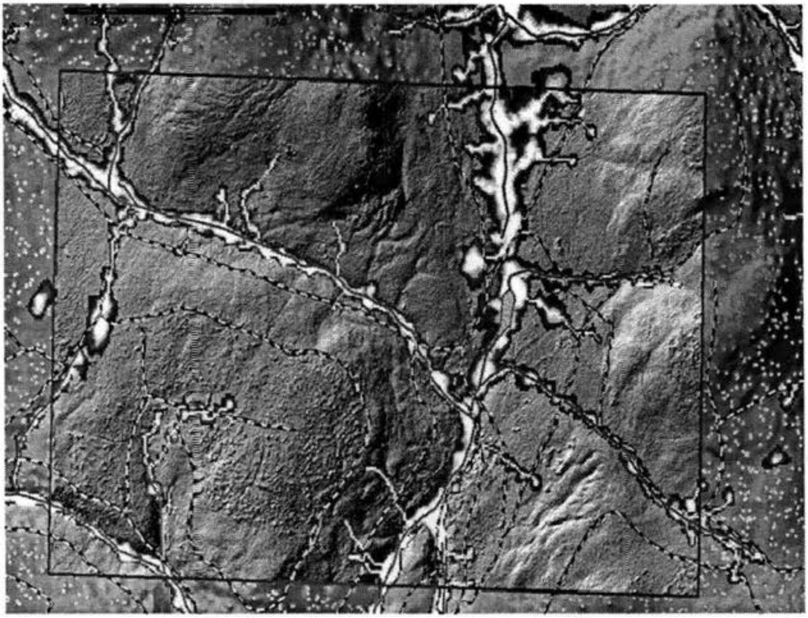


Figure 9. Overlay of: coarse-gridded provincial DEM (random dots), with geospatial interpolation (note colour shading), already mapped flow channels (blue lines), roads, and depth-to-water (white to red, 0 – 1 m, respectively), and LiDAR derived DEM. Some of the ridge tops are densely wooded, leaving the resulting LiDAR DEM rougher than the usually smoother ground features.

Shown in Figure 10 is a direct comparison between wet areas mapped from the coarse–gridded DEM versus the fine-gridded DEM. In general, the outlines of the wet areas are directly comparable. Elevational differences within the wet areas, however, are picked up better by way of the fine-gridded DEM, as is to be expected. On the uplands, the fine-gridded DEM leads to considerable artefacts in densely wooded sections.

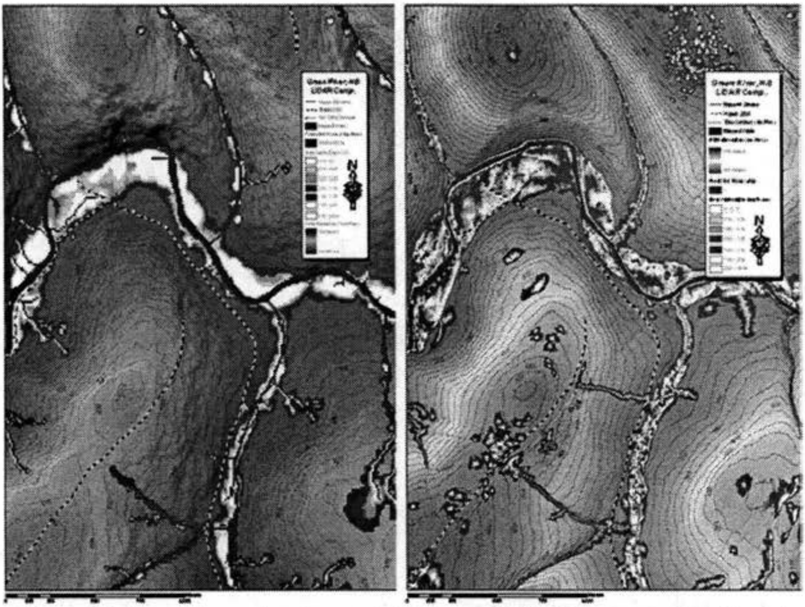


Figure 10. Comparison of wet-areas (white to red, 0 to 10 cm, respectively), derived from a coarse-gridded (left) and fine-gridded DEM (right). Note the general similarity of the overall wet-areas features along the already-mapped flow channels, and elsewhere, except for several ridge-top areas with LiDAR-introduced artefacts on the right (small near circular dots). Note that fine-gridded DEMs are useful to display fine topographic details within the flood plains of the major flow channels.

Discussion

Topograpically-based flow-channel and wet-areas mapping is beginning to prove useful to identify areas of risk with regard to the construction and maintenance of surface structures such as roads, storage depots, housing, and the placement and operation of vehicles. Areas of risk imply potential loss of investment, increased maintenance costs, and creation of new flow channels for pollutant transfer, flooding. As outlined, this mapping is also useful for day-to-day operations planning, reconnaissance, communications, on– and off-road navigation including trafficability assessment, outlining priority fields regarding soil, stream channel and shore-line stabilization and protected areas not only in forestry but also in watershed management, and real-estate management in general. The mapping process by itself is useful for providing an expandable cartographic framework for incorporating other land-based cartographic information (land-use, soil survey, ecological site classification, property) and surface images (various media), and for checking cross-layer data integrity (e.g., do roads, flow channels and select ecological features line up properly with surface images, surface DEMs, etc.).

Topographically derived flow channels, however, do not capture all possible paths by which water flows in the landscape. Sub-surface flow paths that do not conform to surface topography are omitted because predicting these requires not-readily accessed or available information about subterranean flow conditions and geometries, especially for areas with highly permeable terrains and region-wide aquifer flows. However, the systematic digitization of all water surfaces from surface images produces an empirically benchmark of all water surfaces, regardless of flow paths feeding that water body.

Whether or not protocol-derived unmapped flow channels lead to visible flow channels in the field is a function of catchment properties such as the permeability and infiltration capacity of the substrate at each location, and the timing and amount and rate of incoming precipitation. For example, areas overlain by compacted till, or impervious bedrock, can be expected to show flow channels with catchments areas of 3 to 4 ha, and smaller, as soil texture grades from coarse to fine. With a coarse substrate, flow channels are generally found along the predicted flow paths, but at the regolith-bedrock interface.

Mapped depth-to surface-water depends, to some extent, on the exact contouring of the lake, river, island and coast shorelines, and the choices made (consciously or otherwise) in the interpretation of the same during the digitization process of these features, and on the time when the images used for digitization where captured (time refers to time within the local low to high tide cycles and hydrological season). Whatever has been digitized as a water body feature becomes the local high water mark. The maps shown therefore refer to the hydro-static condition where all mapped surface water features would continuously be filled to the already mapped shoreline. In the future, systematic efforts will be required to capture the dynamics of seasonal progressions, from high and to low water marks and back again, for more refined prediction purposes.

While LiDAR-derived DEMs will allow flow-channel and wet-areas mapping at very high spatial resolution, one should not neglect the traditional means for generating local DEMs at, say, 10 m resolution. Higher resolution DEMs would expand the computational time requirements for province-wide mapping, but – for the case of New Brunswick and many other provinces - there would be a 7x7 fold increase in precision regarding the proper placement of flow channels and wet areas across the landscape. Based in the results shown above, this would mean locating streams and wet area boundaries within 10 m or better, on average, i.e., close to the range of precision needed for most forest operations, including flag placement, and close to the scale of road and access trail width, culvert length, and harvesting and site-preparation machines. In many parts of the USA, and other parts of the world, 10 m DEMs are already available, state-wide.

Acknowledgements

The authors acknowledge the assistance of Service New Brunswick and the New Brunswick Department of Natural Resources in providing the data layers for this work (MR-SID, original and re-sampled DEMs, road and stream layers). The work was financially supported by the Nexfor-Bowater Forest Watershed Research Centre, with supplementary support from the New Brunswick Forest Products Association (NBFPA), the Nova Scotia Forest Alliance NFA), Fundy Model Forest (FMF), JD. Irving, the Forest Resource Improvement Association of Alberta (FRIAA), and an NSERC Discovery grant to PAA. Special thanks to JDI personnel for enthusiastically adopting the GIS flow-channel and wet-areas mapping framework.

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SMALL FORMAT DIGITAL PHOTOGRAMMETRY FOR PLANTATION FORESTRY APPLICATIONS

Anton Kunneke
Department of Forest and Wood Science, Stellenbosch University, South Africa
E-mail: ak3@sun.ac.za

Abstract

The purpose of the study is to evaluate the suitability and cost effectiveness of small format digital stereo photography for plantation forest inventory.

Aerial photography is a commonly used management tool for agriculture, forestry, nature conservation and many other disciplines working in open landscapes. Standard aerial photography on 23x23 cm film at scales of 1: 5000 to 1:30.000 allows a synoptic overview on parts of a landscape providing a wide range of either qualitative or quantitative information. Quantitative data like the area covered by a specific crop or the height of a forest stand are determined by using methods in Photogrammetry.

Although aerial photographs can result in costs savings compared to terrestrial surveys, its use has not yet reached its full potential. Due to organisational needs, high cost for producing aerial photographs and a lack of expertise to deal with photo interpretation, managers are often forced to use other and even less effective methods of data capture.

High costs are due to the sophisticated equipment like aerial cameras and special aircraft. To minimize distortion the manufacturing of aerial cameras is very precise and the camera needs to be calibrated. With the arrival of digital sensors, manufacturing of similar digital cameras also started, again with a higher price tag. The platform or mount of the camera needs to be stabilised, using a gyroscope for instance and a big magazine of film is necessary to take a lot of frames for each mission. This system eventually is rather bulky and the aircraft must be able to carry such a system, whilst being capable of steady slow flight etc. There are also limiting factors to such a system, an airfield is necessary and weather conditions may be limiting and a specialised operator is needed.

Although the use of such equipment is economically viable for large areas and when there is a demand for high accuracy, surveys of smaller areas with a medium need of accuracy normally do not justify these efforts. Mapping the growth in measurements on parameters in a forest plantation for example or any other crop at regular intervals, normally do not depend on millimetre accuracy with fully corrected aerial images. Sub-meter accuracy will be sufficient in most cases reducing the costs significantly. Because of relative ease of deployment it could be possible to deliver data in case of disasters which require fast response, like fires.

The study uses a classical comparison of systems to compare a frequently used traditional and terrestrial method with a more technological advanced remotely sensed method.

The system could be used for pre-harvest planning to estimate standing volumes, estimating areas of clearfelled stands and volume of residual biomass. It can also be used to estimate disaster damage e.g. fire.

DETERMINING AREAS OF HIGH WEED GROWTH IN PLANTATION FORESTS USING HIGH RESOLUTION SATELLITE IMAGERY

Mark Norris-Rogers[1], Fethi Ahmed[2], Pol Coppin[3], Jan van Aardt[3]
[1]Mondi Business Paper SA-Forest Ops., South Africa
[2]KZN University, South Africa
[3]Katholieke Universiteit Leuven, Belgium
E-mail: mark.norris-rogers@mondibp.com

Abstract:
High resolution remotely sensed imagery offers the opportunity to quantitatively monitor plantation forestry operations. Using a series of QuickBird images of a plantation forestry site in KwaZulu-Natal, South Africa, a combination of textural analysis and classification techniques was tested to quantify weed development in replanted forest stands less than 24 months old. While the multi-spectral bands could identify areas of strong vegetation, crop rows were identifiable on the panchromatic band. By combining these two attributes, areas of high weed growth could be identified. This was achieved by running an unsupervised classification on the multi-spectral bands, and an edge-enhancement on the panchromatic band. Both the resultant datasets were then vectorised, unioned and a matrix derived to determine areas of high weed. By applying a matrix derived from the unioned data, it was possible to identify and quantify areas of weed infestation.

Keywords: Remote Sensing; High Resolution Imagery; Weed Infestation; Textural Analysis

Introduction

Weed competition can have serious impacts on South African plantation forest stand development if it occurs within the first twelve to twenty four months after establishment of the crop. The ability to identify and quantify any weed infestation by using remote sensing technology can have significant implications for the management of such stands, as visual assessments undertaken during field visits do not always identify problem areas, and tend to be point samples. They also tend to be subjective in nature, and difficult to quantify without a considerable amount of field measurement being done. A previous study (Norris-Rogers, 2004) had attempted to identify weed status within forest stands using medium resolution imagery (Landsat 7 ETM+), but without success. However, based on conclusions from that study, a recommendation was made to test whether an operationally feasible system could be devised utilizing high resolution satellite imagery.

While multi-spectral band sensors can provide very good vegetation information, particularly regarding vigour and density, it is particularly difficult to distinguish different vegetation types using four-band, or even eight-band, multi-spectral sensors. Therefore, any attempt to distinguish between crop and weed, especially where these are sometimes the same species or genera, requires a different approach. It was this aspect that was investigated in this study.

The aim of this study was to determine whether, using high resolution satellite imagery, weed infestations in plantation forest stands could be qualitatively and quantitatively monitored during the first two years after establishment, i.e. until the crop canopy closure had occurred. The objectives were to apply an unsupervised classification technique to the multi-spectral and panchromatic bands of high resolution satellite imagery, as well as textural analysis on the panchromatic band, in order to firstly differentiate crop from weed, and secondly quantify the identified weed infestations levels.

Although the literature cites various studies that have attempted to identify individual tree crowns, mainly for the purposes of stem counts (e.g. Jacobs and Mthembu, 2001; Wulder *et al*, 2000), a unique aspect of this study was the use of crop rows, rather than individual trees, to distinguish crop from weed.

Study Area

The study area consisted of twelve compartments on two adjacent plantations in the Greytown area of the KwaZulu-Natal Province, South Africa. These plantations lie in an area known generically as the Midlands, north of the city of Pietermaritzburg (see Figure 1). Plantation forestry is a major land use in the study area due to suitable climate and soils. Rainfall averages 900mm p.a., mostly falling between October and April. Temperature varies between 24°C to 26°C in summer but drops to between 5°C and 14°C in winter. Frost is a regular occurrence, apart from the low-lying easterly areas. The terrain is generally undulating plains, but incised with steep river valleys, with altitude rising from 850m to 1125m amsl. The geology consists of sandstone and clay formations, which have resulted in sandy clay to sandy clay loam soils.

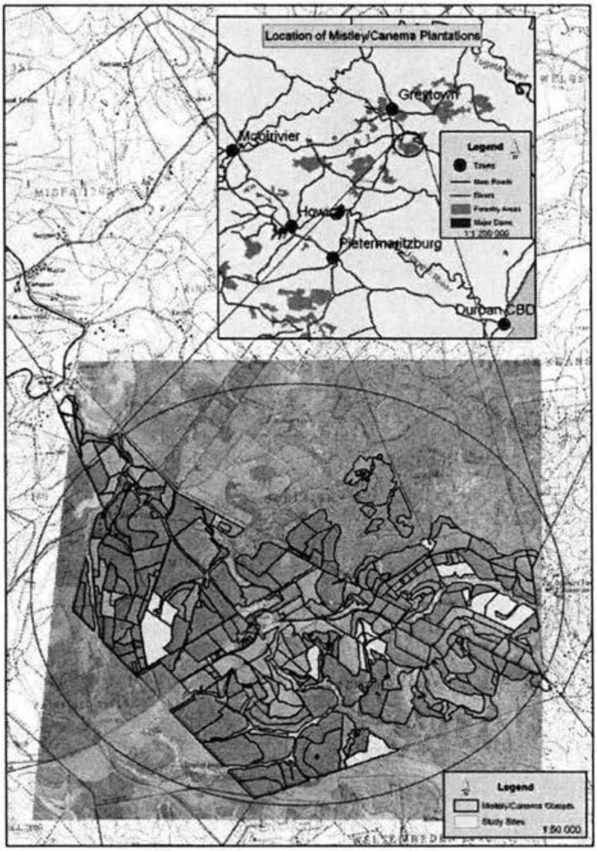

Figure 1. Location of Study Area

Three main genera are grown for commercial forestry, these being Pines (*Pinus* spp.), Eucalypts (*Eucalyptus* spp.) and Wattle (*Acacia* spp.). The main product is pulpwood for the pulp and paper industry.

Twelve compartments, all planted to wattle, were selected on the basis on meeting the criteria of being within the required age range of less than two years following establishment.

Materials and Methods

Materials utilized in this study were satellite and GIS data sets, together with ground-truthed data used in the verification exercises.

Image Rectification

Six QuickBird high resolution images were acquired over a period from December 2003 to June 2005. The March 2005 image was georeferenced to UTM Zone 36 south on a WGS84 datum and spheroid, using the QuickBird RPC model in Erdas Imagine 8.7 (Erdas, 1999), together with 15 sub-metre GPS ground control points and a 20 m digital terrain model, after which all the other images were then rectified to the March 2005 image using an image-to-image rectification process. Problems were experienced in obtaining high registration accuracies, mainly due to the complex geometry inherent in the satellite platform, such as the off-nadir angles at which most of the images were captured. Overall, accuracies approximated Digital Globe's stated accuracies of 3-6 m (Digital Globe, 2005). The panchromatic bands were considerably more difficult to obtain accurate registration, due to their much higher resolution.

Following the ortho-rectification process, all the multi-spectral band images were converted to radiance, and then reflectance values, in order to normalise these images. This process was carried using a *.gmd* model created in the Modeler Module of Erdas Imagine 8.7. The "absCalFactor" and sun elevation values required to run this model were provided in the *.imd* file supplied by Digital Globe with the imagery, while the formulae to calculate both radiance and reflectance were provided by Jha (2005). The ESUN values were based on the Landsat 7 values, as the spectral band ranges of the QuickBird imagery are very similar to the Landsat 7 ranges (Jha, 2005).

Further atmospheric correction was not considered necessary, based on Häme *et al's* (1998) findings. The quantification elements in this study were purely based on area calculations, which are not as susceptible to atmospheric effects on the digital numbers as are other quantifiable measures such as vegetation vigour or disease.

All further processing of the multi-spectral imagery occurred on the reflectance images.

Image Sub-setting

As was noted in the processing of the medium resolution imagery, edge effects along compartment boundaries caused problems due to the mixed-pixel effects. This phenomenon was also noted to occur in the high resolution imagery. In order to reduce this effect, compartment boundaries had a reduction or internal buffering applied to every compartment that was a study site. This was achieved by applying a -10 m buffer distance to the ArcGIS buffering process, which resulted in the compartment polygons shrinking inwards by 10 m. Based on a visual assessment of the study sites, 10 m was found sufficient to remove these edge effects. The effect of this was to reduce false spectral variation within the compartment study sites, thus improving the classification results. This helped counter the problems reported by Heyman *et al* (2003) where the greater variability within the classes caused a reduction in classification accuracies. The subset compartment polygons were then converted to Areas of Interest (AOIs) in

Imagine 8.7, and used in the Data Preparation module to subset each study site. Both the multi-spectral bands of the reflectance images and the panchromatic band of every image were subset in this manner. These subset data sets then served as the input data the next phase of processing.

This next phase split into two parallel process flows, one utilising the multi-spectral bands, and the other utilising the panchromatic band. Again, all study sites across all six images were processed.

Image Classification – Multi-spectral Bands

Initially, several unsupervised classification test phases were run, using 20, 12 and 6 classes. This was done in order to try and identify and extract any unique classes or class combinations. These test classifications were applied to all forest stands simultaneously, but masking out any area that was not a forest compartment. The ranges of stands varied from mature standing trees to clear-felled areas with only soil or slash ground cover. No significant classes could be consistently identified in this manner, and so it was decided to work with individual compartments independently by sub-setting them.

The focus of the study was restricted to compartments that were between 0 and 2 years of age from the time of last clear-felling, as the main aim was to identify weed infestation during the critical period from time of planting to canopy-closure stage. Canopy closure generally occurs within the first 24 months of growth.

By restricting the classification process to individual compartments it was found that the optimal number of classes required was 4. These classes, described in detail below, represented the following ground cover states:

Class 1: Shadow/Soil
Class 2: Soil/Slash
Class 3: Light Vegetation
Class 4: Heavy Vegetation

The unsupervised classification procedure was completed using the Classification module in Erdas Imagine 8.7, utilising a maximum of 6 iterations with a convergence threshold of 0.950.

Image Textural Analysis – Panchromatic Band

Despite the high resolution of 2.4 m, the multi-spectral bands could not identify the crop rows. However, these rows were very clear on the 0.6 m panchromatic imagery, and it was decided to optimise this feature to refine the classification results. This was undertaken by applying an edge-enhancement textural analysis process (Janssen, 2000).

Textural analysis utilising spectral signatures involves the application of a moving convolution window in order to produce the smoothing or sharpening effect of the analysis. In order to determine the optimal window size for every study site, it was necessary to undertake semivariogram analyses of the input data sets. This required converting the raster imagery to vector points, where every raster cell in the image was represented by a point with a value equal to the DN of that cell. This conversion was done using the Raster to Vector Conversion utility in ArcGIS Spatial Analyst extension (McCoy and Johnston, 2002). These point files tended to be very large, often containing millions of points. During the conversion process, all NULL data areas in the raster input image were also converted to points, and these had to be clipped out of the point data set using the buffered compartment boundary polygon in order to reduce the size (and hence processing time) of the point shapefiles. The resultant point shapefiles then served as the input into ArcGIS Geostatistical Analyst extension (Johnston *et al.* 2001), in which an ordinary kriging procedure was run to derive the semivariograms. Based on a series of test runs it was found that the optimal number of lags was 12, while the lag distance was set at 0.6 m, i.e. the spatial resolution of the input data. Using the resultant Range values from the semivariogram calculation, the optimal convolution window size was determined, and applied to the textural analyses procedures. The window sizes ranged from a minimum of 3x3 to a maximum of 11x11. Although not definitive, there was a trend for the larger windows to be more applicable to more diverse stands, while the smaller windows tended to be applied to stands with less variation, such as stands with a closed canopy. However, it was clearly seen that no one single window size could be applied across all sites.

Because of the strong linearity of the crop rows observed in the panchromatic imagery, it was decided to focus the textural analysis on this feature. Several different techniques were tested before an Edge Enhancement process was selected. Using the Edge Enhancement tool available in Erdas Imagine 8.7's Image Interpreter module the applicable convolution window sizes were applied to the input image date sets. The output was an edge enhanced image for each study site. These images then had a grey-level thresholding process applied so that they were reclassified into two classes, "rows"; "no-rows", using the Reclassify function in ArcGIS Spatial Analyst. Reclass Values were assigned to a "Value" field as follows:

NoData:	0
No Rows:	1
Rows:	2

Class break values were assigned based on a visual assessment of the images under a range of break values in order to determine the optimal split between "rows" versus "no-rows."

Image Vectorisation – Multi-Spectral and Panchromatic Bands

The four-class unsupervised classified images contained information regarding the amount of vegetation present, but could not separate crop from weed. The two-class reclassified panchromatic data sets contained the "Row, No Row" information, which could define what was crop. Thus by combining these two datasets, one could then classify the stands utilising all this information to determine what was crop, what was weed and what was soil or slash.

Thus, the two separate data sets, in terms of the multi-spectral and panchromatic bands had to be combined into a single data set in order to derive the final classified data set. However, this task was complicated by the fact that there were two different resolutions (2.4 m multi-spectral and 0.6 m panchromatic). Thus any raster merging of these data sets would mean either the larger resolution cell size being resampled down to the same cell size as the finer resolution cell size, or the finer cell size being resampled up to match the larger resolution cell size. Both of these methods are problematic, in that it is an incorrect procedure to run any analyses on data sets that have been resampled from a coarser to a finer resolution, while if one were to resample a finer resolution into a coarser one, the detail available in the finer resolution is lost, thereby negating the value of the finer resolution.

In order to circumvent the problem of combining different raster resolutions (2.4 m vs. 0.6 m) described above, it was decided to vectorise both the 4-class unsupervised classification data sets and the 2-class reclassified panchromatic data sets. A generalisation technique was applied during this process in order to produce a result that more closely resembled the real world than would be the case if the data followed the raster pattern. In this way, the different resolution issues were overcome, as well as reducing the misregistration problem to a large degree.

Once vectorised, the two data sets for each study site were then unioned utilising the ArcGIS ArcToolbox Geoprocessing Tools functionality. This union function achieved the aim of having a single data set that contained all the information from both the multi-spectral and panchromatic bands, which a classification routine could then utilise to produce a more accurate classification.

Once unioned a new field called "MATRIX" was added to the resultant data set, and the matrix value was calculated by concatenating the "GRIDCODE" field value from the 4-class unsupervised classification polygon layer and the "GRIDCODE" field value from the 2-class reclassified "Row; No Row" polygon layer. Any polygons that had a zero value in either "GRIDCODE" field were deleted. These occurred where there was no intersection between the two input layers, and were an artefact of the different resolutions not matching along the edges. As a final step in this process, in order to simplify the data sets by reducing the number of polygons with identical values, a dissolve routine was applied to the unioned data sets, with the "MATRIX" field used as the dissolve variable. This resulted in a table consisting of the unique records for each matrix variable present in the data set. Two additional fields were created in this table, one of which was used to calculate and record the area, in hectares, of the amount of each matrix value, and the other field used to calculate the overall percentage of the study site that each matrix value represented. This table then provided the quantified ground cover within each study site for the applicable image date. The percentage ground cover measurements for those classes that related to potential weed cover were then compared against a threshold value and if the threshold was exceeded, the area was flagged. The threshold was based on the "Plant-to-Canopy" requirement where no weeded area may exceed 5% of the total compartment area (Da Costa, 2005), and any compartment that had heavy vegetation exceeding this threshold was then flagged.

The Matrix values represented the following classes:

	Rows	
	1-No	*2-Yes*
Class 1: Shadow/Soil	11	12
Class 2: Soil/Slash	21	22
Class 3: Light Vegetation	31	32
Class 4: Heavy Vegetation	41	42

where the classes 12; 22 and 32 represented crop areas, class 31 represented potential light weed areas (<35% ground cover = weed), while classes 41 and 42 areas represented potential heavy weed infestation (>65% ground cover = weed). Classes 11 and 21 represented no potential weed infestation.

Classification Accuracy Assessment

Because of the Vectorisation process it was decided to undertake the accuracy assessment on the unioned data set, as this was the final "classified" result. The accuracy assessment was undertaken using randomised points within every study site, as defined by the buffered compartment polygon. Chi-Square tests for goodness of fit were applied to this data (Zar, 1984). User, Producer and Overall Accuracies were calculated on the error matrices derived from the comparison of the observed (i.e. classified image data) and reference (i.e. ground-truthed data) data (Khorram *et al*, 1999).

Results and Discussion

Unsupervised Classification of Multi-spectral Bands

The four classes that were defined by the unsupervised classification process were:

Class 1: Shadow/Soil
Class 2: Soil/Slash
Class 3: Light Vegetation
Class 4: Heavy Vegetation

Class 1: Shadow/Soil tended to classify particular reflectance values which differed according to the age of the compartment. In stands less than six months, especially those that had been burnt, areas of very dark soil (usually where brushwood rows (see glossary) had previously been burnt) were classified as this class. However, once the crop rows were well established, usually in stands older than six months, the parts of the crop row, and the inter-row areas, that were in shade were classified as this class. Hence, it was not a pure class in all stages of the stand development. However, within the parameters described above, there was a consistency in the areas it classified, and was therefore considered a valid class.

It should be noted that wherever brushwood rows occurred as a result of harvesting operations, these caused a particular signature in the imagery that was noticeable for about a year after the felling operations. This was particularly the case once the rows were burnt, when these areas were consistently classified as Class 1: Shadow/Soil.

Class 2: Soil/Slash occurred in areas where either the new crop was too small to be identified as crop, or as the crop grew and the crop rows became more defined, the inter-row areas were classified as this class. There was no differentiation between pure bare soil and where residual slash was present. However, in terms of what was being investigated in this study, this had no effect on the results, as these conditions were considered the same class.

Class 3: Light Vegetation classified areas that had vegetation present, either in the form of young or sparse crop rows, or where weed was present to some extent, usually in the inter-row. However, it seldom indicated pure crop rows, but rather defined patches of light weed infestation, together with areas of true crop. This inability to define crop from weed was a critical factor in the decision to pursue textural analyses to improve these classification results.

Class 4: Heavy Vegetation classified those areas of major weed growth, as well as crop rows, particularly in stands that were older than 18 months. However, these classification results suffered from the same drawbacks as were experienced with the Class 3: Light Vegetation classifications. These limitations, however, did not mean that this classification process was of no value. On the contrary, these classifications gave accurate information regarding the areas where weed was most likely to be a problem, as well as indicating the areas of good crop growth, particularly as the crop approached an age of 16 months or more.

Texture Analyses on Panchromatic Band

Although the multi-spectral resolution of 2.4 m is regarded as a high resolution (it is in fact that highest commercial resolution currently available from a satellite platform (Digital Globe, 2005)), it was still not sufficient to be able to separate crop from weeds on the basis of the crop rows. However, when viewing the 0.6 m resolution panchromatic imagery the crop rows were very apparent, particularly as the crop age exceeded four months. Even in very young stands, less than three months old, crop rows were often discernable where there had been a "line-cleaning" operation. This is where a clear row is hoed down to bare soil along the planting line. This line is usually 1 to1.5 m wide, with the centre line of this cleared area being a distance of 3 m perpendicular to the adjacent rows on either side. The purpose of this hoed row is to remove any initial weed as the plant crop becomes established, following its planting (if a seedling) or germination (where seed is sown directly into planting line – this occurs only in wattle establishment). It was this visibility of the crop rows that was believed to be a key element in being able to separate crop from weed within the vegetation signal, provided a means could be found to merge the two differing resolution datasets. The most effective methodology to utilise this characteristic was to apply some form of textural analysis (Tso and Mather, 2001; Lillesand and Kiefer, 2000; Janssen, 2000) to enhance the lineation features of the crop rows.

The Edge Enhancement function was able to detect the lineation virtually as soon as it had occurred in the form of a line-cleaning operation. In some cases this was even prior to the crop emerging as a distinctive feature. It also tended to maintain the crop row definition well into canopy closure, with the oldest study site at 26 months still having some indication of the crop rows. This methodology was by far the most successful at defining the crop rows (see Figure 2), and so was selected as the textural analysis method of choice for this study, which was based on the premise that crop rows could be used to assist in separating crop from weed. The edge enhanced images were the input to the two- class classified "Row; No Row" images.

Various studies have attempted to produce tree counts based on individual tree identification (e.g. Jacobs and Mthembu, 2001; Wulder *et al*, 2000), with minimum crown dimensions of 1.5 m required for 1 m spatial resolution imagery being reported (Wulder *et al*, 2000). However, because this study focussed on the tree row as a whole, rather than individual tree crowns, successful identification of tree rows was achieved where crown dimensions were much smaller than figures reported in these other studies. This was one of the unique findings of this study.

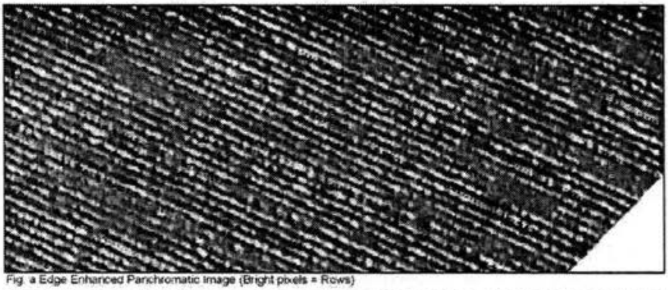

Fig. a Edge Enhanced Panchromatic Image (Bright pixels = Rows)

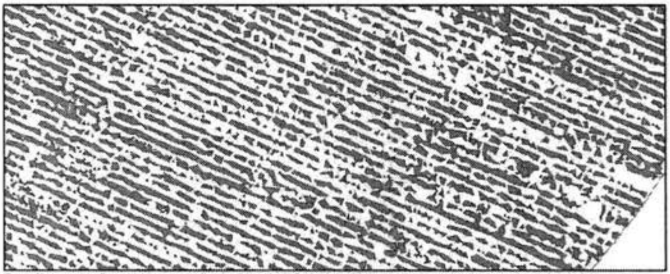

Fig. b Two CLass Reclassified Image highlighting Crop Rows

Fig. c Classified Rows overlain on Enhanced Pan Image

Figure 2. Illustration of Classified Row Image highlighting Crop Rows

Classification of Vectorised Data Sets

The unsupervised classification results of the multi-spectral images were then vectorised, while the edge enhanced panchromatic images were reclassified to two-class "Row, No Row" images, which were also then vectorised. These two vectorised data sets were then unioned to derive the final classified data sets, based on a matrix of values derived from the two input data sets.

The objective of this process was to extract the vegetation signal of the multi-spectral classified imagery in combination with the crop row information derived from the higher resolution panchromatic imagery in order to define areas of potential weed growth, as opposed to crop growth. The logic behind this process was predicated on the basis that a vegetation signal within a crop row would be crop, as opposed to weed, while vegetation signals outside of a crop row should be weed. Where there was little or no vegetation signal but there was a row defined, this should indicate crop as well. A soil/slash signal outside of a crop row should indicate a weed-free environment, and hence not be a potential weed problem area. Based on these criteria, the classification matrix (see above) was assigned the following status:

Class 11: Shadow/Soil
Class 12: Crop
Class 21: Soil/Slash
Class 22: Crop (Crop/Soil in stands <3 months)
Class 31: Light Weed
Class 32: Crop (Crop/Weed in stands <3 months)
Class 41: Heavy Weed
Class 42: Heavy Weed

Three phases in this classification process were noted, each slightly different from the others. This was a function of the degree of crop row delineation, with classifications showing decreasing cross-classification from the very young stands up to an age between 14 and 16 months, after which cross-classification again increased.

In stands less than three months old, there tended to be insufficient differentiation between crop, soil and weed. The evidence for this was seen in the fact that instead of delineating the crop rows, Classes 22 and 32 tended to group larger areas beyond the true crop row, forming more clumped areas. This resulted in a cross-classification between Class 21 and Class 22, such that Class 22 was a mixed class of Crop and Soil (see Figure 3). Where the vegetation signal was stronger a similar cross-classification occurred between Class 31 and Class 32, where the latter class was a mixed class of Crop and Weed (see Figure 3). Having noted this, there were areas of pure crop where the crop row definition was clear enough to be highlighted by the edge enhancement process. Although present in subsequent images, this cross-classification had greatly decreased in extent, such that it became a minor class. While not a pure class, Class 32 did provide useful indications of where the early stages of potential weed problems could occur, particularly as the Class 42: Heavy Weed areas were often associated with this Crop/Weed class. A similar pattern occurred with the Class 42: Heavy Weed, where these areas tended to be concentrated into clumps rather than being in rows, as was expected. However, in the vast majority of these areas, heavy weed growth did occur, and this class was highly indicative of problematic weed growth. Although crop areas did occur within these areas, the weed growth was such that it diluted the crop row delineation and so became more indicative of weed rather than crop. This cross-classification was only of concern in these very young stands, when there was very little crop row development (with any crop crown diameter generally being less than 20 cm). Crop row definition could only be derived from the delineation effect caused by the line cleaning operations.

In stands from three to about twelve months old, crop row delineation was much clearer, with Class 22 now able to effectively define crop areas (see Figure 4). There was still a tendency for some cross-classification between crop and weed in those areas classified as Class 32. However, where this was the case, it correctly identified those areas that did have a weed concentration, and was therefore not an inaccurate classification. Again, this class tended to extend beyond the true crop row and form clumps, although these were smaller in extent than was the case in stands less than three months old.

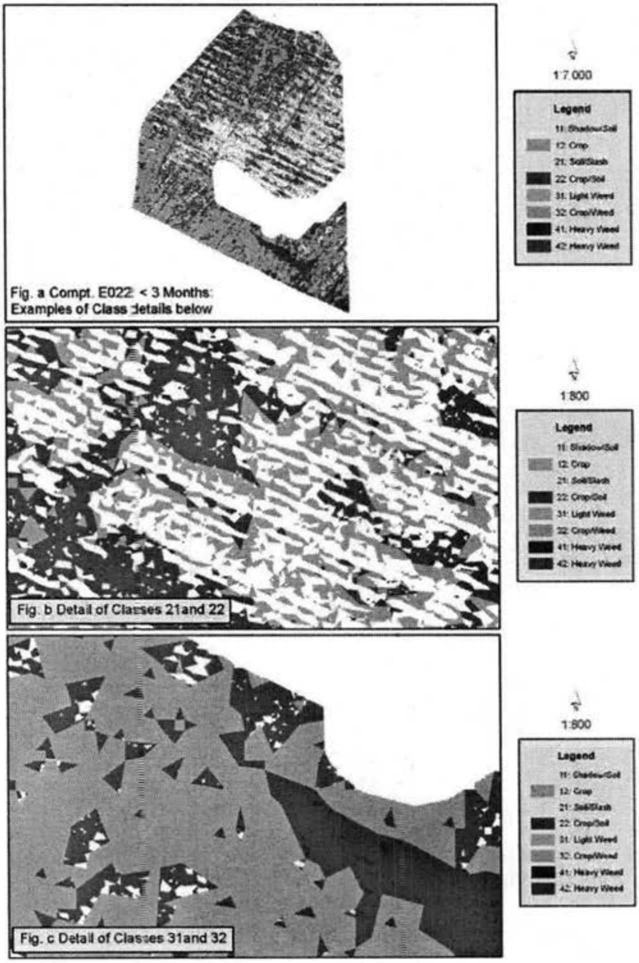

Figure 3. Close-up of Classes 21; 22; 31 and 32, at < 3 Months Phase

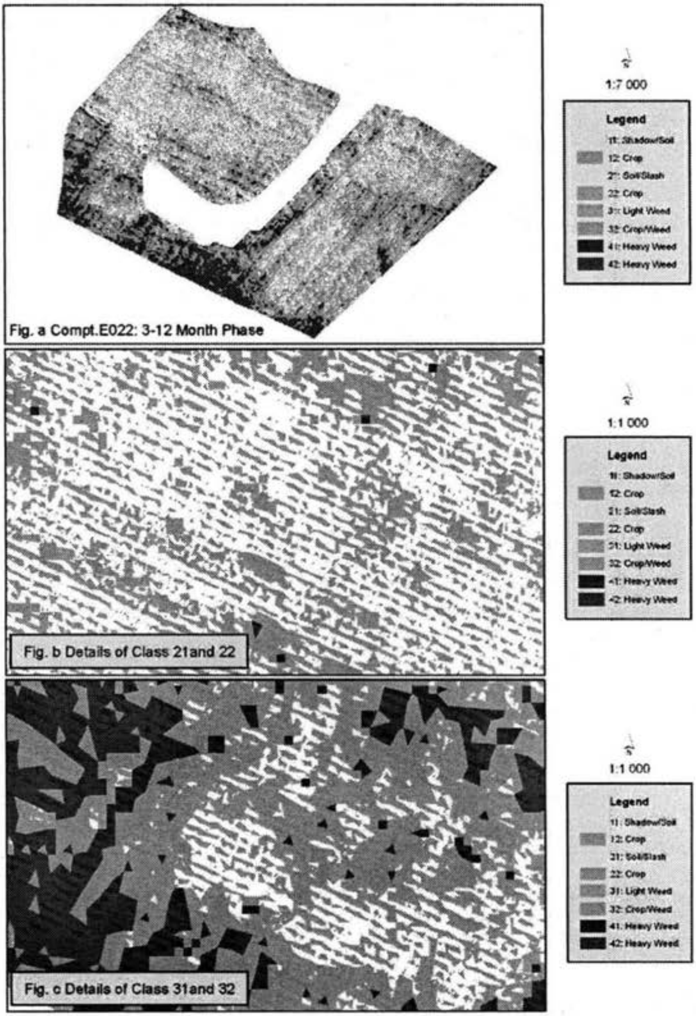

Figure 4. Close-up of Classes 21; 22; 31 and 32, at 3-12 Months Phase

This classification is what would be expected from a newly established stand as it grows, but it was encouraging to see that the classification process mirrored this development. What was clear from the classification results was that one could immediately tell where there were potential weed problem areas, particularly where there were patches of heavy weed. This would certainly provide useful management information to field staff that needed to monitor operations such as weed status. It also gave some visual indication of where stands were under-performing, for instance due to poor stocking or sub-optimal growth. These could then be investigated on the ground and corrective action applied where possible. It was also interesting to note the degree to which the crop row lineation could be determined, and how early on it could be characterised. This was seen in the fact that Classes 12 and 22 correctly classified crop, as opposed to weed. Areas classified as Classes 11 and 21 did not have weed growth, but were either shadow or soil (see Figure 4). The third phase of the classification occurred in compartments that were between twelve months and about 16 months old (it should be noted that these age ranges were not definitive, as these phases occurred at slightly different ages on different sites, due to factors such as site quality, silvicultural treatments etc.). In this stage the classifications were more pure, with the crop signature being much more definite. The anomaly with Class 42: Heavy Weed continued in this phase, with this class being particularly indicative of heavy weed patches, rather than crop, as was anticipated. For this reason, it was classed as heavy weed, rather than crop. However, it was still beneficial to keep it a separate class, rather than merging it with Class 41; Heavy Weed, as when viewed spatially one could obtain useful information about the distribution of the weed infestation as well as some crop row information. Once again the principle of the row delineation identifying crop as opposed to weed proved successful, and even more so than was the case in the younger stands of the first and second phases.

Once compartments were older than fourteen to sixteen months after establishment, greater cross-classification between the weed and crop classes tended to occur, with some areas being classified as weedy, but which were in fact crop. This was due to canopy closure occurring, with a subsequent loss of clear row delineation, but with a strong vegetation signal being present. Therefore, the cut-off limit for successful identification of weed potential was set at fourteen months. With the onset of canopy closure, weed infestation is no longer a major concern, and so the need to monitor this falls away. Thus this cross-classification is not a problem. Based on these results, the optimal period in which to identify potential weed infestation was from three to fourteen months after establishment.

Accuracy Assessment

Accuracy assessment routines were performed on several combinations of the classification data sets, as well as on each of the individual study site classification results. The chi-square test result of the observed frequencies of all the data pooled together was significant ($P < 0.0001$) using a one-tailed test, with an overall accuracy of 80.8%, while a kappa of 0.748 was attained. A contingency coefficient of 0.837 was obtained, compared to a highest possible value of 0.894 for a 5x5 table, showing a very high level of association between the observed and expected classes (Table1).

Table1 Chi-Square; User; Producer and Overall Accuracies for 3-14 Months Pooled Data

Results Report - Chi Square Table of Observed and Reference **Compartments 3-14 Months old**

			Reference					
Observed	**Crop**	**Heavy Weed**	**Light Weed**	**Shadow/ Soil**	**Soil/ Slash**	**Row Total**	**Incremental Chi Square**	**User Accuracy**
Crop	46	2	2	0	1	51	60.967	90.2%
expected	*19.125*	*5.419*	*7.650*	*3.506*	*15.300*			
Heavy Weed	3	15	0	0	1	19	88.111	78.9%
expected	*7.125*	*2.019*	*2.850*	*1.306*	*5.700*			
Light Weed	2	0	20	0	2	24	68.841	83.3%
expected	*9.000*	*2.550*	*3.600*	*1.650*	*7.200*			
Shadow/Soil	5	0	1	11	4	21	74.615	52.4%
expected	*7.875*	*2.231*	*3.150*	*1.444*	*6.300*			
Soil/Slash	4	0	1	0	40	45	93.894	88.9%
expected	*16.875*	*4.781*	*6.750*	*3.094*	*13.500*			
Columns Total	60	17	24	11	48	160 ***Grand Total***	386.428 ***Chi Square Total***	82.5% ***Overall Accuracy***
Producer Accuracy	76.7%	88.2%	83.3%	100.0%	83.3%			
						DF	16	
						P	0.000	

The chi square test result of the observed frequencies of your variables was significant using a one-tailed test

Results of the accuracy assessments done on the pooled data of compartments between three and fourteen months supported the finding that this was the optimal period to identify potential weed infestations. The overall accuracy for this grouping was 82.5% (see Table 1). In addition, the chi-square test results of the 3-14 Month pooled data also proved to be significant using the one-tailed test, while a kappa score of 0.767 was achieved, together with a contingency coefficient of 0.841. This latter measure again indicated a very high degree of association between the observed and expected classes. Gray *et al* (2004) reported classification accuracies ranging from 49% to 69%. However, that study attempted to identify weeds by type, rather than simply differentiating weed from crop, which was the focus of this study. Nilson *et al*'s (2001) study on the effect of successional changes in vegetation cover on ground reflectance values found it difficult to quantify these effects. However, this study was able to quantify the effect such vegetation succession had, in that it was able to calculate the area affected by weed infestation, as well as the change in crop cover.

Compartments less than three months old only achieved an overall classification accuracy of 73.3%, while compartments older than fourteen months achieved a slightly better overall classification accuracy of 80.0%. The chi-square was significant ($P < 0.0001$).

Quantification Process

A significant advantage of the approach adopted in this study was that in addition to highlighting the spatial distribution of the weed infestations within the compartments (i.e. where the weed patches occurred within the stand), it could also quantify infestation levels. Table 2 shows an example of this quantification. It also illustrates the reduction in the number of classes that occurred over time, as the classification improved with increasing row definition. Class 11: Shadow/Soil and Class 21: Soil/Slash were sufficiently similar as to constitute a single class for the purposes of this table, and so the areas reported were combined under the Soil/Slash class. With the improved classification as the crop grew over the three to twelve month period, the cross-classification between crop and soil did not occur, resulting in Class 22 better defining crop, and so was combined with Class 12 to identify the crop area. After twelve months, the crop/weed cross-classification was no longer evident, with vegetation now being classified as crop or weed (light or heavy), and the areas of each class reported as such. Each classification class had the area, in hectares, and the percentage that this represented across the compartment calculated.

Table 2 Illustration of Ground Cover Area and Percentage Quantification

	Compartments < 3 months		
	Class	Dec. 2003	
Compt.	Description	Ha	%
E022	Soil/Slash	4.4	***25.8***
E022	Crop/Soil	6	***35.3***
E022	Crop	1.8	***10.6***
E022	Crop/Weed	3.4	***20***
E022	Light Weed	0.5	***2.9***
E022	Heavy Weed	0.9	***5.3***

	Compartments 3-14 months				
	Class	May. 2004		Dec. 2004	
Compt.	Description	Ha	%	Ha	%
E022	Soil/Slash	9.2	***32.4***	10.1	***35.5***
E022					
E022	Crop	6.6	***23.3***	6.7	***23.6***
E022	Crop/Weed	5.9	***20.8***	4.2	***14.8***
E022	Light Weed	3.9	***13.7***	4.1	***14.4***
E022	Heavy Weed	2.9	***10.2***	3.4	***12***

	Compartments > 14 months				
	Class	Mar. 2005		Apr. 2005	
Compt.	Description	Ha	%	Ha	%
E022	Soil/Slash	7.1	***25***	9	***31.7***
E022					
E022	Crop	13.9	***49***	10.3	***36.2***
E022					
E022	Light Weed	3.1	***10.9***	4.1	***14.4***
E022	Heavy Weed	4.4	***15.5***	5	***17.6***

Conclusions

The 2.4m multi-spectral imagery on its own was insufficient to identify potential weed infestations. However, in combination with the textural information provided by the panchromatic imagery, the vegetation signal inherent in this data was critical to the successful differentiation of crop from weed and subsequent identification of potential weed infestations.

Textural analysis proved to be an essential component in producing successful classification and change detection results in the context of this study. Of the textural analysis techniques tested the edge enhancement technique was the most successful in delineating crop rows. This delineation of crop rows was the key to distinguishing crop from weed, but it was still necessary to combine the crop row data with the multi-spectral data set to achieve a successful classification. These results agree with other studies (e.g. Tso and Mather, 2001; Coppin, 1991; Fung and Le Drew, 1987) that reported improved classification results due to the inclusion of textural analyses in the classification process. However, this approach would most probably only yield meaningful results in plantation forestry, where regularly lineated forest stands is generally a feature.

Stand age played a major role in the classification success, as those stands (or compartments) less than three months old or older than fourteen months were not classified as successfully as stands between these ages. The optimal period within which to identify potential weed infestation in wattle stands is three to fourteen months. However, identification of potential weed problems in stands younger than three months can still be done with reasonable success. Stands older than fourteen months tend to be close to canopy closure, when it is no longer necessary to monitor weed infestations. Hence, knowledge of stand age is probably a prerequisite.

Despite some level of cross-classification, particularly in the "early crop" stage, the four-class matrix provided a good basis for deriving the weed infestation levels.

In addition to effectively identifying weed infestations spatially, it was possible to quantify the level of infestation and report it on a hectare basis, as well as the percentage of the compartment affected. The success in identifying and quantifying weed infestation achieved in this study was higher than reported in other studies.

Recommendations

Techniques involving the combination of multi-spectral and edge enhanced panchromatic high resolution imagery should be used to identify and quantify potential weed infestations as a management tool to improve the monitoring of weed status within plantation forest stands.

Due to the number of processes required to run these analyses, techniques should be developed to automate as much of the processing as possible. This will allow results to be provided more timeously, which is a critical factor due to the time-sensitive nature of monitoring weed infestations.

The application of the techniques described in this study should be tested in both *Eucalyptus* coppice stands and *Eucalyptus* planted stands, as well as in Pine stands, as each of these types have some unique characteristics that differ from wattle stands, as well as from each other.

Acknowledgements
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RECLASSIFICATION METHODS FOR THE HIGH-RESOLUTION SATELLITE PHOTOGRAPH BY MULTI AGENTS

Tetsuro Sakai
Graduate School of Informatics Kyoto University, Japan
E-mail: sakai@i.kyoto-u.ac.jp

Abstract

We tried the acquisition of individual tree and forest information using the high-resolution satellite photograph. In the image classification by conventional cluster analysis, due to the high resolution, slight difference in brightness values may result in classifying similar pixels into to difference classes. Especially in forests, the effects of the lower vegetation and the difference in the angles of tree crowns against the sun are strong. To solve such problems, we examined the reclassification method using our proposed degrees of belonging in the cluster analysis and membership function of fuzzy cluster analysis. The degree of belonging is calculated from the classification distance as a result of cluster analysis. In our method, the reclassification is done by the agent system considering the classification continuity using indices such as MS. The agents that have re-classification strategies are assigned random positions, and reclassify neighboring pixels.

Keywords: IKONOS, Cluster analysis, Agent

Introduction

In the natural environment problem of the earth, it is important to have a finger on the pulse of the land cover. Especially, the forest gives large effect in the natural environment, and an investigation of resources information is important. The remote sensing technique is one of the useful means for obtaining environment and resources information of the forest. The much researches in relation to forest resources using middle resolution satellite photograph such as Landsat is ever reported. In the remote sensing using the middle resolution satellite photograph, it was possible to obtain land use and vegetation information. It is possible to get the rough forest stand information as conifer or broad-leaved tree. In the meantime, it is possible to get really good and more detailed information in high-resolution satellite photograph which becomes recently available. Many people expect the usefulness for forest investigation. It seems to be possible to get various information of individual tree in the high-resolution satellite photograph. It is expected that tree species division and individual tree information extraction are possible. As researches utilizing remote sensing data, land cover classification [Kenji 2004] and tree species classification [Kazuaki 2004] using satellite images. As a method for recognizing the individual tree using the high-resolution satellite photographs, approximate colors circle retrieval method, etc. are reported [Aaron 2003, Darrel 2003 Ramanathan 2003, Naoko 2005].

However, there are various problems in the analysis by the high-resolution satellite photograph. For example on analysis of one tree, the luminance value is different by the angle of the tree crown that faces the sun. By the high resolution, the difference of the partial luminance causes a problem of the analysis. That is to say, the pixels that are classified into the equal class as individual tree under ordinary circumstances may be classified into the different class in the image classification by cluster analysis. In the analysis using middle resolution satellite photograph, mixel was a problem, while on the other hand in the analysis using high-resolution satellite photograph the continuity of classified class of neighboring pixel becomes a problem. The object technique is proposed in order to cope with this problem. It is a method for the analysis at the unit that similarity and neighboring pixels are grouped together as. We examine the reclassification technique using the result of the cluster analysis. In this method, the agent reclassifies using the certainty of the classification. In this report, the technique is reported.

Data and Methodology

Area and Data

We selected Hokkaido research forest of Kyoto Univ. Field Educational Research Center as object areas. The forest is a flatland forest that did not receive the geomorphologic constraint, and that contains conifer and broad-leaved forest and the pastureland. Hokkaido is located in the north in Japan, and the climate belongs to the polar zone.

IKONOS satellite image for high-resolution satellite photograph was used in the examination of this method. Data of IKONOS satellite image composed of the 4 bands that are RGB and near infrared. As a pretreatment, normalized DN values that divided each band by the total of the 4 bands DN value were calculated. Three normalization vegetation indexes (NDVI) were calculated from RGB and near infrared DN value. And, the result of texture analysis for RGB, Nir and NDVI value, Average, contrast, dispersion, energy and entropy were calculated for texture index. Size of the subject area of texture analysis is 3*3 and 5*5 pixels, and the shape is rectangle and diamond. Next, for making the forest type map and tree species map, it made cluster analysis by K-means method using variables as a result of the pretreatment. In the classification, the simple Euclidean distance was used.

The certainty of the classification

In usual cluster analysis, the distance (it is called the following classification distance) between variable value of each pixel and variable value of each class center is a classification index. Each pixel is classified into the class in which the classification distance is the shortest. Therefore, when classification distance to some classes is little difference, classified class is different by the cases. Then, the index of classified into the specific class is proposed. In this paper, this index is called the degree of belonging. The degree of belonging is calculated using average and standard deviation of classification distance of each class. If classification distance is under the mean value of the class, the degree of belonging is 100. If classification distance is over the value that added mean value and double of standard deviation, the degree of belonging is 0. The value of the interval is complemented in the decrease function as Fig.1. The degree of belonging is 0-100. There is the high possibility of belonging to the class, as the value is bigger. The possibility of belonging to the class rises, as the value is bigger. However, it is not always classified into the class, as the degree of belonging to the class is big. That is to say, the classification class is not decided according to the amount of the degree of belonging.

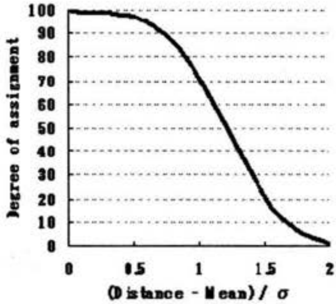


Fig.1 Relationship between assignment and classification distance

On the other hand, in the fuzzy cluster analysis, membership value that shows the belonging degree of the class and the classification class are calculated. In the fuzzy cluster analysis, it is classified by the value of the membership value. The membership value is calculated on all classes, and the total value is 1. In this paper, the membership value was transformed in linearity so that the total may become 100 for the comparison degree of the belonging. The degree of belonging has shown the expectation value in which individual pixel belongs to the individual class. Therefore, the total degree of the degree of belonging of the pixels to each class may greatly exceed 100, and it becomes not always 100. Like the above, degree of belonging and membership value are different in some points. However, we consider that these indexes are together important in the examination of the reclassification. These are index of the certainty of the classification

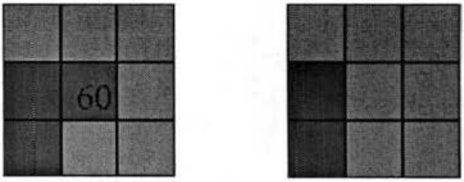
Classification method

Procedures of the classification are as follows.

- Step 1: Classification is done by the conventional technique (k-means, fuzzy cluster analysis, etc.). Class center value and statistic of the classification distance are calculated.
- Steps 2: Degree of belonging (it is the membership value in the fuzzy cluster) of the every pixel to each class is calculated.
- Steps 3: The agent reclassifies the classification result of Step 1 using degree of belonging or membership value.

Objects of the reclassification are target pixel and the neighbored 8 pixels. Degree of belonging or membership values of those pixels is used for the reclassification. One of the 3 next reclassification strategies is randomly given each agent.

"The majority decision subordination" is the strategy that changes classification class of the target pixel is changed to the majority classification class in 9 pixels. It is based on premise that the degree of belonging or membership value for majority class of the target pixel is in the range of the threshold. Fig.2 shows the reclassification by "The majority decision subordination" strategy.



Before Reclassification After Reclassification

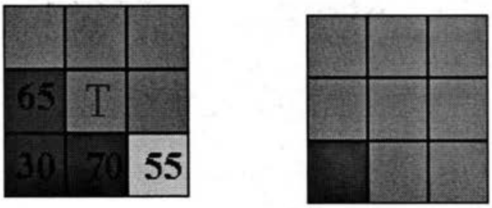
Number means belonging/membership value

Minimum threshold is 40 and maximum threshold is 80 for reclassification.

Fig.2 Reclassification of the majority decision subordination strategy

"The majority decision persuasion" is the strategy that if target pixel belongs majority classification class, neighbored 8 pixels are changed to the majority classification class. . It is based on premise that the degree of belonging or membership value for majority class of the neighbored each pixel is in the range of the threshold. Fig.3 shows the reclassification by "The majority decision persuasion" strategy.

"Persuasion" is the strategy that neighbored 8 pixels is changed to same classification class of the target pixel. It is based on premise that the degree of belonging or membership value for the target pixel's class of the neighbored each pixel is in the range of the threshold. Fig.4 shows the reclassification by "Persuasion" strategy.

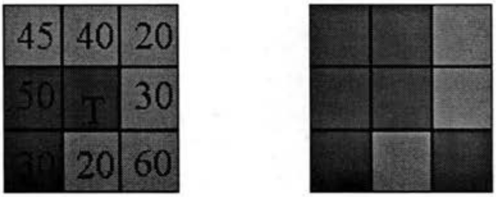


Before Reclassification After Reclassification

T is target pixel and number means belonging/membership value

Minimum threshold is 40 and maximum threshold is 80 for reclassification.

Fig.3 Reclassification of the majority decision persuasion strategy



Before Reclassification After Reclassification

T is target pixel and number means belonging/membership value

Minimum threshold is 40 and maximum threshold is 80 for reclassification.

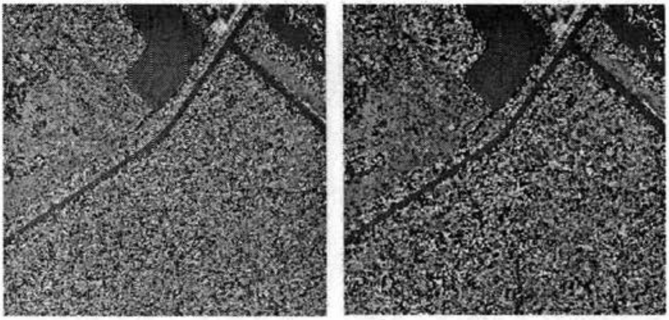
Fig.4 Reclassification of Persuasion strategy

This reclassification is carried out using the agent as following.

1. The setting of initial values such as number of the agent, the reclassification strategy, maximum and minimum threshold and repeated time.
2. The appointment of the target pixel for each agent randomly.
3. The reclassification based on the reclassification strategy -"The majority decision subordination", "The majority decision persuasion" and "Persuasion".
4. 2 and 3 is repeated, until it reaches the repeated time.

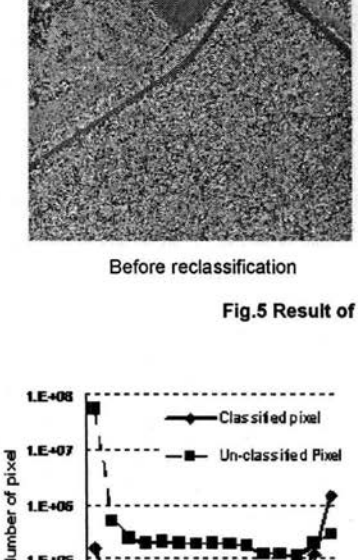
Result and Discussion

The object area was classified into 30 classes by both method of un-supervisor cluster analysis (K-Means method) and fuzzy cluster method. Fig.5 shows the relationship between the number of pixels and the degree of belonging in result of un-supervisor cluster analysis. And Fig.6 shows the relationship between the number of pixels and the membership value in result of fuzzy cluster analysis. In usual k-means cluster analysis, the average of the degree of belonging of classified pixels is 84.8, and the average of un-classified pixels is 2.5. There is clear difference between both values. The degree of belonging of boundary between classification and non-classification is over 80-90. And in the fuzzy cluster analysis, the membership value of them is about 20-30. In both cases, it is clear that many pixels are classified another class (non-classified), even if their degree of belonging or membership value is high. As a means for obtaining the continuity of the classification of pixels, possibility and usefulness of using these index values are suggested. Based on the above result, the threshold that is one of the parameters of the reclassification was decided. The thresholds sort out the reclassification pixel, and they are shown as maximum value and minimum value of the degree of belonging and the membership value. In usual cluster analysis, the maximum value is set with 80. And in the fuzzy cluster analysis, the maximum value is set with 40. The minimum value is set with 10 in both cases.



Before reclassification After reclassification

Fig.5 Result of reclassification



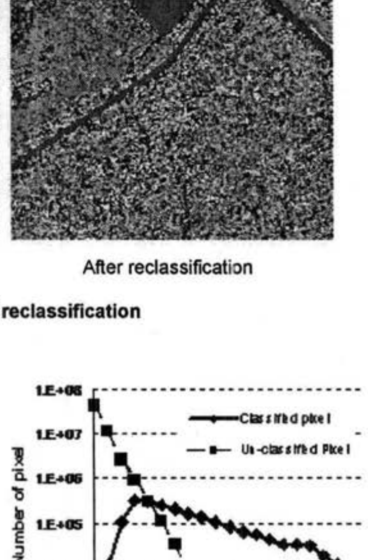


Fig.6 Distribution of degree of belonging **Fig.7 Distribution of memberships value**

Fig. 7 shows the part of vegetation map by the cluster analysis (500*500 pixel) and the result of the reclassification. It is proven that the fine texture differs further than before reclassification and after reclassification and that the pixels classified into the identical class are grouped. In the reclassification by the agent, neighboring similarity pixel has been grouped as expected of the beginning. Two of the three-reclassification strategies – "majority decision subordination" and "majority decision persuasion" promote the grouping. But, "persuasion" not always promotes the grouping. Neighboring majority is cut into, when the pixel as a target belongs to the classification class of the minority. Therefore, it is generated, when the grouping zone is also segmented. How the proportion of the reclassification strategy is set, is a very important problem. In the current, the proportion is searched in trial and error. In the future, we want to produce some procedures and standards.

In this reclassification method, the number of agent and the number of trial times can be also set as a parameter. Trial time is counted, when all agents set finish the task of the reclassification. Therefore, the classification class is changed, if the pixel is correspondent to the reclassification in each trial. In this reclassification, whether the pixel once changed is targeted afterwards reclassification object is large problem. The number of changed pixels decreases depending on the trial times, when they are not targeted reclassification. Fig. 8 shows the relationship between trial times and the number of changed pixel when once reclassified pixels are not targeted reclassification. However, the number of changed pixels greatly does not change without relating to the trial times, when once reclassified pixels are targeted reclassification. The pixels that belong to some classification classes change the class in the chance of reclassification, so the number of changed pixel is not decrease.

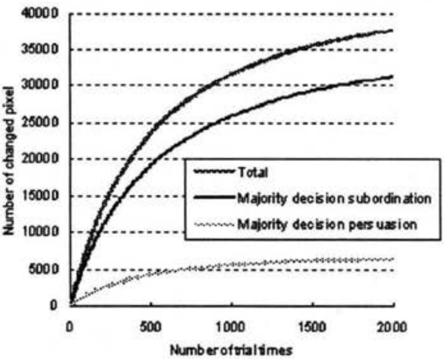


Fig.8 Relation between number of changed pixel and trial time

As a method for integrating similar pixels, there is a method using dendrogram of the classification class. The dendrogram is calculated by hierarchical cluster-analysis that made the central value of the each classification class to be a variable. Between integrated classification classes, the mean value of the degree of belonging and membership value is bigger than other class. Class integration that made the degree of belonging between the classification classes to be an index was tried. As the result, the group of which the degree of similarity was high in dendrogram was almost same. It is considered that degree of belonging and membership value are effective as an index to the degree of similarity.

Conclusion

The method of the reclassification using the agent was proposed in order to maintain the continuity of the classification of neighboring pixel. The degree of belonging and the membership value were useful as an index to the similarity of the pixel. And, this method was useful as the technique that grouped pixel. In the future, we want to consider the standard of the parameter of this method for various analyses

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SEGMENT-BASED FOREST VOLUME-BY-TYPE MODELLING USING SMALL FOOTPRINT LIDAR HEIGHT DISTRIBUTIONS

Jan A.N. van Aardt[1], **Randolph H. Wynne**[2]
[1]Department Biosystems (M3-BIORES), Faculty of Bioscience Engineering, Katholieke Universiteit Leuven, Belgium
[2]Department of Forestry, Virginia Polytechnic Institute and State University, USA
E-mail: jan.vanaardt@biw.kuleuven.be

Abstract

This study explored a segment-based approach to coniferous and deciduous forest volume-by-type estimation using small-footprint lidar. The study area is located in the Appomattox Buckingham State Forest (Appomattox County, Virginia, USA) in the Virginia Piedmont physiographic region, and consists of a variety of pine, upland hardwood, and mixed stands. A multiresolution, hierarchical segmentation algorithm was applied to a lidar-derived canopy height model. Lidar multiple return distribution characteristics (mode, mean, range, skewness, etc.) were used to develop volume prediction models and classify coniferous and deciduous segments based on *in situ* mapped basal area (BAF) plots. Volume modelling results were promising with adjusted R^2 values of up to 0.66 for coniferous and 0.56 for deciduous species. Object-oriented classification accuracies were as high as 89% (deciduous-coniferous). Results hint at possible operational implementation, especially when the variability in Virginia Piedmont forests is considered. Such a comprehensive lidar-based inventory approach ultimately could lend itself to large scale, precise, and relatively inexpensive inventories.

Keywords: Multiresolution, Segmentation, Object-oriented, Distribution, Modelling

Introduction

Extensive field methods or aerial photography volume tables long have been regarded as the standard methods of forest inventory (Avery and Burkhart, 1994). These methods frequently are time consuming and expensive, but provide unbiased estimates. Synoptic remote sensing could provide a cheaper option for estimation of forest biophysical parameters over large tracts, while potentially also providing accurate and unbiased estimates. The structural nature of lidar height data makes it especially suitable for gauging forest volume and biomass. Lidar-based forest measurements have been shown to be applicable to general forest inventory and canopy structure modelling (Lefsky *et al.*, 2002; Næsset, 2002; Popescu *et al.*, 2004) and have been implemented to gauge forest fuel loads (Riaño *et al.*, 2003; Seielstad and Queen, 2003) and derive digital elevation models (Popescu *et al.*, 2002; Hodgson *et al.*, 2003). Lefsky *et al.* (2002) have proven that lidar sensors can provide accurate and non-asymptotic estimates of various forest indices, e.g., LAI and aboveground biomass. A lidar-based approach to forest inventory furthermore could negate the need for ground-based, small scale measurements of tree heights and/or canopy parameters.

Although large footprint lidar sensors have been used extensively for forest volume and biomass estimation (Lefsky *et al.*, 1999; Means *et al.*, 1999), the spatially discontinuous nature of large footprint lidar sensors limits their applicability at local scales. Small footprint lidar sensors are more amenable to volume and biomass estimation on small tracts of forest and have been used as early as the mid-1980's for forest volume estimation (Maclean and Krabill, 1986; Nelson *et al.*, 1988). Lidar studies have included both plot- and stand-based approaches (Nilsson, 1996; Popescu *et al.*, 2004) while lidar height distributional approaches have come to the fore more recently (Means *et al.*, 2000; Næsset, 2002). These authors exploited the relationships between distributional height metrics, e.g., mean, range, skewness, and percentiles, and forest biophysical parameters. This approach lends itself to segment- or stand-level application and approximates a waveform-type return found in the case of large footprint lidar sensors. These pseudo-waveforms are useful for characterization of vertical forest structure, a feature which is potentially valuable for large scale, stand-level volume- and biomass estimation (Magnussen and Boudewyn, 1998; Means *et al.*, 2000; Drake *et al.*, 2002; Næsset, 2002).

Means *et al.* (2000) implemented a lidar distributional approach to estimate height and basal area for Douglas-fir stands, ranging from shrub-like (18 m^3/ha) to old-growth (1313 – 2051 m^3/ha) stands. Lidar returns were extracted from 10 x 10 m grid cells within larger 50 x 50 m measured plots. Distributional parameters, e.g., canopy cover percentiles, maximum height, elevation, average mean height, and average of the maximum heights were calculated for grid cells. Stepwise regression analysis was used to determine the relationships between ground data and lidar measurements, with dependent variables height, basal area, and volume. R^2 values of 0.93 (RMSE = 3.4 m), 0.95, and 0.97 (no RMSE for latter two values) were obtained for height, basal area, and volume, respectively. R^2 values for plots excluding old-growth plots were 0.98 (RMSE = 1.7 m), 0.94 (RMSE = 5.4 m^2/ha), and 0.95 (RMSE = 73 m^3/ha), for height, basal area, and volume, respectively. Various percentile variables, e.g., the 90th height percentile and 20th coverage percentile, were shown to be significant predictor variables. Næsset (2002) predicted volume and crown parameters for Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) stands in Norway, using a stratum-specific (young forests; old-growth, on poor and good sites) approach. Observed volume values ranged between 41 m^3/ha and 639.8 m^3/ha. Lidar first- and last pulse distribution based regression equations were used to model volume and crown parameters. Various quantiles, maximum- and mean values, canopy density measures, and coefficients of variation were used as independent variables. R^2 values for 61 reference stands were 0.87 (dominant height) and 0.91 (volume). Standard deviations ranged between 0.7 – 1.33 m (dominant height) and 18.3 – 31.9 m^3/ha (volume).

The extension of distributional grid-cell approaches to object- and stand-level applications was deemed the next logical step. According to Burrough and McDonnel (1998), an object (segment) refers to a spatial entity that is homogenous in terms of a selected property, as opposed to the traditional, continuous field approach found in spatial analysis. Segments therefore can be treated as entities or objects, since each segment is homogenous in terms of a defined variable. Douglas *et al.* (2003) have shown that such an application requires that distinct forest cover and structural types have different, unique lidar canopy densities or distributions. Segment-level estimate errors also can be minimized (Makela and Pekkarinen, 2001; Pekkarinen, 2002). Segment-based modelling furthermore is amenable to stand-level scaling, since segments can match existing structural boundaries in forests, but this based on the assumption that segments are hierarchical and topologically sound.

The basic precept of this study was that extraction of lidar distributions on a grid-cell basis, used to model volume and biomass (Means *et al.*, 2000; Næsset, 2002) and classify forests, could be extended to estimation/classification at the segment level. The specific objectives of this study therefore were (i) to determine whether volume and aboveground biomass estimation and (ii) mapping of 2-class (deciduous-coniferous) and 3-class (deciduous-coniferous-mixed) segments in the Virginia Piedmont successfully can be performed using object-oriented analysis of lidar distributions.

Materials and Methods

Study Area and Data

The 946 ha study area is located in Appomattox Buckingham State Forest (Appomattox County) in the Piedmont physiographic province of Virginia, southeastern U.S.A at 78°41' W, 37°25' N (Figure 1). The mean elevation of the study area is 185 m (606 ft.), with minimum and maximum elevations of 133 m (436 ft.) and 225 m (738 ft.), respectively. Local topography can best be described as gentle rolling slopes and flat terrain. Vegetation is composed of various coniferous (*Pinus taeda, P. virginiana, P. echinata*, and *P. strobus*), deciduous (*Quercus coccinea, Q. alba,* and *Liriodendron tulipifera*), and mixed forests.

Lidar data (2002) were acquired by Spectrum Mapping using the DATIS II (small-footprint, high-density, multiple return) system (Table 1). Field data consisted of 256 mapped basal area plots (BAF; basal area factor 10) on a 16 columns by 16 rows, 201.17 m (10 chains) grid spacing. Field data were collected during the summer, fall, and winter months (May – December) of 2003. Differentially corrected plot location, plot basal area, and diameter at breast height (dbh), height, and species were determined for all plots and tallied trees. A total of 37 plots were located on private land or had basal area values of zero (no type differentiation possible), which left 219 BAF plots for use in the statistical analysis.

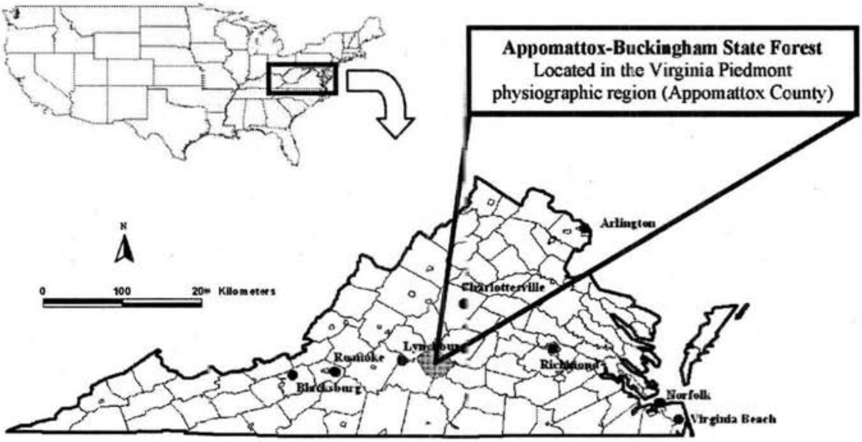

Figure 1. Study Area: Appomattox Buckingham State Forest

Table 1. DATIS II lidar data set characteristics

Characteristic	Specifications
Laser altitude	2,000 m (6,562 ft.) above ground level
Laser scan field-of-view	75° maximum
Swath width and centreline spacing	800 m (2,625 ft.) and 400 m (1,312 ft.)
Scan rate	25 Hz
Laser pulse rate	35 kHz
Scan angle	± 13.5°
Returns	≤ 5
Resolvable distance between returns	0.75 m
Footprint	0.46 m (1.51 ft.)
Spacing across / along track	1 m (3.3 ft.) / 2 m (6.6 ft.)
Accuracy (X,Y,Z)	X,Y: 0.5 m; Z: 0.15 m (X,Y: < 1.6 ft.; Z: < 0.49 ft.)
Post-processed GPS accuracy	< 0.05 m
Wavelength	1,064 nm

Basal area percentages were used to assign plots to 2- and 3-class forest type schemes. A strict majority rule was used to assign "Deciduous" (140 plots) or "Coniferous" (79 plots) types, while a "Mixed" class was used in the 3-class type designation for plots that had less than 90% basal area contribution for either of the two pure types. The 90% cut-off was due to the fact that the 3-class analysis consisted of 112 deciduous, 56 coniferous, and 51 mixed plots, which allowed for volume and biomass model development based on adequate plot samples (> 30). For instance, only 25 (11.4%) of the plots were mixed when a 75% cut-off was used, resulting in a class that was too small for viable statistical analysis.

BAF plots were expanded to a per-hectare basis for each segment. This was done using standard BAF expansion equations (Avery and Burkhart, 1994). Single-tree volume and biomass equations (Saucier and Clark, 1985; Clark *et al.*, 1986; Schroeder *et al.*, 1997; Sharma and Oderwald, 2001) were used, with specific volume and biomass equations for loblolly and other southern pines, as well as for hardwoods. Plots were assigned to the segment in which they were located through post-stratification of selected segmentation results. BAF plot values were averaged in cases where larger segments contained more than one field plot. Descriptive statistics for all basal area plots are given in Table 2.

Table 2. General descriptive information for deciduous, coniferous, and mixed plots

Class	Type	Parameter	Minimum	Maximum	Average	σ
2-class	Deciduous plots (140)	Volume/ha (m^3/ha)	6.94	350.65	157.64	84.14
		Biomass/ha (Mg/ha)	11.11	269.01	113.60	58.60
		Basal area/ha (m^2/ha)	2.30	34.44	16.32	7.84
	Coniferous plots (79)	Volume/ha (m^3/ha)	8.32	350.93	114.49	75.44
		Biomass/ha (Mg/ha)	4.67	155.56	41.47	26.64
		Basal area/ha (m^2/ha)	2.30	36.73	14.24	7.91
3-class	Deciduous plots (112)	Volume/ha (m^3/ha)	6.94	350.65	156.16	89.32
		Biomass/ha (Mg/ha)	11.11	269.01	117.31	62.53
		Basal area/ha (m^2/ha)	2.30	34.44	15.97	8.21
	Coniferous plots (56)	Volume/ha (m^3/ha)	8.32	278.99	100.45	66.42
		Biomass/ha (Mg/ha)	4.67	81.65	33.66	19.95
		Basal area/ha (m^2/ha)	2.30	36.73	13.61	8.11
	Mixed plots (51)	Volume/ha (m^3/ha)	31.68	350.93	156.85	72.60
		Biomass/ha (Mg/ha)	20.06	175.75	81.49	38.93
		Basal area/ha (m^2/ha)	4.59	36.73	16.84	6.68

Lidar Data Processing

A canopy height model (CHM) was derived for subsequent segmentation efforts. First and last, bare-soil lidar returns, as supplied by the data provider, were interpolated to a 1 m spatial resolution grid using regular Kriging (Popescu *et al.,* 2002). Interpolation was performed using Surfer 7.0 software (Golden Software, Inc.). First return data were assigned to top-most canopy heights, while last, vegetation–removed returns were attributed to ground hits. The differenced first- and bare-soil return surface (CHM) was used as input to the eCognition segmentation algorithm. This allowed for extraction of forest segments based on height homogeneity and distinct stand breaks, e.g., roads and slope breaks.

Raw lidar data had to be processed on a per-return basis so that information related to the return hierarchy was retained for use in the distributional approach. Ground hits, regarded as an important component of overall lidar distributional patterns, were removed for each unprocessed lidar return file using Terrascan V. 003.002 (Terrasolid, Inc.) and MicroStation V. 08.00.04.01 (Bentley Systems, Inc.) software.

Non-ground hits, designated as vegetation hits, were normalized for varying terrain elevations (Means *et al.*, 2000) by calculating the difference between the vegetation hit and the bilinear interpolated height of the four corner cells of the DEM cell directly beneath each hit.

Segmentation of the Study Area

The multiresolution, hierarchical eCognition V. 3 algorithm (Definiens) was used to segment the lidar-derived CHM of the study area. The goal was to derive unique structural segments based on lidar data, a structural data type. The eCognition algorithm required Color:Shape and Smoothness:Compactness ratios as input parameters. The Color:Shape ratio was set at 0.8:0.2, based on the recommendation of the developers (Baatz and Schäpe, 2000; eCognition, 2003) and visual inspection of results when using alternative parameter inputs. Segment smoothness was considered more important than shape in a forestry context, since smooth, boundary-following segments are preferable to compact, blocky segments. The Smoothness:Compactness weight combination therefore also was set at 0.8:0.2. eCognition was the chosen segmentation algorithm because of its hierarchical nature, correspondence to input data, and since results from this algorithm have been validated in the natural resources context (Kayitakire *et al.*, 2002; Nugroho *et al.*, 2002; Kressler *et al.*, 2003). One could, however, argue that the segmentation method is subordinate to the utility that resultant objects have to analyses.

Segmentation results were chosen for subsequent analysis based on average segment size. These ranged from average BAF plot area, with radii defined by average tallied tree distance from field-collected BAF plot centres, plus one and two standard deviations, to the segment sizes where within-segment variance was smaller than between-segment variance of the CHM heights. This procedure ensured that segments with limited within-segment variability were selected for analysis. Ten average segment sizes, ranging from 0.035 ha/segment to 3.942 ha/segment, therefore were chosen for subsequent volume and biomass model development and forest type classification. The segmentation result that approximated the average Appomattox stand area, as well as the actual stands, also was included in the analysis. Selection of the stand-corresponding segment size made comparison of segmentation-based modelling and stand-based modelling possible. Vegetation and ground lidar data sets were extracted on a per-segment basis for all segmentation results using ARCGIS V. 8.3 software (ESRI). Resultant data sets were exported to SAS V. 8.02 software (Level 02M0; SAS, Inc.) for subsequent regression analysis.

Regression and Classification Analysis

Distributional parameters were derived only for first and second return vegetation data sets, since multiple segments had missing parameter values for the third through fifth returns. Distributional parameters included the mean, coefficient of variation, kurtosis, maximum, minimum, mode, range, standard error of the mean, skewness, standard deviation, number of observations, height percentile points at 10% intervals of height values, and canopy cover percentiles. Canopy cover percentiles were based on the proportion of first returns smaller than a given percentage of maximum height, e.g., the 10% canopy cover percentile included all first returns lower than 10% of the maximum height for that segment. The ratio of the number of vegetation or ground hits and the total number of lidar hits per segment also was calculated. This was done for second, and third through fifth group vegetation hits, as well as first, second, and third through fifth group ground hits. The vegetation ratio for each segment was calculated as the ratio of the number of vegetation hits per segment and the total hits for that segment. Means *et al.* (2000) has shown that these distribution metrics are useful descriptors of tree volume for 10x10 m grid cells in Douglas-fir, western Oregon stands, while Næsset (2002) used the same approach for 200 m^2 sample plots in Norway spruce and Scots pine stands in southeast Norway. Lidar intensity distributional parameter values for the first and second returns included the intensity mean, median, coefficient of variation, maximum, minimum, range, standard error of the mean, and standard deviation.

Linear regression analysis, with segment volume and biomass as dependent variables, and discriminant classification were performed as follows:

- Variable reduction was done by using a forward selection process with α-values set between 0.075 and 0.350 as significance levels for remaining in the model. The goal was to reduce independent variables from 75 initial variables to fewer than 10 variables in all cases.
- Validation of selected variables was performed using Pearson's correlation coefficients between independent and dependent variables. All variables with correlations of 0.8 or lower were retained, while only the variable with the highest correlation to the dependent variable (volume/biomass/type) was retained in cases where independent variable correlations were higher than 0.8. A value of 0.8 was chosen based on data characteristics, with the knowledge that all lidar-derived variables are height-related, resulting in inherently high correlations. Statistically invalid models (overfitting) were thereby avoided in the final regression step, namely linear regression using Mallow's Cp and adjusted R^2 as selection criteria.
- Mallow's Cp selection takes all combinations of independent variables into account, while calculating a value related to the mean square error of a fitted value for all models (Draper and Smith, 1981; Montgomery *et al.*, 2001). RMSE (where applicable), model simplicity, and model validity also were considered.
- A discriminant classification approach, similar to the one used by van Aardt and Wynne (2001), was applied to the lidar distributional parameters for forest type classification. It has been shown that discriminant approaches, as opposed to non-parametric classifiers, are better suited to the classification of images where training data exhibit distinct overlap in the feature space (Cortijo and De la Blanca, 1999).
- General classification statistics (cross-validation), including overall accuracy, user's and producer's accuracies, and Kappa-statistics (Congalton and Green, 1999), were calculated for all segment sizes. A normalized z-test statistic, derived from the proportion of correctly classified samples ($\alpha = 0.05$; H_0 = no difference between classification accuracies for different segment sizes; H_0 rejected if $z > 1.96$) (Foody, 2004), was used to compare classification outcomes for different average segment sizes. Samples were considered independent, given the variable sample numbers for different segment sizes. The standardized normal test statistic for cases with independent test samples is given by:

$$z = \frac{\frac{x_1}{n_1} - \frac{x_2}{n_2}}{\sqrt{p(1-p)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \qquad [1]$$

where x1, x2 = correctly allocated number in two independent samples of size n_1 and n_2, respectively; $p = (x_1 + x_2)/(n_1 + n_2)$ Foody, 2004)

- Significance tests were performed for both 2- and 3-class classification schemes and were iteratively repeated for the highest and lowest accuracies in ascending order if the two extreme accuracies were significantly different from each other. This was done until no significant differences between the highest accuracy and the other accuracies were found. It should be noted that accuracies could be found significantly different by chance alone, given the number of possible comparisons among twelve segmentation treatments. These tests were based on a standard T-test ($\alpha = 0.05$) with paired samples (average segment size) for differences between classification accuracy means.

Regression analyses and classification were performed for segmentation results of 0.035 ha/segment, 0.091 ha/segment, 0.141 ha/segment, 0.318 ha/segment, 0.642 ha/segment, 0.964 ha/segment, 1.263 ha/segment, 1.885 ha/segment, 2.53 ha/segment, 3.942 ha/segment, 5.632 ha/segment, and the Appomattox Forest stands (5.666 ha/segment). Models were fitted to "Deciduous" and "Coniferous" groups, as well as for all segments combined. Deciduous segments ranged between 61 and 140 segments and coniferous segments between 34 and 79 segments, depending on the average segment size and number of BAF plots that were averaged for larger segment sizes. Analyses were performed on "Deciduous" (43 - 112 segments), "Coniferous" (22 - 56 segments), and "Mixed" (30 - 51 segments) classes in the case of the 3-class forest scheme. Analyses were limited to segments with non-missing values for distributional parameters. The only case with missing distributional parameter values occurred at 0.035 ha/segment (27,050 segments) for the 2-class (16/140 deciduous and 9/79 coniferous missing segments) and 3-class (14/112 deciduous and 1/51 mixed missing segments) forest definitions.

Results and Discussion

The various variable reduction methods were successful in reducing independent variables from the original 75 variables to fewer than 10 in each case. There were no distinct trends in selected variables, with vegetation hits from the 1st and 2nd returns, intensity variables, percentiles, canopy cover percentiles, and ratio variables all well represented across forest types and segmentation treatments. However, intensity mean, maximum, and range variables of both first and second return vegetation hits were especially well represented. This corroborated findings by Means *et al.* (1999) and Brandtberg *et al.* (2003) and indicated that intensity values are of significance in the modelling of forest biophysical parameters. The representation of intensity values (near-infrared: 1,064 nm) as part of variables selected for classification was especially evident, with the median intensity of first return vegetation heights present in all data sets. Other studies have found near-infrared wavelengths to be highly discriminant among vegetation types, especially between deciduous and coniferous species (Martin et al., 1998; van Aardt and Wynne, 2001). The broad range of selected variables, in general, build a strong case for the use of multiple return lidar data and associated intensity-per-return when modelling forest biophysical parameters. This might be especially critical in areas that contain forests with high variability in site, growth, and composition. Second returns, which contribute to defining height levels other than the topmost canopy and describe aspects of forest vertical structure besides canopy height, also were prevalent.

Figure 2 indicates that lidar height distributions were representative of BAF plot measurements. Low-volume segments exhibited either fewer hits at taller tree heights, or generally shorter trees than segments with higher volume-per-hectare measurements, while distributions for lower volume-per-hectare segments also were skewed to the right, and *vice versa*. Distributions such as these served to illustrate why variables such as percentile, skewness, canopy cover, and kurtosis variables were selected. Figure 3, on the other hand, shows an example of deciduous and coniferous segments with similar volume-per-hectare values across increasing average segment sizes. Distributions visually remained similar in shape as average segment size increased. The increase of upper- and lower tail values in the case of deciduous segments was attributed to trees of above-average height and undergrowth, respectively, commonly found in an uneven-aged stand.

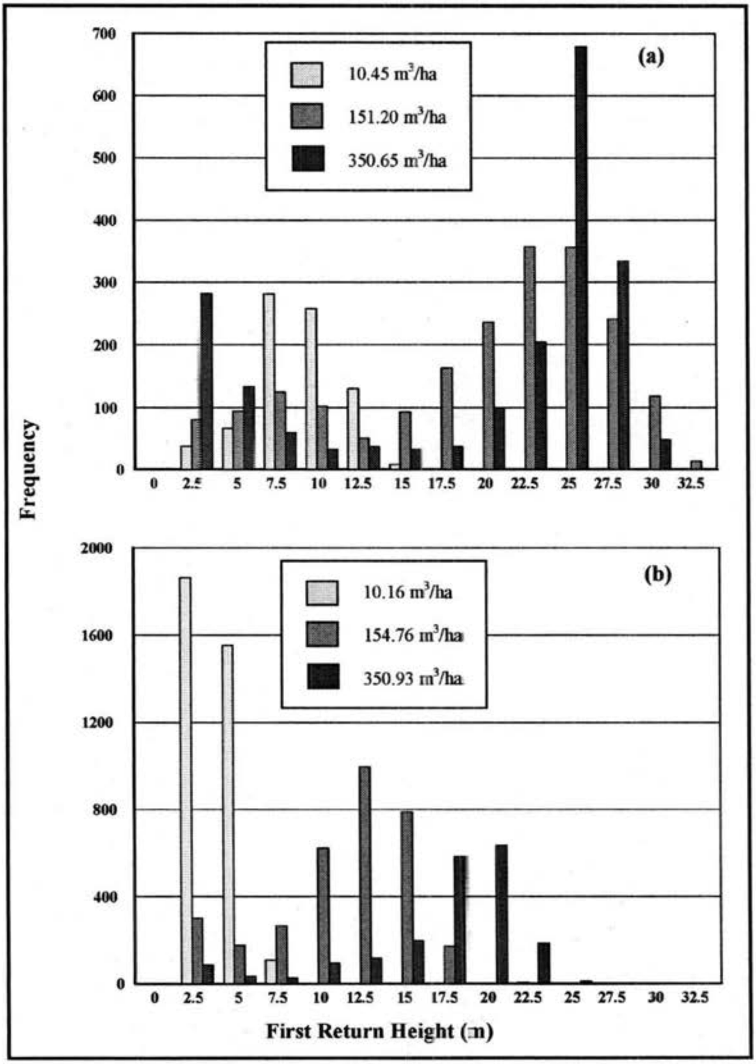

Figure 2. (a) Deciduous and (b) coniferous per-object (0.035 ha/object) histogram plots for lidar first return vegetation hits across a range of field-measured volume-per-hectare

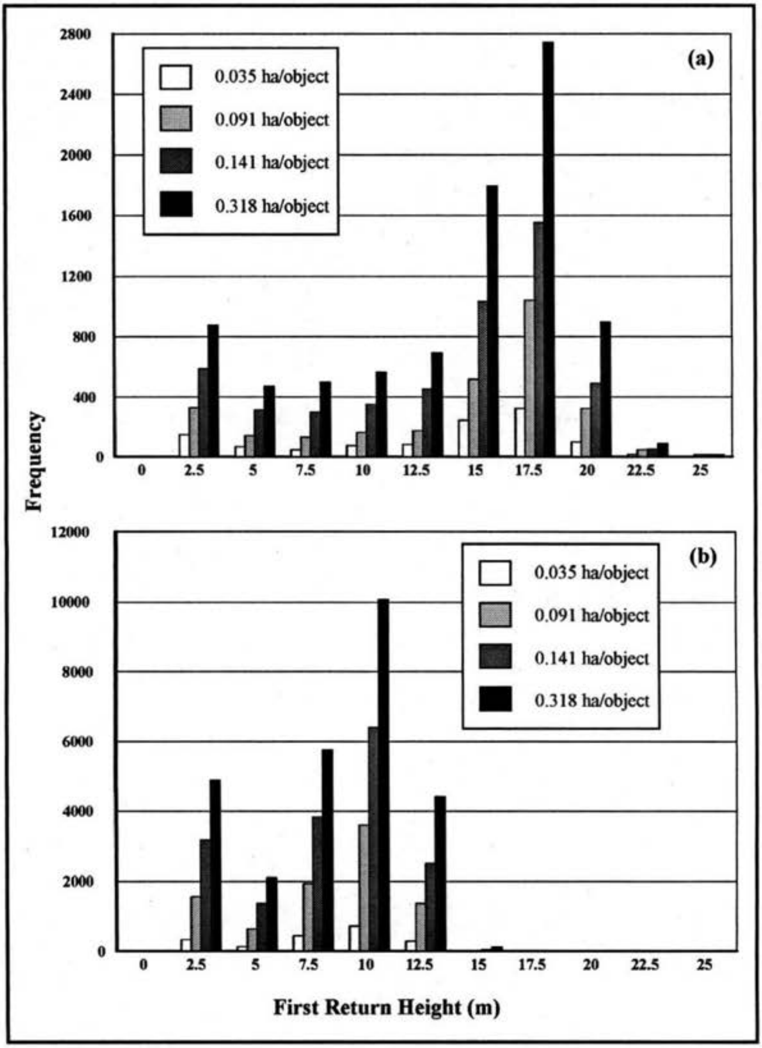

Figure 3. (a) Deciduous and (b) coniferous first return, vegetation height distributions for variable size objects with 153.02 m^3/ha and 159.50 m^3/ha volume, respectively

Table 3 shows the best performing models (adjusted R^2) and associated descriptive statistics for 2- and 3-class forest schemes and the Appomattox stands. Residual behaviour for the best performing 2-class volume and biomass models, 5.632 ha/segment and 0.091 ha/segment, respectively, are shown in Figures 4 and 5. The majority of models could be limited to 5 or fewer independent variables, except for coniferous volume and biomass models, which was attributed to increased variation present in the case of coniferous segments. Highly variable stands are common in the Virginia Piedmont, since pure forest stands in public ownership are relatively limited. A deciduous-coniferous stand likely added more variability to the coniferous group, whereas mixed deciduous stands have similar characteristics.

Table 3. Volume and biomass models with the highest adjusted R^2 values for volume and biomass modelling for 2- and 3-class schemes

Model			Segment adjusted R^2	Stand adjusted R^2	Segment RMSE (m^3/ha or Mg/ha)	Stand RMSE (m^3/ha or Mg/ha)	Segment size (ha)
2-class Volume	D	262.37385 + 19.92957 P_Veg2_70 + 208.14833 ZeroNgrnd3_5ratio -387.67008 Canopy80P	0.59	0.44	51.15	63.56	5.632
	C	458.52340 -4.18276 ModeVeg1 + 15.43186 P_Veg1_40 -5.59238 RangeVeg2 -0.36692 StdInt2	0.66	0.48	38.03	55.61	5.632
	A	309.84855 + 0.29731 CVVeg1 + 13.66277 MinVeg1 + 11.12989 P_Veg1_50 - 0.14246 MedianInt1 -432.13149 MinVeg2 + 55.39894 Canopy30P	0.59	0.42	53.75	62.36	0.091
2-class Biomass	D	271644 + 13993 P_Veg2_75 -286090 ZeroNVeg2ratio -75577 Canopy70P	0.58	0.43	37.41	45.84	5.632
	C	185653 + 2262.86568 P_Veg1_20 - 29.74409 MedianInt1 + 3533.08872 P_Veg2_40 -91682 Vegratio -20694 Canopy70P	0.59	0.40	17.15	19.45	0.091
	A	343583 -1370.95705 CVInt1 + 316.85290 CVVeg2 + 15082 P_Veg2_75 -132911 ZeroNVeg3_5ratio -314776 Canopy80P	0.66	0.46	33.14	41.18	5.632
3-class Volume	D	-31.77814 + 19.67658 P_Veg2_70	0.62	0.46	55.98	68.16	5.632
	C	303.72815 + 15.71060 P_Veg1_30 - 1.78646 StdMeanInt2 -0.59669 StdInt2 + 0.06230 MedianInt2 + 737.63803 ZeroNgrnd1ratio + 146.83730 Canopy70P	0.67	0.73	38.24	40.08	0.642
	M	255.71328 -3.17225 ModeVeg1 + 1.54155 MinInt1 -5.84654 StdMeanInt2 -444.06932 ZeroNgrnd1ratio -111.50951 Canopy10P - 145.92581 Canopy50P -413.21393 Canopy80P	0.74	0.57	28.02	46.68	5.632
3-class Biomass	D	-134083 + 16205 P_Veg2_75 + 2460.48834 StdMeanInt2 + 159205 ZeroNgrnd3_5ratio	0.62	0.46	39.48	48.61	5.632
	C	-84498 + 6498.76606 P_Veg1_25 + 44.56384 MedianInt1 -81.96051 StdInt2 + 78560 ZeroNgrnd3_5ratio	0.63	0.70	12.06	12.56	3.942
	M	1493940 -601912 MinVeg1 + 4984.27818 P_Veg1_10 -370.80540 RangeInt1 + 84546 ZeroNVeg3_5ratio -612016 Canopy80P	0.79	0.68	16.32	20.29	5.632

Veg = Vegetation lidar hit; Grnd = Ground lidar hit; Int = Intensity associated with lidar hit; Veg1, 2, or 3_5 = 1st, 2nd, or grouped 3rd through 5th returns; P_..._10-90 = Percentiles; CV = Coefficient of variation; StdMean = Standard error of the mean; Std = Standard deviation; Canopy10-90 = Canopy cover percentiles; N..ratio = Vegetation or ground hits as a ratio of return totals; Vegratio = Vegetation hits as a ratio of total hits

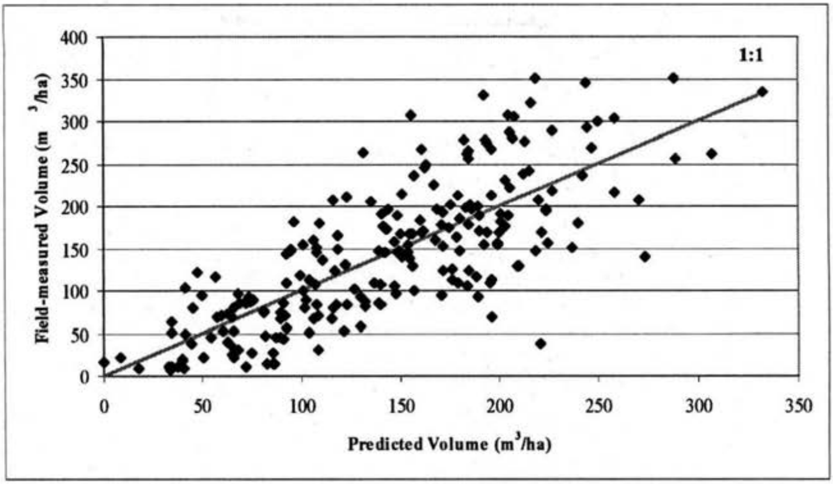

Figure 4. Two-class volume model (0.091 ha/segment): Field-measured vs. predicted volume/ha values for all plots combined (adjusted $R^2 = 0.59$)

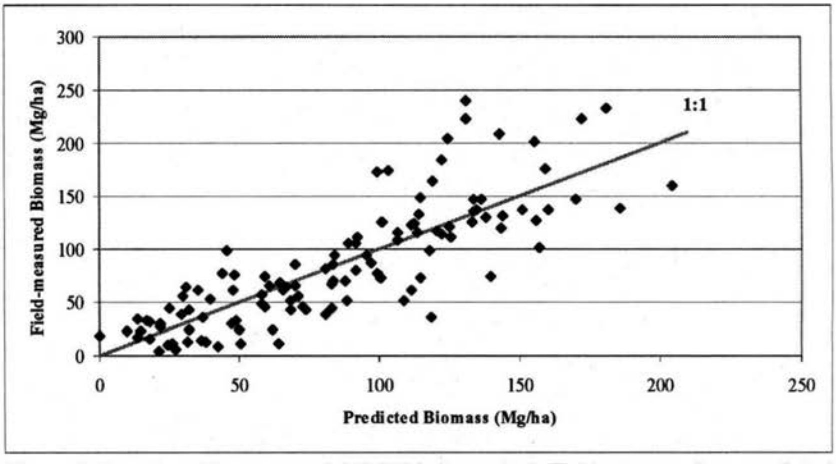

Figure 5. Two-class biomass model (5.632 ha/segment): Field-measured vs. predicted biomass/ha values and residuals for all plots combined (adjusted $R^2 = 0.66$)

Adjusted R^2 values for coniferous species volume were lower than those found in two comparable studies by Means *et al.* (2000; adjusted R^2) and Næsset (2002; R^2), both of which used a grid-cell based lidar distribution approach to volume modelling. The range of forest volume and growth-types, low single species variability, averaging effect of plot-based measurements, and fixed plot measurements that directly corresponded with lidar plot boundaries could have contributed to higher R^2 values in these two studies. RMSE values, on the other hand, were comparable to those found by Means *et al.* (2000; 73 m^3/ha, old-growth plots excluded) and Næsset (2002; 18.3 – 31.9 m^3/ha). This indicated that a segment-based approach has potential for extension to operational application, since it could be argued that RMSE values (estimate and precision) operationally are more important than R^2 values.

Coniferous adjusted R^2 values for volume in this study ranged from 0.46 (2-class; 1.885 ha/segment) to as high as 0.67 (3-class; 0.642 ha/segment. Lower adjusted R^2 values were attributed to a narrower range in volume and biomass-per-hectare values for this study (6.94 – 350 m^3/ha; 4.67 – 269.01 Mg/ha). This was due to more intrinsic variability found in this narrower range, while an increased observed range with lower variability likely will result in better model fit statistics. Plot sampling technique also was a potential source of variability. Unlike the complete grid-cell inventory by Means *et al.* (2000), not every tree within a segment was measured in this approach. Although BAF plot measurement is an established forestry inventory technique, it does not account for all trees on a given plot. Each segment was assumed to be represented by its enclosed BAF plot. This assumption also could have impacted the results.

Adjusted R^2 values for deciduous types were significantly higher than those calculated for a plot-level lidar study in the same area Popescu *et al.* (2004). Values of 0.59 (2-class; 5.632 ha/segment) and 0.62 (3-class; 5.632 ha/segment) compared well to an unadjusted R^2 of 0.36 found by Popescu *et al.* (2004). This hinted at the potential of a segment-based approach for deciduous volume- and biomass modelling. The diverse structure of deciduous growth therefore lends itself to segment-based approaches, while small-radius plot-level deciduous volume and biomass modelling are problematic due to stand variability and the large size (crown width) of old-growth deciduous trees. It was concluded that segments encapsulated deciduous units better than a fixed plot-based approach.

Lower coniferous adjusted R^2 values found in this study were attributed to the diversity in coniferous segments, where a 2-class (deciduous-coniferous) modelling approach included segments with only marginally more coniferous than deciduous basal area. The associated increase in within-segment variability led to reduced adjusted R^2 values. However, there was no distinct difference between 2- and 3-class model metrics. Deciduous adjusted R^2 values ranged between 0.51 and 0.59 (2-class) and 0.52 and 0.62 (3-class), while coniferous values ranged between 0.46 and 0.66 (2-class) and 0.47 and 0.67 (3-class). Adjusted R^2 values for the mixed class in the 3-class scheme ranged between 0.43 and 0.74. It subsequently was concluded that a simpler, 2-class approach was preferable for the study area, while a 3-class scheme remains optional to the user, based on operational implications.

Model fit statistics generally deteriorated with increasing average segment size, although distinct differences among segment sizes were not evident. The exception was the 5.632 ha/segmentation result, with high adjusted R^2 values for coniferous ($R^2 \approx 0.66$), deciduous ($R^2 \approx 0.59$), and combined models ($R^2 \approx 0.54$). These relatively high values were attributed to better representation of BAF plot data at the larger segment size, while within-segment variability remained adequately small. The segment sizes between 0.091 ha/segment and 3.942 ha/segment, however, exhibited a general decreasing trend in adjusted R^2 values and an increasing trend in RMSE values. The lack of distinct differences among average segment sizes is an artefact of the hierarchical segmentation algorithm - within-segment variance was minimized at smaller segment size levels, with the hierarchical structure not further contributing in reducing within-segment variance. Results for the operational Appomattox stands, however, were distinctly lower than those found in the case of segmentation applications. Deciduous adjusted R^2 and RMSE values for volume modelling were 0.44 and 63.56 m^3/ha, while values for coniferous stands were 0.48 and 55.61 m^3/ha, respectively. Overall modelling results were 0.42 and 62.36 m^3/ha, which indicated that segmentation has distinct advantages over current defined stands in the study area. Relatively high adjusted R^2 values for 3-class coniferous volume ($R^2 \approx 0.73$) and biomass ($R^2 \approx 0.70$) were attributed to stand definition being based on homogenous, even-aged coniferous stands, but came at the cost of low adjusted R^2 values for deciduous stands.

Accuracies for the 2-class discriminant classification approach are shown in Figure 6. Overall accuracies ranged from 81.4% to 89.2% for the 2-class, deciduous-coniferous classification. It was concluded from the producer's and user's accuracies for the deciduous and coniferous classes that deciduous class assignment was more reliable than for coniferous objects. Kappa statistics for the 2-class classification ranged between 60.2% and 76.7%. Although overall and Kappa statistics peaked at 1.885 ha/segment, significant differences were only found between 1.885 ha/segment (89.2%) and 0.035 ha/segment (82.2%) and 0.964 ha/segment (81.4%) ($\alpha = 0.05$; $z = 1.96$). Overall accuracies for the 3-class, deciduous-coniferous-mixed classification ranged from 61.6% to 70.8%, while the Kappa statistics varied between 40.4% and 53.5%, with peak values again found at the 1.885 ha/segment segment-level. No significant differences were found in the case of the 3-class classification scheme. Significance testing indicated that there were minor to non-existing differences within the 2-class and 3-class schemes, but the T-test revealed a significance difference between the mean classification accuracies for the 2- and 3-class schemes at $\alpha = 0.05$ ($p < 0.001$). Producer's accuracies generally were highest for coniferous, followed by deciduous and mixed objects. User's accuracies typically decreased from deciduous to coniferous to mixed object classification.

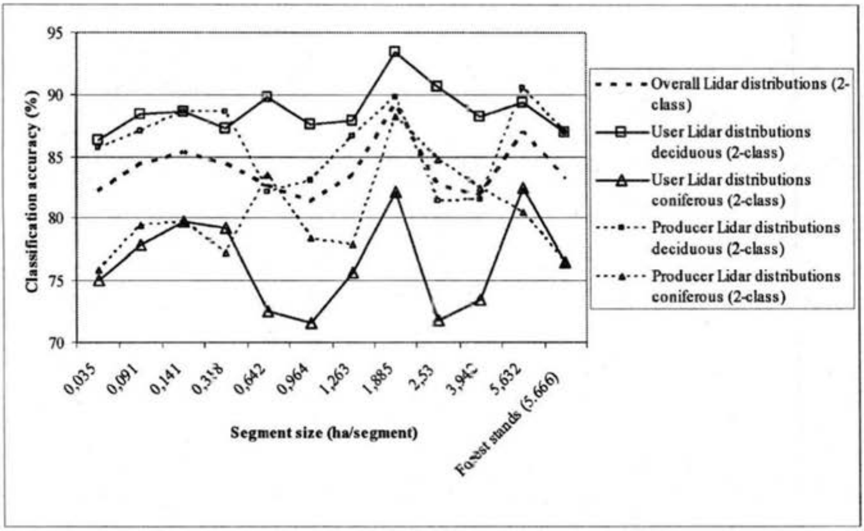

Figure 6. Overall, producer's, and user's classification accuracies for the 2-class classification based on lidar and CHM distributions

The following findings also are worth mentioning

(i) Maximum classification accuracies generally were not statistical improvements over accuracy results for other segment sizes, indicating that average segment size did not influence classification for the study area. This result again was attributed to the hierarchical nature of the segmentation algorithm which merges smaller, homogenous segments to form larger segments at higher hierarchical levels.
(ii) The significance of the highest accuracies for the 2-class vs. 3-class scheme indicated that a deciduous-coniferous forest delineation was better suited to the Virginia Piedmont, as opposed to the inclusion of a mixed category as well. This was attributed to the forest types found in the study area, with most of the stands represented by one distinct taxonomic group and few completely mixed stands. Only 25 (11.4%) of the BAF plots were inherently part of a mixed class when a 75% basal area purity cut-off was used, further corroborating this conclusion.
(iii) The lack of a significant difference between segment-based classification and classification based on existing forest stands in the study area was ascribed to the definition of forest stands in an operational context. Forest stands are more often defined by their species make-up (coniferous-deciduous-mixed) than by their height structure (even-aged vs. all-aged). This effectively made the Appomattox stand map a thematic species map However, classification accuracies were very encouraging if one considers that classification of segments was based on forest structure and not forest type definition.

Conclusions

Deciduous and coniferous volume and biomass modelling results based on object-oriented (segment) analysis were very promising, even though coniferous and combined adjusted R^2 values for volume and biomass were lower than those found in other published studies. Lower coniferous R^2 values were attributed in part to a smaller range of volume and biomass observed values, as well as to the inherent variability found in Virginia Piedmont forests. Adjusted R^2 values for deciduous segments were higher than those found for a comparable, plot-level study in the same area. This result indicated that a segment-level approach to deciduous volume and biomass modelling is a potential improvement over plot-based approaches, while the lack of modelling differences across varying segment sizes was attributed to the hierarchical nature of the segmentation algorithm. Segment-based modelling efforts were distinctly better than those found for existing, operational forest stands in the study area. This was attributed to the larger within-stand height variation in the case of existing stands when compared to the variation found within homogenous segments. RMSE values compared favourably with those found in other distributional modelling studies. Low RMSE values indicated that models could find applicability in an operational context, even when low R^2 values were considered.

Modelling and classification variables spanned the whole spectrum of possibilities, from general mean and range height values, to more abstract coefficient of variation and standard deviation-type variables. Regular and canopy cover percentiles also were well represented. The inclusion of intensity variables was interesting since few studies have included intensity values as part of forest biophysical modelling, even though these variables have proven to be useful for forest classification attempts. The wide range of variables indicated that sophisticated lidar scanners, capable of recording multiple returns and intensity associated with each lidar return, might well be necessary for effective modelling of variation in more complex forests.

Object-oriented classification results, as high as 89.2% (2-class scheme), were promising when one considers the type of input data and the variability in natural ecosystems. The absence of a decreasing classification accuracy trend at larger segment sizes again was attributed to the hierarchical nature of the segmentation algorithm. Stand-based classification also was not significantly different from segment-based approaches, which was attributed to the definition of operational forest stands on a per-species or type basis.

The increased classification accuracies for the 2-class forest type definition (deciduous-coniferous), as opposed to a 3-class (deciduous-coniferous-mixed) approach, was ascribed to high basal area percentages, in terms of deciduous or coniferous types, that had to be used for mixed class definition. This mixed class subsequently was closely associated with the deciduous group, resulting in reduced deciduous producer's accuracies. Higher producer's accuracies for the coniferous class (3-class scheme) indicated that the deciduous-mixed classes were main contributors to lower overall accuracies with increased between-group confusion.

Forest managers strive to obtain estimates of volume-by-type with high economical and statistical efficiency. The approach presented here would constitute a stand-alone forest inventory based on remote sensing inputs, but further research is needed to determine the associated precision and cost. The hierarchical nature of object-oriented approaches also is amenable to recombination of object-level results to any required scale. Lastly, the simplicity of the approach is attractive, since only per-object height/intensity values are potentially required. The synoptic coverage provided by remote sensing technologies could enable extension to net primary productivity modelling efforts, while local, sampling-based applications are not excluded.

Acknowledgements

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FOREST RESOURCE ASSESSMENT USING STOCHASTIC GEOMETRY

Guillaume Perrin[1], Xavier Descombes[1], Josiane Zerubia[1], Jean-Guy Boureau[2]
[1]Ariana Research Group – INRIA, France
[2]IFN, France
E-mail : Guillaume.Perrin@inria.fr

Abstract

Aerial and satellite imagery has a key role to play in natural resource management, especially in forestry application. The submetric resolution of the data enables to study forests at the scale of trees, and opens up new prospects to inventories in their will to get accurate assessment of the resources, with some automatic algorithms when possible. In this paper, we present a method to extract tree crowns from high resolution aerial Color Infrared images (CIR) of forests using marked point processes. Our approach consists in modelling the trees in the forestry images as random configurations of ellipses or ellipsoids, whose points are the positions of the stems and marks their geometric features. The goal is to find the best configuration of objects, from which 2D and 3D vegetation resource parameters can be extracted. Results are shown on aerial CIR images of plantations and isolated trees provided by the French National Forest Inventory (IFN).

Keywords: remote sensing, aerial photography, image analysis, tree crown extraction, probabilistic models

Introduction

The French National Forest Inventory (IFN) carries out the continuous survey of the forest resources in France. Firstly, the inventory focuses on the estimation of the surfaces pertaining to the main categories of land cover, and on the estimation of the available wood resources in production forests : volumes and yields, by species, stand types and product categories. Another objective complies with environmental concerns. The method implemented by IFN relies on an extensive use of aerial photographs : each metropolitan department is the target of a complete aerial cover, renewed approximately every 10 years. The IFN photographic library, built from the beginning of the 1960s until today, hosts more than 400,000 pictures representing almost 3.5 times the total area of France [6]. But this method is currently evolving. IFN tends to use the Orthophoto Database of the French Mapping Institute (IGN) with their 4 bands digital camera (colour and near infrared) and to explore 10% of each department each year (instead of 1 department every 10 years). This change has been done in order to get yearly some representative statistics on forest resources in France, and to be able to react more rapidly to exceptional events (storm damage, fires, ...).

The aerial photographs, once scanned to a resolution of 50cm/pixel, represent precious data for the image processing community. The aim is to design some algorithms which would give automatically or semi-automatically some resource parameters by analysing the image, and extracting its components (trees, stands, ...). Moreover, the color, the shape and the texture information of the trees could be used in the algorithm to infer the species of the tree. Then, statistics such as the number of trees, their size or the density of the stands could be obtained. These parameters could give a more accurate evaluation of the resources, and complete the work of human operators in forest monitoring.

Different algorithms for segmenting individual tree crowns without information on Digital Elevation Model have been proposed over the past few years. For CIR images, some tools are based on a pixel-based method and give the delineation of the tree crowns, such as the valley following algorithm [5], or the region growing model [3]. Other tools use an object-based method, by modelling a synthetic tree crown template to find the tree top positions [7].

In this paper, we propose to use marked point processes to extract the tree crowns. They enable to model an unknown number of geometrical objects in a scene within a stochastic framework. They are increasingly exploited in image processing because they can manage both some prior information about the interaction between the features to be extracted (alignments, overlapping, ...), and some data information to fit them in the image. Marked point processes have been widely used in forestry statistics inference [8].

In a first part we remind the methodology of this approach. Then, we detail the data energy that we propose to extract some 2D and 3D resource parameters from forestry images. Some results obtained on CIR images provided by the French National Forest Inventory (IFN) are presented and commented in the last part of this paper.

Methodology

Marked point processes

We model the high resolution forestry data as composed of trees whose positions and attributes in the image (here the only attributes are size parameters, but it could also be the species, the age, the owner of the stand, ...) are some realization of a probabilistic model *X*, called a marked point process. *X* is a random variable whose realizations are random configurations of objects belonging to a set space S. The objects of the process, which account for the trees, are supposed to be geometric features (ellipses or ellipsoids). This simplification enables us to work on a low dimension set space in order to accelerate the optimization process, and is adapted to deal with the tree crown format viewed from above. Each object of S is defined by its position in the position set space P (continuous domain given by the image location), and the set of its marks, or attributes, in K. We note Ψ the space of all configurations of a finite number of objects.

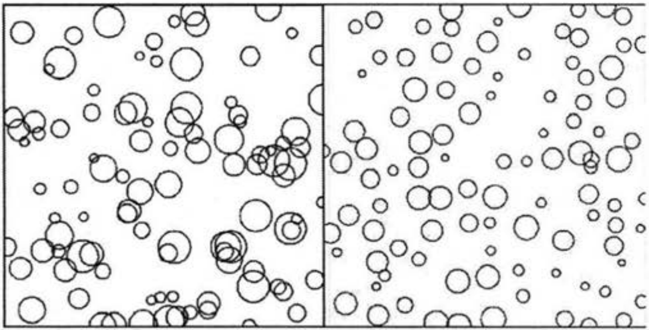

Figure 1 : Left : Poisson process of discs (random configuration of discs). Right : Strauss process of discs (penalization of intersections).

Some examples of marked point processes are given in Figure 1. The most common one is the homogeneous Poisson process of intensity $\lambda(.)$, which uses the Poisson law of parameter $\lambda(S)$ to get the number of objects, and then distributes them randomly in S according to the intensity $\lambda(.)$. Another process quite useful in forestry is the Strauss process, which penalizes intersection between objects. Then, a random configuration will tend to have less intersections than in the Poisson process case. See [1,14] for more mathematical details on point processes, [2,13] for some applications in image processing.

Objects of interest

The objects of the marked point process are some geometric features that should extract the trees from high resolution images. Depending on the kind of images we are dealing with, a 2D model or a 3D model could be chosen.

The 2D model, used to extract tree crowns from plantations and dense areas, consists of a marked point process of ellipses. The associated set space S_2 is :

$$S_2 = P \times K = [0, \mathrm{X_M}] \times [0, \mathrm{Y_M}] \times [\mathrm{a_m}, \mathrm{a_M}] \times [\mathrm{b_m}, \mathrm{b_M}] \times [0, \pi[$$

where X_M and Y_M are respectively the width and the height of the given image, (a_m, a_M) and (b_m, b_M) respectively the minimum and the maximum semimajor axis and semiminor axis, and $[0,\pi[$ the orientation of the objects (see Figure 2, left).

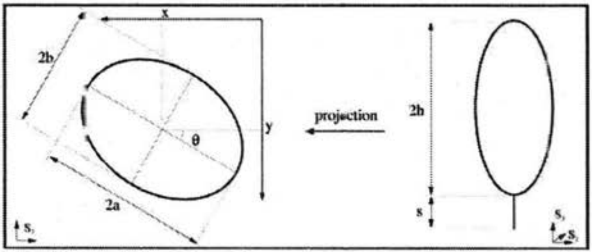

Figure 2 : Left : position and marks of an ellipse of S_2.
Right : additional mark for an ellipsoid of S_3.

The 3D model, used to extract isolated tree crowns or border tree crowns in plantations, considers the height of the trees (available thanks to the tree shadow and the given position of the sun) and deals with ellipsoids. The associated state space S_3 is :

$$S_3 = S_2 \times [\mathrm{h}_m, \mathrm{h}_M]$$

where (h_m, h_M) are the minimum and the maximum semi height axis of the ellipsoid. Moreover, in order not to add a new irrelevant parameter, we consider that the size of the shank s is fixed (see Figure 2, right)

Probability distribution of *X*

The stochastic process X is fully defined by its probability distribution $P_X(.)$. We write this distribution with respect to the Poisson measure $\mu(.\ )$ of intensity $\lambda(.)$, pondered by an energy U(x) defined for each configuration of objects x. This energy will be minimized on Ψ by the seeked tree crown extraction, ie the solution. Using the Gibbs energy formulation, $P_X(.)$.can be written as :

$$P_X(dx) = \frac{1}{Z}\exp(-U(x))\mu(dx)$$

where Z is a normalizing constant. The energy of a configuration takes into account the interactions between the geometric objects (the prior energy $U_p(x)$), and the way they fit to the data (the data energy $U_d(x)$). The latter one will be fully developed in this paper :

$$U(x) = U_p(x) + U_d(x)$$

Energy

The prior term $U_p(x)$ formulates the knowledge we have on the way the objects interact. Its goal is also to make the objects reproduce the behaviour of the trees. Then, we added in this energy some repulsion between two overlapping objects, depending on the intersection area, and in the case of plantation images we include some attraction when there are some regular alignments. These two properties are described in Figure 3. See\bib{Ferrin05} for more details about the prior term.

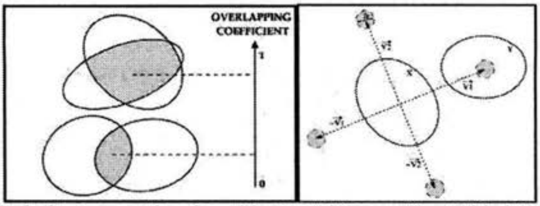

Figure 3 : Left : two overlapping objects and the quality of this interaction. Right : The four regions around one objects where some alignments can appear.

In this paper we present a non Bayesian model for the data energy. This one is calculated at the object level. The global data energy of a configuration x is :

$$U_d(x) = \gamma_d \sum_{u \in x} U_d(u)$$

where $\gamma_d>0$ and $U_d(u) \in [-1,1]$. An object u will be attractive and therefore favoured if its data energy is negative, and repulsive if its data energy is positive. See some examples of attractive and repulsive objects in Figure 4.

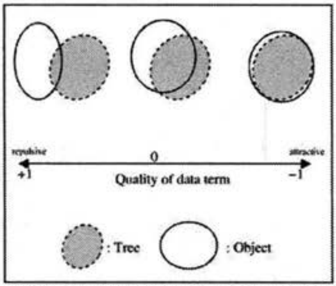

Figure 4 : Quality of the data term of one object. Negative data term are favoured (because the algorithm minimizes the global energy), while positive data term are penalized.

Simulation and Optimization

We use a Reversible Jump Markov Chain Monte Carlo algorithm [4] coupled with a Simulated Annealing in order to find the configuration which minimizes the energy U(x) (ie the seeked extraction). It is an iterative algorithm where at each iteration k, a perturbation is proposed to the current configuration at temperature T(k). This perturbation, or move, is accepted or rejected with a probability which insures the convergence of the algorithm. The cooling schedule of the temperature is based on an heuristic which gives better results in a fixed number of iterations (finite time simulations) than classical schemes (see [9] for more details).

The set of moves proposed to the current configuration contains birth and death (ie add or remove one object), translation, dilation or rotation of one object, split and merge between two overlapping objects, and birth and death in a neighbourhood (useful in the plantations where we expect some alignments between objects). Some of these moves are presented in Figure 5.

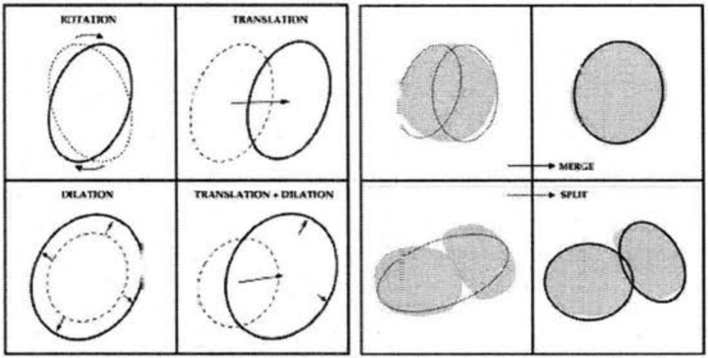

Figure 5 : Left : non jumping kernels (change of one object attributes). Right : split and merge of ellipses.

In practice, the algorithm could start with a void configuration. During the process, objects appear and disappear, move in the image domain, and the lower the temperature is, the better they are located. The final configuration represents the tree crown extraction.

Description of the data energy

Images

The French Forest Inventory hosts some CIR aerial photographs of forests which cover the whole territory. The scale of the photographs which, from one county to the other, can vary from 1/15,000 to 1/25,000 is generally around 1/20,000. The wavelengths of the three bands are between 520nm and 900nm approximately. The photographs are taken between June and September. This choice is justified by generally favourable weather conditions in summer, some limited shadows, and the period of full chlorophyll activity for all plant species. In CIR images, healthy vegetation presents some peaks in the near infrared wavelength band. Moreover, the infrared reflectance changes between different species and at different periods of the year. That is why the information given by the radiometry is useful to detect and classify the trees. See [6] for more details.

Some of the photographs were scanned at a resolution of 50cm/pixel in the image. In our algorithm dedicated to tree crown extraction, another application of the infrared sensitivity of the vegetation is to use the Normalized Difference Vegetation Index (NDVI) to ponder the intensity $\lambda(.)$ of the reference Poisson process. The stochastic process becomes inhomogeneous by giving more weight to some objects located in high NDVI areas, which is what we want because the trees will be located in these areas (see Figure 6).

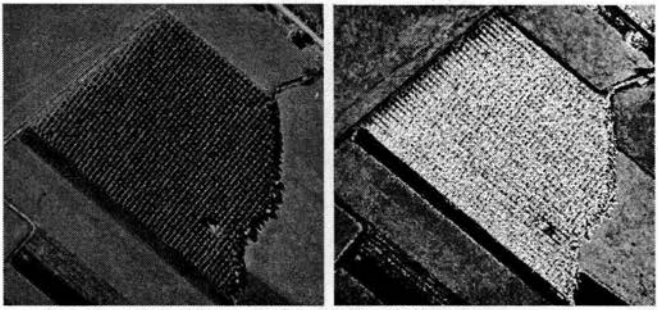

Figure 6 : Left : original image ©IFN. Right : NDVI, birth proposition map (the brighter the pixel is, the more births will be proposed).

In the different models for the data energy, we assume that the ground is flat, and that the extracted trees are close to the Nadir point, in order not to take into account the induced deformation of the objects. If not specified, the computations involving radiometry in the following are done on the near infrared band.

2D Model

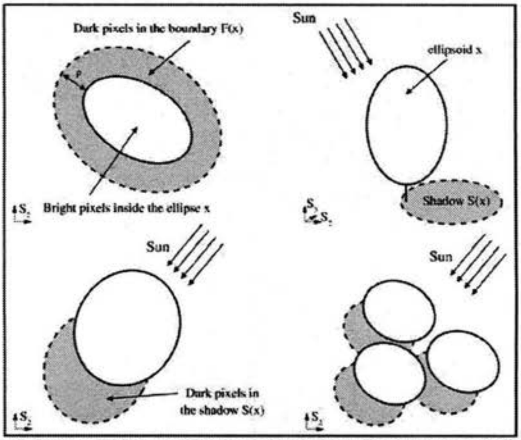

Figure 7 : Top left : an ellipse and its boundary F(x). Top right : an ellipsoid and its shadow S(u,x), 3D view. Bottom left : an ellipsoid and its shadow S(u,x), 2D view. Bottom right : competition between some ellipsoids and their respective shadows.

In dense areas (plantations for instance), the tree crowns can be detected thanks to their radiometry (picks in the near infrared band) and some shadow that surrounds them. These dark pixels around the trees are used in all the existing segmentation and delineation algorithms. Thus, we define the boundary of an ellipse F(u), as the neighbourhood of u included in a concentric ellipse (Figure 7, top left). This boundary stands for the shadow that comes from the tree itself and from its neighbours. Then, we calculate the Bhattacharya distance $d_B(u,F(u))$ between the reflectance distributions of the object and its boundary. The more similar the reflectance distributions are, the lower the distance is. Trees also tend to have a high d_B value. Then, we define the data energy $U_d(u)$ as :

$$U_d(u) = Q_b(d_B(u, F(u)))$$

where $Q_b(d_B) \in [-1,1]$ is a quality function.

The quality function is designed to favour well located objects (negative energy) and to penalize badly located objects (positive energy). As shown in Figure 4, it gives a negative value to high Bhattacharya distance (high difference of reflectance between the object and its boundary : well located objects) and positive value otherwise (low difference of reflectance between the object and its boundary : badly located objects). See [12] for more details on the quality function.

3D Model

In mixed height stands or in the case of isolated trees, individual tree shadows can be observed. Knowing where and when the photograph has been taken, we can get the position of the sun and deduce the height of the trees (for isolated trees). This new feature is useful to calculate more precisely some statistics at the scale of the stand such as the wood volume, or to retrieve some physiological parameters from the tree. The dark pixels are now searched in the tree own shadow, result of the projection of the ellipsoid on P in the direction of the sun light (cf Figure 7, top right and bottom left). We define S(u,x), the shadow of an ellipsoid u belonging to the configuration x, as the set of P containing this projection and excluding all the orthogonal projections of the other objects in x : then, the final shadow excludes some parts of the original projection hidden by other objects (cf Figure 7, bottom right). Note that if the sun cannot be located, its orientation could become a new parameter to be estimated in the algorithm.

To calculate the data energy of one ellipsoid u, we first calculate the Bhattacharya distance $d_B(u,S(u))$ between the reflectance distributions of the object and its shadow, and its quality $Q_b(d_B) \in [-1,1]$. Unfortunately, this is not sufficient to segment correctly the objects : ellipsoids could have a good d_B value without delineating correctly the border of the tree. As we do not look at dark pixels on the opposite side of the shadow, nothing stretches them. To solve this problem, we add a gradient $Q_g(G(u, S(u,x))) \in [-1,1]$ which tends to maximize the gradient on all the contour of both the object u and its shadow S(u), and we multiply these two terms by a volume parameter $V(u) \in [-1,1]$ which favours big objects. Without this volume term, the algorithm tends to prefer several small objects than one big object. A texture parameter $Q_t(T(u)) \in [-1,1]$ can be added to extract predefined species in a mixed stand.

Finally, the data energy is :

$$U_d(u) = V(u)\{\alpha_b Q_b(d_B(u, F(u))) + \alpha_g Q_g(G(u, S(u,x)))\} + \alpha_t T(u) \in [-1,1]$$

where $\alpha_b + \alpha_g + \alpha_t = 1$ are some positive weights.

Results

In this part we present some results obtained with our 2D and 3D data energy models (Figures 8 and 9).

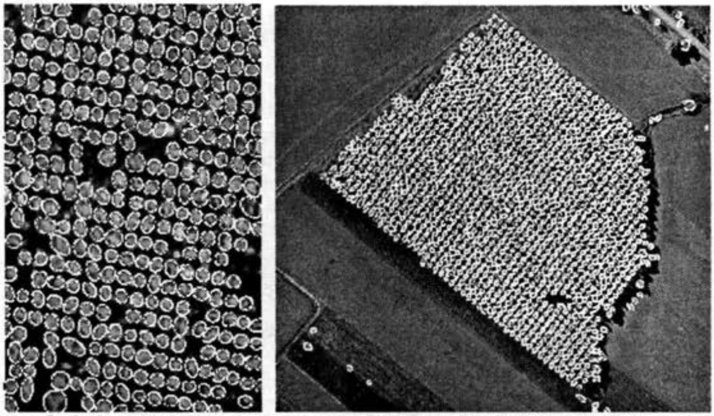

Figure 8 : Left : extraction result on a zoom on a poplar plantation (image size : 220 x 140). Right : extraction result on a poplar plantation in its landscape (image size : 510 x 540).

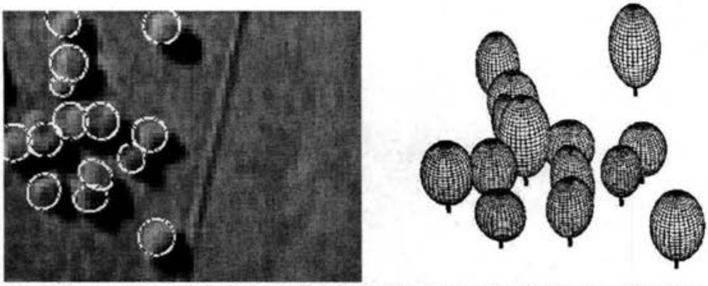

Figure 9 : Left : isolated trees extraction with the 3D model on a 65 x 85 image ©IFN. Right : 3D reconstruction.

The first image is a zoom on a plantation, and contains approximately 300 trees. The second one represents a complete plantation containing more than 1300 trees and its neighbourhood (7 hectares). The last one contains 14 isolated trees. The poplars extraction has been performed with the 2D model (Figure 8), while the isolated trees have been extracted with the 3D model (Figure 8). Note that the 3D model could be used for the border trees of the plantation too: in a post processing, we could obtain the height of these trees thanks to their shadows, and then we could get an estimation of the trees on the whole plantation (supposing that the height is homogeneous) and also the wood volume.

Computation took a couple of minutes for each result. It depends highly on both the number of objects to be extracted and on the size of the image. Depending on the desired accuracy or the available time, the simulation can be accelerated or slowed by changing the speed of the temperature decrease (in the adaptive scheme). Obviously, the minimization of the energy will be better for a slow decrease of the temperature, and the extraction result too. To the best of our knowledge, our 3D model is the only one proposed in the literature to extract 3D tree crown parameters in CIR images. See [12] for more extraction results.

By analysing the obtained results, we can see that both models work correctly, and are quite robust w.r.t. the density in the stands. Some false alarms can be detected in the complete plantation image because of the data energy which answers well for some objects (for example in some crops in the bottom of the image). However, these isolated objects could be deleted with a post-processing. Moreover, we remark that the border trees at the top left of this plantation are not detected, because of the deformation induced by the view angle. In that case, there is not enough shadow around the tree to extract it.

Generally speaking, the 2D and 3D algorithms give some useful information at the scale of the tree which are not conceivable without any help of image processing (it would take too much time for an operator to get these statistics, and also be very costly). For instance, the minimum mapped surface by IFN is 2.25 ha in France, while smaller surfaces like alignments or isolated trees are only statistically assessed via explorations and data measurements on the ground. To be able to respond to increasing (private or public) demands in precision, the inventories need such automatic algorithms. Once the extraction is performed, parameters such as the number of trees and their size, or the density of the stand, can be directly obtained by operators, and complete their knowledge on the forest. Finally, these results could interest plantations managers by giving them an estimation of the global wood volume of their stand.

Conclusion

In this paper we propose an algorithm to extract some 2D and 3D vegetation resource parameters from high resolution aerial CIR photographs of forests. Based on a stochastic geometry approach, this algorithm considers that each tree is one geometric object to extract in the image. It turns out to be efficient for segmenting the tree crowns in different kinds of stands, and gives precious information on the stand at the scale of the tree (number of trees, their size, density, ...). The 3D model for the data energy is of particular interest because it gives access to statistics such as the wood volume. Such automatic algorithms are of economic importance because they can complete the work of forest managers and operators by giving them a more precise knowledge on the forest at a reasonable cost.

Future work will involve some tests on other kind of images and the implementation of a cooperation between the different models. Indeed, we could imagine a pre-processing of the image which would cut it into pieces and determine the correct model to apply for vegetation resource extraction. Then, much work has to be carried out using shape and texture information, in order to try to associate a group of species or a class of age to one object by studying its shape, its texture, and the stand it is belonging. The radiometry could then help to classify as much as possible the object (deciduous or conifer for instance).

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ADVANCED TECHNIQUES FOR MEASURING AND MAPPING THE IMPACTS OF HARVESTING OPERATIONS ON FOREST SOILS USING HIGH RESOLUTION SCANNING METHODOLOGIES

A. Kunneke and WP de Clercq
Faculty of AgriSciences, Stellenbosch University, South Africa
E-mail: ak1@sun.ac.za

Abstract

Forest harvesting operations, using heavy wheeled machines, change the structure and composition of the forest floor and underlying mineral soil layers. The extent of the impact varies according to the soil type and moisture conditions (season) at the time of harvest. A variety of methods can be used to measure this impact for rehabilitation of the site and also to correct or advise for wrong harvest method or system selection. Auger pits, penetrometers and moisture sensors can be used to characterise site damage. This investigation looked at the application of an EM38 scan of a site in the Highlands plantation south of Grabouw. The site was harvested partially during winter and partially during the summer of 2005 which presented the opportunity to study differences between winter and summer harvesting. On this site visual evidence of harvest tracks can be seen. Measurements with high precision of differences in density between the vehicle tracks and undisturbed forest soil were made using a penetrometer as control instrument.

The main aim of the investigation was to study the differences between soil in tracks and undisturbed soils after harvesting of the compartment. This compartment will not be replanted and a follow up on the investigation will be done during the coming winter to compare vegetation growth and various soil parameters between the undisturbed soil and tracks.

This initial part of the study, used high resolution EM38 and soil penetrometer measurements on both a summer harvested site and a winter harvested site. All measurements were logged with a Trimble high accuracy GPS system so that the results could be overlaid and modelled in a GIS and to allow comparison with the follow up study.

A good correlation was found between the EM38 data and the penetrometer data. A good comparison was also found between the visible and both EM38 and penetrometer readings. The dense grid of measurements done with the EM38 scan presents a bulk record of the site in a short time. It however does not only log density of the soil but rather a combination of density, soil water content and soil bulk EC.

The EM38 will therefore help us explain the variability in plant growth that is not accounted for by penetrometer measurements alone.

Keywords: soil compaction, EM38, temporal spatial variability.

THE USE OF HIGH RESOLUTION AIRBORNE IMAGERY FOR THE DETECTION OF FOREST CANOPY DAMAGE CAUSED BY *SIREX NOCTILIO*

Ismail, R, Mutanga, O and Bob, U.
Sappi Forest, South Africa
E-mail: riyad.ismail@sappi.com

Abstract

More than a decade after its initial discovery in the Western Cape, the Eurasian woodwasp, *Sirex noctilio,* has spread to the southern parts of KwaZulu-Natal posing a serious threat to pine species in the region. Whilst foresters are able to provide broad scale assessments of *S. noctilio* infestation, there are no existing frameworks in place to provide quantifiable measurements of the spatial or temporal distributions of this damaging agent, and the impact it has on commercial pine forestry. Remote sensing technology offers an alternative to the current broad scale methods of assessing forest health. In this study, high resolution (50cm) imagery was acquired over commercial *Pinus patula* vegetation of varying age classes which had been ground assessed and ranked on an individual tree crown basis using a visual severity scale (i.e. healthy, green, red and grey). A series of ratio and linear based vegetation indices were calculated and compared to the different *S.noctilio* crown condition classes. Of the vegetation indices calculated, significant differences ($p<0.001$) between the pre-visual (healthy and green) and visual (red and grey) crown condition classes were obtained, using the normalised difference vegetation index (NDVI) and the green normalised difference vegetation index (GNDVI). Canonical variate analysis further revealed that greater discriminatory power between the different *S.noctilio* crown condition classes is obtained when using NDVI as compared to the other vegetation indices. Overall the study demonstrated the importance of using vegetation indices obtained from high resolution airborne imagery to discriminate between healthy trees and trees that were in the visual stage of infestation (red and grey stages).

Keywords: *Sirex noctilio*, high resolution imagery, vegetation indices, canonical variate analysis

Introduction

More than a decade after its initial discovery in the Western Cape (Tribe, 1995; Tribe & Cillie, 2004), the Eurasian woodwasp, *Sirex noctilio*, has spread to the southern parts of KwaZulu-Natal, posing a serious threat to pine species in the region. In an effort to minimise the potential threat to commercial pine production in the region, an integrated management strategy combining detailed detection and monitoring methods, silvicultural treatments and biological controls has been implemented on an industry wide basis in South Africa. The primary control of established *S.noctilio* populations is achieved by biological means using the nematode *Deladenus siricidicola* and parasitic wasps such as *Ibalia leucospoides* and *Megarhyssa nortoni; while* silvicultural methods such as thinning are carried out to improve tree vigour and thereby keep damage within acceptable levels. However, successful implementation, of the above control measures, depends on our ability to spatially quantify the severity and extent of infestation so that forest managers can adopt the most appropriate course of intervention before the stand reaches a point of non-recovery. For example, moderate *S.noctilio* infestations (<10%) require the inoculation of infested trees with nematodes whereas heavy infestations (between 10 and 50%) would require sanitization and salvage operations to be implemented. Additionally, Geographic Information Systems (GIS) and forest planning systems, which include harvesting schedules, timber volume analysis and species growth models have been developed to help foresters manage affected areas, and these systems require accurate spatial information on the severity and extent of *S.noctilio* damage.

Current methods used to identify the severity and extent of *S.noctilio* infestation include broad scale visual aerial reconnaissance, followed by field based exercises to verify the results. Although visual assessments of infestation are widely used to measure forest health (Haara & Nevalainen, 2002) the effectiveness of visual assessments are questionable because they are qualitative, subjective and dependent on the skill of the surveyor (McConnell *et al.*, 2000; Stone & Coops, 2004). Previous forest health studies have shown estimation errors between 25 and 75% (Belanger & Anderson, 1988). The ability of remote sensing technology to augment traditional forest health evaluation procedures has been demonstrated by researchers for a diverse range of pests and pathogens (Muchoney & Haack, 1994; Vogelmann & Rock, 1995; Majeed, 1999; Bonneau *et al.*, 1999a; Franklin *et al.*, 2003; Wulder & Dymond, 2004) and imagery types (Vogelmann & Rock, 1995; Bonneau *et al.*, 1999b; Coops *et al.*, 2003). Using remote sensing to detect infestations is based on the assumption that the canopy damage caused by the pest *S.noctilio* creates differences in foliar constituents, foliage amount and canopy structure (Entcheva *et al.*, 2004) thus affecting the absorption of light energy thereby altering the reflectance spectrum of the tree (Entcheva *et al.*, 1996; Stone *et al.*, 2001). Thus by reliably measuring the reflectance spectrum, the health status of the tree can be determined.

Overview of vegetation indices

Researchers have studied the spectral effects of declining forest health (Ahern, 1988; Stone *et al.*, 2001; Entcheva *et al.*, 2004; Stone & Coops, 2004) and the various methods (Collins & Woodcock, 1996; Radeloff *et al.*, 1999; Levesque & King, 2003; Skakun *et al.*, 2003; Wulder & Dymond, 2004) which can be then used to detect the health status of trees. It has been reported that plants under stress display a decrease in canopy reflectance in the lower portion of the near infrared (NIR), a reduced absorption in the chlorophyll active band (red) and a consequent shift in the red edge (Carter & Knapp, 2001). For example, Entcheva *et al.*, (1996) found that reflectance at the 698 nm wavelength was significant in explaining needle reflectance response to southern pine beetle damage in *Pinus elliottii* while Ahern, (1988) found reflectance at 700 nm to be an indicator of needle stress in lodgepole pine caused by mountain beetles.

The most widely used vegetation indices (VI) exploit these spectral characteristics i.e. chlorophyll absorption by vegetation in the red portion of the spectrum and the high reflectance by vegetation in the NIR portion (Tucker, 1979; Treitz & Howarth, 1999). Additionally, the advantage of using remotely sensed VI includes the removal of variability caused by canopy geometry, soil background, sunview angles and atmospheric conditions (Gilabert *et al.*, 2002). Consequently, a number of narrow (Leckie *et al.*, 2004; Stone and Coops, 2004) and broad band vegetation indices (Vogelmann, 1990; Collins & Woodcock, 1996) have been successfully used to assess changes in the reflectance due to the declining health status of the tree. For the purpose of this study we have generally divided the broadband VI into two categories i.e. ratio based indices and linear based indices, although other categorisation may be appropriate for other purposes or imagery types (e.g. narrowband red edge indices). It is not our intent to provide a complete review of VI, for a complete review see Jackson & Huete (1991) and Thenkabail *et al.*, (2002), but we will review certain VI to the extent necessary to formulate our hypothesis regarding which indices would successfully detect and discriminate forest canopy damage caused by *S.noctilio* infestations.

Ratio based Indices

Ratio based indices operate by contrasting the intense chlorophyll pigment absorption in the red portion against the high reflectance, due to multiple scattering in the NIR portion of the electromagnetic spectrum (Elvidge & Chen, 1995). The most widely used ratio based indices such as the ratio vegetation index (RVI) (Jordan, 1969), normalized difference vegetation index (NDVI) (Rouse *et al.*, 1973), difference vegetation index (DVI) (Tucker, 1979) and green normalised difference vegetation index (GNDVI)(Gitelson & Merzlyak, 1998) respond to these differences in the near infrared and visible regions (Lillesand *et al.*, 2004).

For example, using Landsat MSS data, Nelson (1983), examined image differencing, image ratioing and vegetation index differencing in detecting gypsy moth defoliation and found the NIR /red ratio to be more useful in detecting defoliated areas than any of the other examined VI. Results from a study using Landsat TM conducted by Vogelmann (1990) indicated that NDVI provided an accurate assessment of insect induced defoliation damage to deciduous trees. NDVI also appeared to be very good at discriminating between high, medium and low deciduous damage categories; however the NDVI was only partially successful in measuring conifer forest damage (Vogelmann, 1990). Ekstrand (1994) on the other hand, suggested that moderate defoliation damage in Norway spruce (*Picea abies*) could be estimated using Landsat TM band 4 (NIR) and classification accuracies of 80% were achieved in sites that were predominately spruce in composition. The study concluded that ratio based algorithms are more applicable to regions suffering from both chlorosis (yellowing) and defoliation and were inappropriate in areas where defoliation is the sole symptom of forest decline (Ekstrand, 1994).

Linear Based Combinations

Linear combinations of spectral bands have been used to develop physically significant indices (Jackson, 1983) such as the tasseled cap transformation (TCT) which was developed by Kauth and Thomas (1976). Using Landsat MSS bands, Kauth and Thomas (1976) established four new indices (brightness, greenness, yellowness and nonsuch) in the spectral data which could be useful for vegetation monitoring. Linear based VI are especially useful for the discrimination of vegetation from the soil background (Jackson 1983) because linear VI are based on a predetermined soil line rather than the inherently assumed soil line underlying the ratio based NDVI (Lawrence & Ripple, 1998). Crist and Cicone (1984) later extended the transformation concept to Landsat TM data and more recently TCT have been calculated for high resolution, Ikonos (Horne, 2003) and QuickBird imagery (Yarbrough *et al.*, 2005). Several studies using broad band imagery (Collins & Woodcock, 1996; Price & Jakubauskas, 1998; Sharma & Murtha, 2001; Skakun *et al.*, 2003; Healey *et al.*, 2005; Jin & Sader, 2005) have shown the value of using the TCT when assessing forest health condition. According to Skakun *et al.* (2003) this is largely due to the fact that colour changes (chlorosis) associated with damaged trees are organized along the principal directions of brightness (TCB), greenness (TCG) and wetness (TCW) which are determined by the TCT. Additionally, Sharma & Murtha (2001) reported that differences between mean TCB, TCG and TCW of attacked stands and healthy *Pinus contorta* were statistically significant. Similar results were reported by Price & Jakubauskas (1998) who suggested that when using TCT components it was possible to distinguish stands that were progressively thinned as a result of beetle damage.

Research has shown that ratio and linear based vegetation indices have the potential to successfully quantify the severity and extent of infestation caused by various pests and pathogens. However, to date, no research has examined the benefits of using these vegetation indices to detect forest canopy damage caused by *S.noctilio*. Additionally, there is a need to identify small clusters or individual trees because pine plantations infested by *S.noctilio* have a scattering of dead and dying trees (Haugen *et al.*, 1990; Haugen & Underdown, 1990). This study intends to address these issues by firstly, using VI derived from high resolution imagery (50cm) to characterise *S.noctilio* induced stress in *Pinus patula* compartments. This allows for the identification of individual crown characteristics, thereby exploiting both spectral and spatial resolutions. Secondly, we intend to test the relative strength of various ratio and linear based vegetation indices in discriminating the crown condition classes associated with *S.noctilio* infestations. The overall objective of this study is to develop remote sensing techniques that will assist in the management of *S.noctilio* infestations. Once developed and tested, these techniques offer the potential to be applied operationally and should improve our ability to map those stands at high risk of infestation.

Materials and Methods

Description of the Study Area

The study area is approximately 1750 ha and forms part of the Sappi Pinewoods plantation which is dominated by *Pinus patula* compartments. The site is located approximately 30 km outside the town of Pietermaritzburg, KwaZulu-Natal. The average altitude for the site is 1190m with an average air temperature of 16.1° C. The mean annual rainfall of the area is 916mm.The terrain consists of low mountains and undulating hills. The geology of the area is a mixture of mudstone, sandstone, tillite, ampholite and basalt. Soils in the area are mostly sandy-clay and sand-clay loams (Macfarlane, 2004).

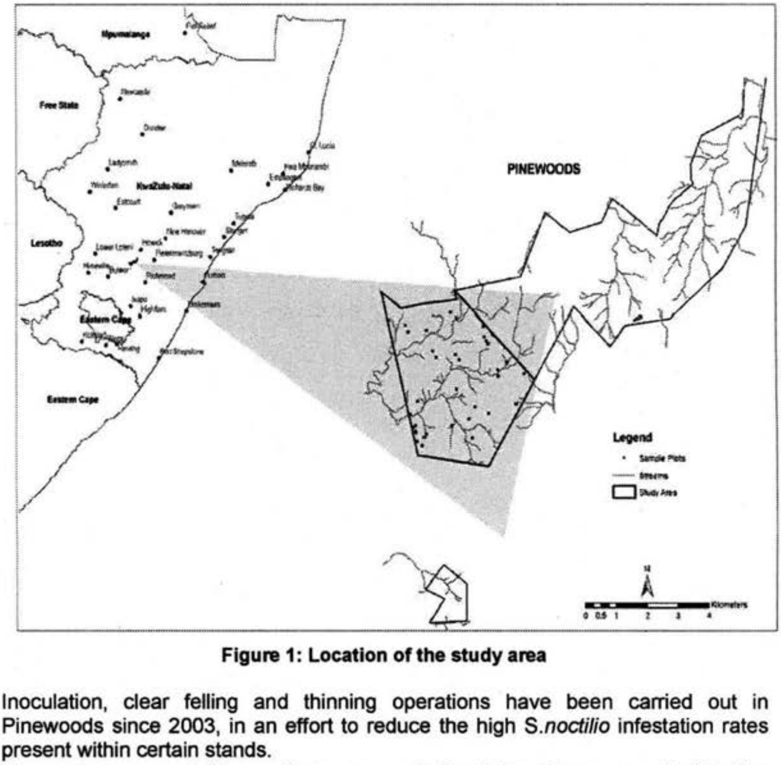

Figure 1: Location of the study area

Inoculation, clear felling and thinning operations have been carried out in Pinewoods since 2003, in an effort to reduce the high S.*noctilio* infestation rates present within certain stands.

These management interventions are carried out based on age stratification guidelines i.e. less than 7 years, from 8 to 9 years, 10 to12 years and older than 13 years .The age strata have been developed to account for insect-tree dynamics. S.*noctilio* typically attacks older stressed trees however as the insect population increases , an increasing percentage of healthy pine trees are attacked (Haugen *et al.*, 1990; Ciesla, 2003). Therefore intervention measures such as clear felling operations would be implemented in older compartments (> 13 years) in order to salvage "utilizable" trees, while inoculations would be carried out in stands that are between 10 to 12 years old to reduce S.*noctilio* populations from reaching epidemic proportions.

Data acquisition

High Resolution (50cm) multispectral imagery was acquired on the 9th September 2005 by Land Resources International (LRI) Inc, Pietermaritzburg (South Africa) with their manufactured LrEye aerial imaging system. The LrEye sensor is composed of a series of four monochrome Sony cameras. Each camera collects data for one of the bands shown in Table 1.The resulting four bands are registered to form an image with four co-registered bands that are referenced to the Gauss conformal projection (central meridian: 31). To minimise bidirectional reflectance and to cover the study area, flight lines were oriented away from the sun and flown as a series of north-south strips. Field data collection took place one week after the image was acquired.

Table 1: Spectral range of Landsat TM compared to the LrEye sensor

Band	TM spectral range (nm)	LREye spectral range (nm)	Colour
1	0.45-0.52	450 to 480nm with the peak at 465.88nm	Blue
2	0.52-0.60	550 to 580nm with the peak at 568.42nm	Green
3	0.63-0.69	650 to 680nm with the peak at 664.67nm	Red
4	0.76-0.90	850 to 900nm with the peak at 870.53nm	Near Infrared

Field Data Collection

A stratified random sampling technique was adopted for this study. Pine compartments that were harvested, or that were recently planted, were excluded from the sample. A 50 m x 50 m grid was generated over the study area and 10 grid cells were randomly selected from each predetermined age stratum (i.e. less than 7 years, from 8 to 9 years, 10 to12 years and older than 13 years). This age stratification was adopted because it reflects current *S.noctilio* management guidelines. At the centre point of each grid cell, a 10 meter radius plot was created. Tree crowns located within each plot were manually identified on the LrEye data and subsequently located in the field using a Global Position System (GPS). In total, 782 trees were assessed for *S.noctilio* infections based on a visual severity scale that is shown in Table 2.This process was undertaken with the assistance of Sappi forest planners and technical staff who have a detailed understanding of the identification and classification of *S.noctilio* infestations. Additionally, trees that were classified as 'red' were destructively sampled to evaluate the presence of *S.noctilio* larvae.

Table 2: The crown condition classes assessed in the ground survey

Class	Stages	Visual Symptoms
1	Healthy	No signs of S.*noctilio* infestation
2	Green	Green crown, presence of resin droplets, cambium stain, ovipositors found on the trunk and no needle loss
3	Red	Severe chlorosis , reddish brown canopy and high needle loss
4	Grey	Emergence holes, no canopy , most branches intact and 100% needle loss

Vegetation Indices

According to Coops *et al.*, (2004) the method used to obtain the spectral reflectance of individual trees when using high resolution imagery is important because significant variation in brightness exists depending on the pixel position within the crown. In a study conducted by Leckie *et al.*, (1992) to account for effects of the variation on individual crown delineation it was concluded that either the whole tree or the sunlit tree sampling methods were the most suitable methods to derive consistent and representative spectral response. In this study, the whole crown method was used, each of the selected crowns was manually delineated on the LrEye imagery and the crown spectral response extracted for the VI used in this study (Table 3).

Table 3: Ratio based vegetation indices used in this study.

	Vegetation Index Name	Index	Equation	Reference
1	Normalized difference vegetation index	NDVI	NDVI = (NIR−red)/(NIR + red)	Rouse et al, 1973; Jackson, 1983
2	Ratio vegetation index	RVI	RVI = NIR/red	Jordan, 1969
3	Difference vegetation index	DVI	DVI = NIR−red	(Tucker, 1979)
4	Green normalised difference vegetation index	GNDVI	GNDVI = (NIR – green)/ (NIR + green)	Gitelson and Merzlyak, 1998

Tasseled cap transformation

The Gram-Schmidt orthogonalization process was used to derive the tasselled cap transformation (TCT) coefficients. Initially, a soil line and the vector in the "brightness" direction are determined; subsequently from the "brightness" vector all other vectors (i.e. greenness and yellowness) are orthogonally calculated. Yarbrough *et al.*, (2005) and Jackson (1983) provide a mathematical description for calculating coefficients for *n* space indices using the Gram-Schmidt orthogonalization process .Coefficients (Table 4) are based on the grey level values (DN) of the LrEye imagery of the four land cover types i.e. wet soil, dry soil, green vegetation and senesced vegetation. Water was used to represent wet soil values because pixels representing wet soils were not found in the imagery. Dry soil values were collected from dirt roads while tree crowns represented green vegetation.Dry grass values were used to represent senesced vegetation.

Table 4: Gram-Schmidt coefficients

	B	G	R	NIR
Brightness (TCB)	0.337663	0.586272	0.638220	0.367348
Greenness (TCG)	-0.227113	-0.131965	-0.288569	0.920724
Yellowness(TCY)	0.097931	-0.781721	0.607311	0.102451

The resulting linear equations for brightness, greenness and yellowness are as follows:

Brightness (TCB) = 0.337663 (blue) + 0.586272 (green) + 0.638220 (red) + 0.367348 (NIR)
Greenness (TCG) = -0.227113 (blue) -0.131965 (green) -0.288569 (red) + 0.920724 (NIR)
Yellowness (TCY) = 0.097931 (blue) -0.781721 (green) 0.607311 (red) + 0.102451 (NIR)

Statistical Analysis

We tested the hypothesis that ratio and linear based vegetation indices could differentiate among the various stages of infestation (i.e. healthy, green red and grey) caused by *S.noctilio*. Analysis was undertaken to compare the crown condition classes for each of the indices in order to determine which of the VI consistently discriminated at least some of the classes as determined by the visual severity scale (Table 2). This was tested using an analysis of variance (ANOVA) with a Tukey's HSD post hoc test.

Canonical variate analysis (CVA) is a multivariate statistical technique which discriminates among prespecified groups of sampling entities based on a suite of characteristics (McGarigal *et al.*, 2000). The technique involves deriving linear combinations (i.e. canonical functions) of two or more discriminating variables that will best discriminate among the *a priori* defined groups (Mutanga, 2005). In this study vegetation indices (VI) are entered into the analysis based on their ability to increase group separation (i.e. crown condition classes). This reduces the number of indices to a subset that provides the best discrimination among classes. The best linear combination of VI is achieved by the statistical decision rule of maximising the among group variance, relative to the within group variance (Mutanga, 2005). The first discriminant function provides the best separation among classes, while the second function separates classes using information not used in the first function and so forth. Additionally, the functions will be independent or orthogonal, that is, their contributions to the discrimination between groups will not overlap (Lawrence & Labus, 2003). Based on this background, we used CVA to exhibit optimal separation of the crown condition classes based on the linear transformation of the calculated VI, and establish which VI are most related to the separation of these classes.

We used the leave-one-out cross validation technique for estimating the error rate conditioned on the training data. The advantage of using the leave-one-out cross validation technique is that all the data is used for estimating error. Using this cross validation technique, each observation is systematically removed, the canonical function re-estimated and the excluded observation classified (Mutanga, 2005). A confusion matrix is then constructed to compare the field (true) crown condition classes with the class assigned by the VI to the sample dataset. It depicts accuracies of the crown condition classes (producer's and user's accuracies). Producer's accuracies are calculated by dividing the number of correctly classified trees in each crown condition class by the number of training data used for that class (i.e. column total in the confusion matrix). User accuracies are computed by dividing the number of correctly classified trees by the total number of trees that were classified in that crown condition class (i.e. row total in the confusion matrix). Additionally a discrete multivariate technique called kappa analysis that uses the *k* ("KHAT") statistic as a measure of agreement with the reference data was calculated (Congalton & Green, 1999; Skidmore, 1999). This statistic serves as an indicator of the extent to which the percentage correct values of an error matrix are due to "true" agreement versus "chance" agreement (Lillesand *et al.*, 2004). If the kappa coefficients is one or close to one then there is perfect agreement between training and test data. Conceptually *k* can be defined as:

$$k = \frac{\text{observed accuracy –chance agreement}}{\text{1-chance agreement}} \quad (1)$$

Results

We tested the hypothesis that ratio and linear based vegetation indices would discriminate among the various crown condition classes by conducting a one-way ANOVA. Of the vegetation indices calculated, significant differences (p<0.001) were obtained using NDVI, GNDVI, DVI, RVI, TCG and TCB. A one-way ANOVA shows that there is a significant difference between the vegetation indices and the *S.noctilio* crown condition classes, but it does not show which crown condition classes are different. We therefore executed a Tukey's HSD post hoc test in order to establish differences between each of the crown condition classes (i.e. healthy, green, red and grey). Results with their respective level of significance are shown in the table below.

Table 5: Analysis of variance results with a Tukey's HSD post hoc test. Class 1 (healthy), class 2 (green), class 3 (red) and class 4 (grey).

NDVI	1	2	3	4	TCG	1	2	3	4
1	..	**	*	*	1	..	**	*	*
2	**	..	*	*	2	**	..	*	*
3	*	*	..	*	3	*	*	..	*
4	*	*	*	..	4	*	*	*	..
GNDVI	1	2	3	4	TCB	1	2	3	4
1	..	**	*	*	1	..	**	**	*
2	**	..	*	*	2	**	..	**	*
3	*	*	..	*	3	**	**	..	**
4	*	*	*	..	4	*	*	**	..
DVI	1	2	3	4	NIR	1	2	3	4
1	..	**	*	*	1	..	**	*	*
2	**	..	*	*	2	**	..	*	*
3	*	*	..	*	3	*	*	..	*
4	*	*	*	..	4	*	*	*	..

P< 0.001 =*, Not Significant =**

The results indicate that both ratio and linear based indices are poor at discriminating between class 1 (healthy) and class 2 (green stage). However, the VI tested are capable of discriminating between the previsual (classes 1 and 2) and visual crown condition classes (classes 3 and 4). The most significant degree of separation occurs between class 1 and classes 3 and 4 and between class 2 and classes 3 and 4. All indices are capable of discriminating between these classes except for TCB which can only discriminate between class 1 and class 4 and between class 2 and class 4. Based on the results from ANOVA, it is difficult to determine which index has the best discriminatory power. Therefore, we carried out a canonical variate analysis and included all indices (discriminatory variables) except for the TCB component. Additionally, to improve the discriminatory power of the VI, class 2 (green stage) was grouped with class 1 (healthy trees) while the rest of the classes remained the same i.e. class 3 (red stage) and class 4 (grey stage)

Canonical variate analysis (CVA) results

We tested the relative strength of various ratio and linear based vegetation indices in detecting *S.noctilio* infestations by conducting a canonical variate analysis (CVA). Table 6 shows the eigenvalues as well as the factor structure matrix from the canonical variate analysis using 3 crown condition classes (i.e. healthy, red and grey stages). The measure of information contained in the functions is represented by the eigenvalues corresponding to those functions. The eigenvalues are interpreted as the ratio of variances along each function (Richards, 1993). The largest portion of the explained variance (97.5%) is contained in the first canonical function while the reminder is contained in the second function (2.5%). The factor structure coefficients contained in the matrix below represent the correlations between the variables and the canonical functions and are used to interpret the canonical functions (McGarigal *et al.*, 2000). Results indicate that the highest factor structure coefficients are contained in the NDVI (0.633) and the GNDVI (0.629). The second canonical function also shows that one of the largest contributions is contained in the GNDVI (0.605) and to a lesser extent NDVI (0.369), however the magnitude for the second canonical function is much smaller that that of the first canonical function. The scatter plot in Figure 2 shows the position of the crown condition classes in canonical space.

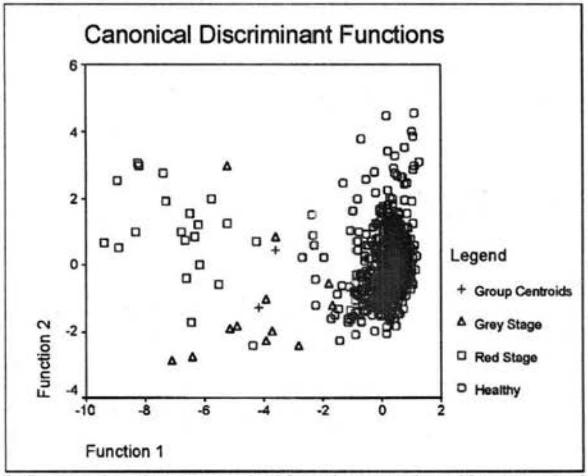

Figure 2: Scatterplot of two canonical functions produced by canonical variate analysis

Table 6: Factor structure matrix representing the correlation between variables and canonical functions (3 classes)

	Function 1	Function 2
NDVI	.633	.369
GNDVI	.629	.605
DVI	.559	.550
TCG	.500	.669
NIRR	.484	.463
Eigenvalue	0.961	0.025
% Variance	97.5	2.5

Classification

To further investigate the effectiveness of high resolution airborne imagery to discriminate between crown condition classes we classified the samples using Fisher's linear discriminant functions(McGarigal *et al.*, 2000; Mutanga, 2005).To test the predictive discriminatory power of the canonical functions we used the leave-out-one technique for estimating the error rate conditioned on the training data. In the leave-out-one technique each observation is systematically dropped and the canonical function re-estimated and the excluded observation classified. The confusion matrix including the kappa statistic, user accuracy and producer accuracies are shown in Table 7.

Table 7: Confusion matrix showing the predicted accuracy of Sirex noctilio using a 3 level classification system: class 1 (healthy), class 2 (red), and class 3 (grey)

Class	1	2	3	UA
1	695	2	2	99.43
2	8	26	3	70.27
3	2	3	11	68.75
PA	98.58	83.87	68.75	
KHAT	0.79			

Discussion

High resolution remote sensing provides a reasonable and robust tool to improve our ability to spatially quantify the severity and extent of *Sirex noctilio* infestations while not excluding the importance of visual assessments made by forest health experts. Both ratios and linear based vegetation indices are able to significantly ($p < 0.001$) discriminate between the previsual (healthy and green) and the visual stages of infestations (red and grey).Canonical variate analysis further reveals that greater discriminatory power between the different crown condition classes is obtained when using NDVI as compared to the other vegetation indices. Accuracy assessments show that NDVI is successful in locating and predicting the condition of tree canopies on the imagery when crown condition classes are reduced to a three classification system, in which case producer accuracies range from 84% (red stage) to 69% (grey stage) . The results obtained from this study are comparable to previous studies on declining forest health (Vogelmann, 1990; Leckie *et al.*, 2004; Wulder *et al.*, 2004; Leckie *et al.*, 2005) and emphasize the importance of the visible and NIR bands when studying the effects of declining forest health especially when infestation results in foliar discolouration.

Mapping the red stage of infestation is regarded as a priority among forest managers because it gives an accurate indication of the severity and extent that is taking place that year (current infestation) (Leckie *et al.*, 2005). Additionally, the depiction of infestation levels by mapping out the red stage of infestation meets current operational requirements. Forest managers can now quantify the potential effects of S.*noctilio* infestation on fibre supply and stand vulnerability, thereby allowing for the design of the most appropriate intervention measures.

The difficulty in discriminating the green stage of infestation is in consistent with other studies that have attempted to classify light to moderate symptoms using high resolution remotely sensed imagery (Leckie *et al.*, 2004; Leckie *et al.*, 2005).The success of discriminating green stage infestation is dependent on the detection of subtle changes in the spectral reflectance of the tree (Ekstrand, 1994). Slight changes in the spectral reflectance of stressed vegetation, when measured by various broad band sensors, are often masked by the high degree of variation in reflectance caused by factors such as varying view geometry, illumination, and canopy density (Runesson, 1991).Given this limitation, hyperspectral remote sensing offers possibilities to investigate the early stages of infestations based on narrow bands using the entire electromagnetic spectrum. These narrow bands allow for the detection of detailed features which would otherwise have been masked (Schmidt & Skidmore, 2001).

The performance of linear based indices as compared to ratio based indices was disappointing. However, previous studies (Collins & Woodcock, 1996; Skakun *et al.*, 2003) found changes in the tasseled cap wetness component (TCW) to be a good indicator of conifer mortality and the most consistent indicator of forest change due to the inclusion of the short wave infrared (SWIR) band. However in this study, the calculations of the tasselled coefficients were limited to the visible and NIR parts of the spectrum (400-900nm) and included only the tasselled cap brightness (TCB) and greenness (TCG) components. Additionally, spectrometer research conducted by (Leckie *et al.*, 1988) regarding discolouration caused by the spruce budworm indicated that the SWIR regions are better than the visible and NIR for discrimination. Similarly, initial attack by *Sirex noctilio* changes the water balance of the attacked tree, (Neumann & Minko, 1981; Slippers *et al.*, 2003) ,so using a sensor that captures SWIR wavelength has the potential to improve overall classification accuracy as well as discrimination between crown condition classes.

Conclusion

The use of ratio and linear based indices calculated from high resolution imagery has resulted in the successful detection and mapping of canopy damage caused by Sirex *noctilio*. Although it is difficult to discriminate between the healthy and green stages of infestation, classification accuracies are improved when using a three class crown condition index that differentiates between the healthy and the visual stages of infestation. More importantly, this has lead to the development of a detection and mapping framework that augments current management initiatives designed to reduce *Sirex noctilio* infestations.

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AUTOMATION OF FORESTRY MACHINES - an important piece in precision forestry

Björn Löfgren
Skogforsk, Uppsala, Sweden
E-mail: bjorn.lofgren@skogforsk.se

Abstract

In times when forest operations have been fully mechanized, we are entering a new era in which automation will probably come to the fore. This will involve automation of entire operations, knuckle boom manipulation and other parts of the process. A lot of work to reduce the physical stress to which operators are subjected has already been done successfully over the years. However, the higher tempo of work today, combined with the many qualified decisions that the operators must make under pressure, is imposing a greater mental load on them. Skogforsk have conducted comparative studies in a forest machine simulator, such as fidelity, automation on a harvester and man machine interaction. Our tests carried out in the simulator, clearly demonstrate that automation of forestry machines is a feasible way to increase productivity and to improve the working conditions of operators. Automation should be directed both at knuckle boom work and processing.

Keywords: Automation, head up display, boom tip control,

Introduction

In times when forest operations have been fully mechanized, we are entering a new era in which automation will probably come to the fore. This will involve automation of entire operations, knuckle boom manipulation and other parts of the process—such as the collection, transmission and reporting of information.

Another incentive for bringing in automation is to improve the working conditions of the machine operator. A lot of work to reduce the physical stress to which operators are subjected has already been done successfully over the years. However, the higher tempo of work today, combined with the many qualified decisions that the operators must make under pressure, is imposing a greater mental load on them. Automating the boom operation would therefore reduce the mental pressure on the operator. This would not only give the operator more time but also greater opportunity to concentrate on other tasks, such as tree selection, bucking options and assessing any damage or defects visible on the next tree. We have conducted comparative studies in a forest machine simulator, such as fidelity, automation on a harvester and also man machine interaction.

Analysis points the way

Operations analysis
Operations analysis is an analysis of the activities set in a broader context. It includes different players and regulations, both economic and organizational, and also the technical and human conditions of the activities. We interviewed users and analysed the views of Skogforsk member groups on increased automation.

Member groups
Thus, our analysis assessed the views on increased automation as put forward by the different member categories; namely, the woodlot owners, forest enterprises, machine manufacturers, forestry contractors, machine operators, and the general public. Mind-mapping was used to analyse the various views, which can be summarized as follows:

- Automation will probably be profitable in the long term, but not in the short term
- Automation can have a positive effect on social and humanitarian conditions in the short term, but it is difficult to assess these effects in the long term
- The main benefits are likely to be that round-the-clock operation will be possible, there will be a reduced risk of RSI, and machine operators will enjoy a higher status
- The main obstacle to automation will be finding a sufficient number of competent people, businesses and forestry contractors willing to invest in advanced technology. Moreover, round-the-clock operations are not desirable from the viewpoint of employees and working conditions.
- It might be that the industrial forest enterprises will have to procure and maintain ownership of the forestry machinery until such a time that the technology has become established and widely accepted
- Perhaps only certain selected functions should be automated (in deference to both economics and people).

Users

Most of the contractors had a positive attitude to the idea of automating certain machine functions. There was also a high-level of concurrence among the views of the contractors, including which functions should be given priority in automation.

Similarly, it was generally agreed that automation would be beneficial for complicated functions that had to run simultaneously with others—such as detecting quality defects, grading of timber, planning, and optimization of extraction routes. The contractors were also in favour of automating simple, repetitive knuckle boom functions.

All the contractors emphasized that automatic functions should not be allowed to upset the rhythm of manual operations, as this would create stress and reduce productivity.

Depending on the standpoint of those questioned (concerned respectively with profits, ergonomics, productivity, and customer satisfaction), the answers, and thus the priorities, were very different—which only goes to show how important it is to conduct detailed analyses before deciding on the direction of future developments.

Job analysis

Thorough analysis of the individual tasks makes it possible to specify the work and the requirements that must be met by the operator and the machine under different operating conditions.

Systems analysis: unmanned machines

We have analysed the effects on logging of three conceivable future unmanned harvesting systems, and we have compared the costs of these with those of today's harvester and harwarder systems.

The three unmanned systems are:

- A harvester that is remotely controlled by one or two forwarders
- A harvester operating with one or two unmanned shuttles
- A harwarder operating with one or two unmanned swap loaders

The costs of the systems in our analysis are based on today's harvesters and forwarders, with estimated reductions or additions being made for features that have either been removed from the "standard" machine version or added to it.

One of the findings of the analysis is that automating parts of the logging work does not always lead to a reduction in costs. On the contrary, logging costs can go up if waiting time occurs because of the harvesting and extraction machines being out of phase.

In systems deploying a remote-controlled harvester, and in shuttle systems, the machines are tied to each other during harvesting/loading, which automatically gives rise to waiting times unless two extraction vehicles are in use, and harvesting and extraction are in phase. This should be possible if the combination of extraction distance and mean stem volume is optimized.

The system that is most competitive with today's harvesters is that in which a conventional, manned harvester is served by two unmanned shuttles (see Fig. 1).

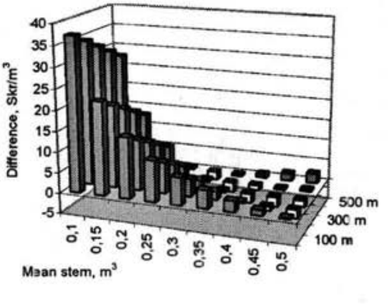

Fig. 1 System with two shuttles vs. conventional harvester system

The analysis shows the shuttle system to be more competitive than the remote-controlled system, but, in practice, the difference is much smaller because the technology required for remote control is known and, in principle, already available. In contrast, the shuttle system requires navigation and a robot for unloading, both of which call for technology that will not be available until sometime in the future.

We also need to take into account the costs associated with moving and start-up of the shuttle system on a new site—costs which are difficult to assess.

Based on the assumed costs, a harvester that is remotely controlled by two forwarders would be competitive under certain limited conditions in final felling (see Fig. 2).

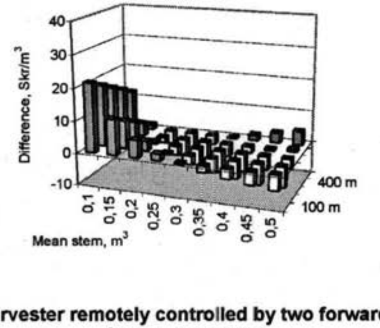

Fig. 2 System with harvester remotely controlled by two forwarders vs conventional harvester system

In practice, work on the development of a system based on a remote-controlled harvester has been going on for some time, and has only recently been exposed. It is a remote-controlled harvester with the name Besten ("The Beast"). The harvester is controlled by a forwarder that moves in parallel with the harvester.

The forwarder has a slewing load bed, which enables the timber to be loaded by the harvester straight onto the forwarder. Thanks to numerous technical refinements, the hourly costs of the harvester are considerably lower than those presented in the analysis above.

Besten is significantly more competitive than indicated in the original analysis—by a factor of three (see Fig. 3). What is perhaps more interesting is that the system now is competitive over a wider range of conditions—in all final felling in effect.

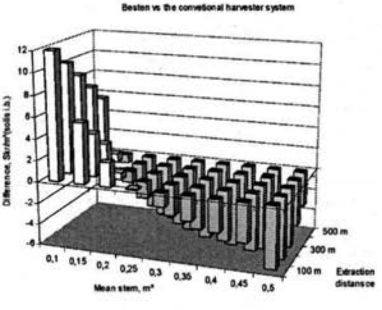

Fig. 3 The "Beast" system vs. the conventional harvester system

Analysis findings confirmed by simulator

With the wealth of ideas that exist in the field of automation, an important task is to verify which of the many concepts are best suited for development. The usual procedure has been to build a prototype, develop the software, conduct tests and, finally, carry out trials in the field. Such a procedure consumes considerable resources and time, and the assessment comes late in process.

For many years, simulators have been used for both training and research purposes. Rapid advances in computer technology have now made it possible to conduct advanced real-time simulation of logging machines at an affordable cost. This opens the door to using simulators as a tool in R&D. Thus, it is now possible to study the consequences of modifications made to the design of machines and components, or to the control of different functions, without the need to actually build the machines or to modify existing ones. So we can now determine much sooner which concepts should be developed into prototypes and subsequently be put into production.

Before new technology, methods or prototypes are launched, the usual question that has to be answered first is, "What sort of a profit or savings will it make?" Thanks to simulation technology, we are now in a position to provide the answers in advance.

Skogforsk has purchased a forestry machine simulator. We have used the simulator to evaluate ideas and concepts. But to ensure that our simulator and field studies are analogous, we needed to determine the level of congruity between the findings from field studies and those from simulators in which existing stands have been reproduced by simulation.

Fidelity studies

We have conducted comparative studies, known as fidelity studies, to find answers to the following questions:

- Given the same operator and the same stand conditions, are there differences between the productivity figures derived in the field and those produced by the simulator?
- Are the differences in productivity between two operators found to be the same in both the simulator and reality?

We have carried out detailed time studies of all the work elements of a single-grip harvester in operation, together with the corresponding loading and unloading work of a forwarder. Accurate measurements were made of the stand in which the trials were carried out. We then recreated the stand in the simulator and repeated the time studies, using the same operator as in the field studies - in effect, harvesting the same stand again.

Table 1. Percentage difference between the real figures and the simulated figures

	Boom out	Felling–luffing	Limbing–bucking
Difference, %	-7.2	-5.4	4.4

As can be seen in Table 1, the results from the simulator corresponded well with the "real" figures. However, it is impossible to achieve 100% agreement; one example of why this is so is the absence of slip in simulated limbing, which makes for a perfect result—something we obviously cannot achieve in real operating conditions.

In our view, the simulator is an effective research tool for evaluating new technical solutions on logging machines.

Automation

Logging-machine operators work under a great deal of mental pressure. They have to deal with a large volume of information and make crucial decisions while under considerable time pressure. What's more, operating the controls with their hands is also quite demanding on the brain.

Automation of the boom operation would therefore reduce the mental pressure on the operator. This would not only give the operator more time but also greater opportunity to concentrate on other tasks, such as tree selection, bucking options and assessing any damage or defects visible on the next tree.

Degrading the job

The downside of automation of the boom operation is that it could degrade the work of the operator, particularly those tasks characterized as skilful, and those valuable interventions that the operator makes. On the other hand, technological advances that give the operator wider scope for making qualified decisions could counter such risks. New technology should focus on removing time constraints on decisions (reducing the need for decisions having to be made at a given moment), and in making the operator more responsible for qualified decisions that can increase the value of the yield.

Automation of a single grip harvester

Through a series of time studies, combined with an analysis of the joystick and pushbutton functions used by the operator, we were able to identify a number of work elements or sub functions that could be worth automating.

Automation of boom

From our analysis of the breakdown of joystick/pushbutton usage over time, we find that Boom up/down was the function used most frequently by the operator, followed by Boom slewing, Rotator and Telescopic boom in/out. The following proposals for automating harvester work (taken from the list above), have been implemented and evaluated in the simulator:

- Automatic alignment of harvester head on Boom out
- To enable tree selection to be done concurrently with the previous function, thus allowing time for the operator to focus on other decisions on felling
- Automatic boom repositioning after felling

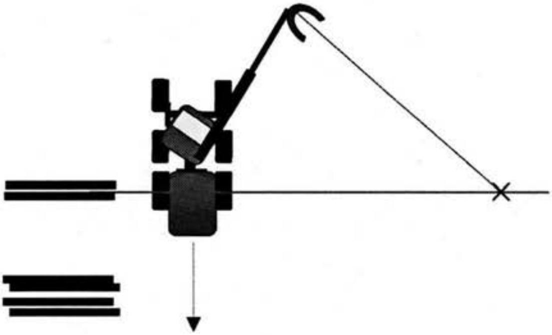

Fig. 4 Atomatic alignment of harvester head on boom out.

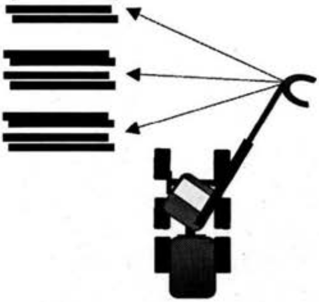

Fig. 5 Automatic boom movements to right pile.

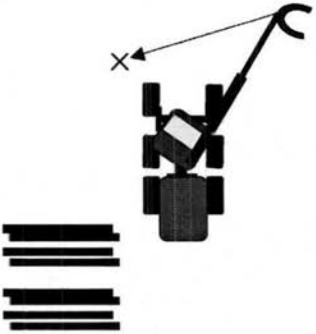

Fig. 6 Automatic boom repositioning after felling.

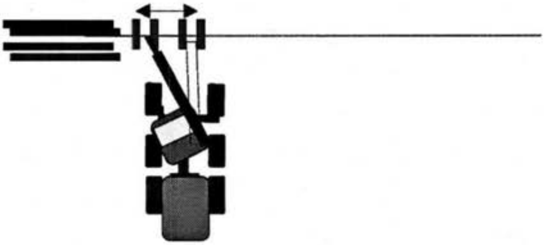

Fig. 7. Automatic boom movements between delimbing and pile .

Forestry-school students took part in a test that involved both conventional control and semi-automated functions on a harvester. The usage of joystick and pushbutton controls was much lower when functions were semi-automated than in conventional operator control which gives the operator time to take micro breaks.

The results also pointed towards an increase in productivity. Even though we introduced only a few semi-automated functions, the findings clearly demonstrated the potential for introducing semi-automation in harvester operations. We also compared the students with a very skilled operator.

Comparison between students

- 30 % less use of rotation of harvester head.
- 60 % less use of joystick functions.
- 30 % increased productivity

Comparison between skilled operator and students

Conventional control	75 % longer time consumption.
Automation	21 % longer time consumption.

Automation of assortments

We also put automatic assortment sequences into the simulator (see Fig. 8).

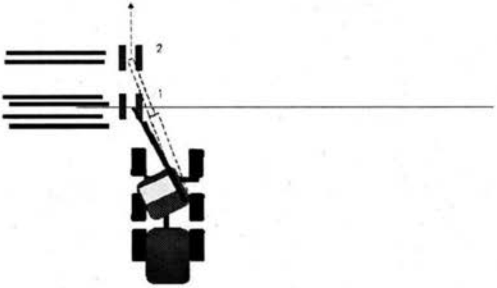

Fig. 8. Automatic boom movements at different assortments.

Even in this case we used a very skilled operator to evaluate the difference between conventional control and automation. The operator accounted that this automated function very positive. The number of micro pauses increased (see Fig.9). A micro pause is a pause which is longer than 3 seconds. This will give the possibility for the muscles to recover during the operator's normal work.

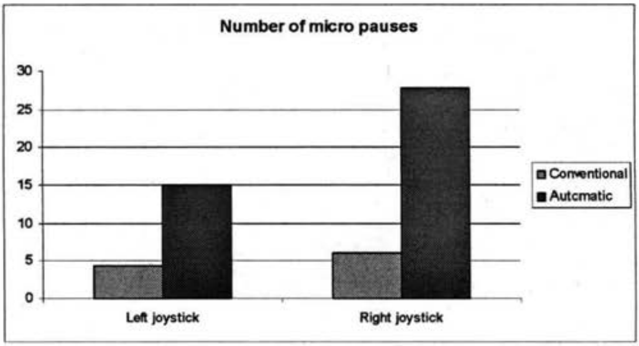

Fig. 9. Number of micro pauses at conventional control and with automatic sequences.

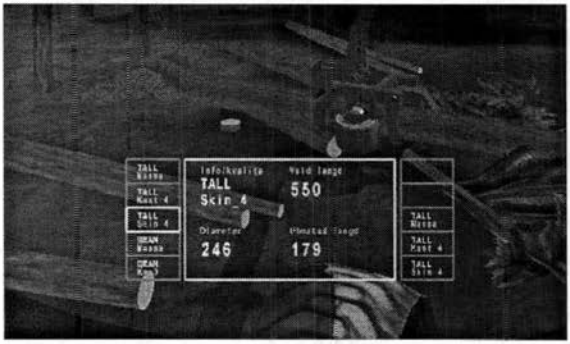

Fig. 10. Head up display with assortments according to the bucking computer.

Automation of a forwarder

Semi-automation of the knuckle boom has been identified as the most important target for development. One solution would be to introduce boom-tip control, which would simplify the boom work and reduce the need for multiple, simultaneous control movements. Boom-tip control means that movement of the tip of the knuckle boom is effected by a single joystick or pushbutton. Thus, an upward or downward movement generates an up or downward movement of the boom tip; an outward or inward movement of the control generates a corresponding outward or inward movement of the boom tip; and a left or right movement of the control produces a corresponding left or right movement of the boom tip. Moreover, the up/down movement describes a vertical path, and the out/in movement a horizontal path (see Fig. 11).

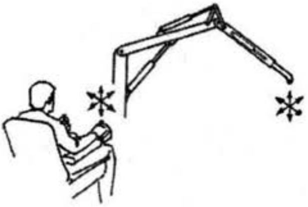

Fig. 11 Movement pattern of boom tip with boom-tip control

To evaluate boom tip control we perform a test in our simulator. A test track was designed in the simulator to be able to evaluate the difference between conventional control and boom tip control, (see Fig.12). Students from a forestry-school took part in the tests. They had no experience at all from forestry machines.

The students should move the boom to five different places around the forwarder as fast as possible without hitting any obstacles or the forwarder. If they hitted any obstacle or the forwarder extra time was added to final time consumption.

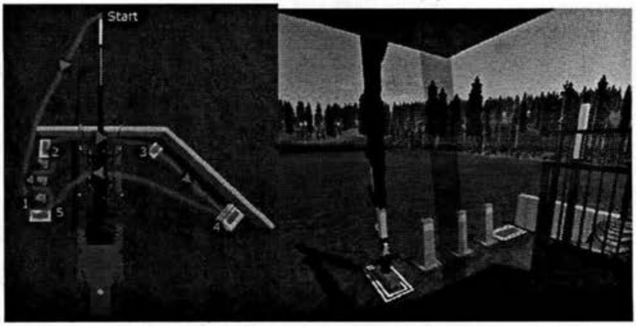

Fig.12 Test track in the simulator.

The students where divided in two groups, one was learning conventional control and one was learning boom tip control. Each group was practicing 15 hours during a two month period.

The results show that the boom tip group performed better in all categories than the conventional group, (see Fig. 13).

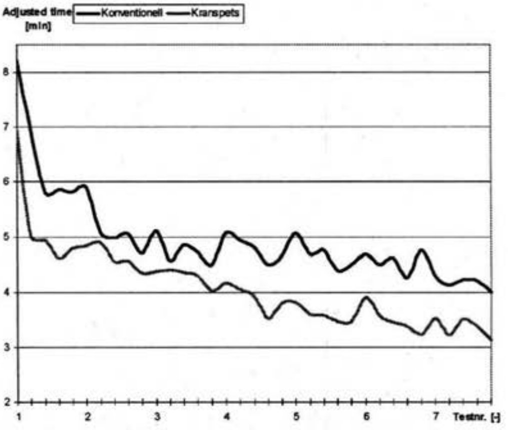

Fig. 13. Adjusted time consumption during the test series

If you just compare time consumption the difference was not so big but the boom tip group showed greater improvements then conventional group, who almost stayed on same level (see Fig. 14).

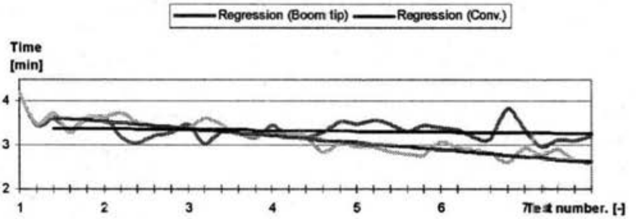

Figure14. Time consumption during the test series..

This shows that boom tip control is easier to learn when you start learning new controls in a forestry machine.

Man Machine Interaction

Operators of forestry harvesters will take in a lot of visual information from the world around him and from displays in the machine. This will increase the mental stress of the operator. The information on bucking computer is placed low at the cabin windshield while the operator's main attention is directed to control of the boom and the harvester head (see Fig. 15).

Fig. 15. View of the cabin in a Valmet harvester

The display presents a lot of alphanumeric information (see Fig. 15) and to able to see this information the operator has to change focus form the tip of the boom to display and thereby lose a lot information. By improving the interface of the display it will be easier to obtain information and thereby decrease the mental stress.

Info / Kvalitetslängd [cm]
Gran
3/Konstrukti

Vald längd [cm]
432

Diameter [mm]
271

Utmatad längd [cm]
434

Stamkvalitet
3

Fig. 16. Ordinary alphanumeric display

By presenting the information on the windshield with a head up display, as on a fighter plane, the operator has the possibility to obtain necessary information from the bucking computer without moving the gaze from the harvester head. While you have the bucking information on the windshield it is possible to use the normal display for other use such as a map of the working area (see Fig. 17).

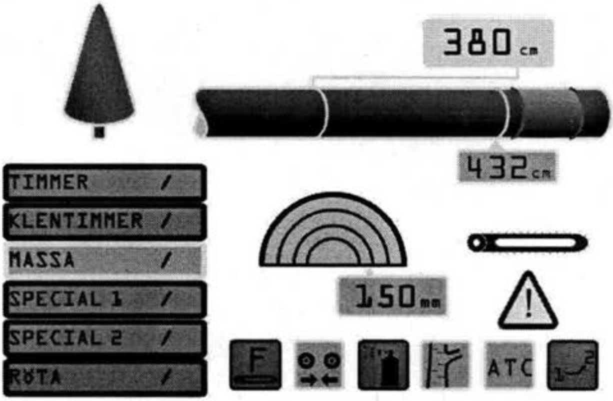

Fig. 17. Head-up display on the windshield.

The head up display was incorporated into simulator and evaluated with a very experienced operator. The operator experienced the head up display very positive and he felt that the amount of information maybe should decrease even more which will be tested later this year.

Conclusions

Our theoretical analysis work, together with the tests carried out in the simulator, clearly demonstrates that the automation of forestry machines is a feasible way to increase productivity and to improve the working conditions of operators. Automation should be directed both at knuckle boom work and processing. However, it is important that automation on forestry machines does not give rise to increased pressure on the operator. Skogforsk is to continue using the simulator to evaluate automated functions on both forwarders and harvesters.

Even if our studies have been focusing to reduce the mental and physical stress on the operator this is the base towards a more precision forestry.

ACCURACY OF GPS/GIS APPLIED HARVESTER SKIDDING TRACKS

A. Kopka, B. Reinhardt
HAWK – University of Applied Sciences and Arts, Göttingen, Germany
E-mail: Kopka@hawk-hhg.de

Abstract

Onboard satellite navigation can assist foresters by marking skidding tracks in forest stands. The planning of fine logging systems at the PC by geographical information systems (GIS) and satellite navigation systems has already become an international standard. The accuracy of these satellite navigation systems has been controversially discussed in the last years. Can an accuracy of 10% deviation in forest stands or even in the "sub-meter-region" be achieved?

In this context two different satellite navigation systems, the Russian GLONASS and the American NAVSTAR-GPS, have been compared in a diploma thesis investigating their accuracy and usefulness in forestry. The Research area was a two hectare forest stand in Northern Germany (Harz). A total of 31 skidding tracks have been applied. Onboard the Timberjack 1470 the "Timber Office" software and "ArcGIS" have been deployed. In addition to these systems corrected data of a mobile differential satellite navigation service has been used.

After the skidding tracks had been exactly measured and oriented, the harvester was guided only by the tracking function of the GPS software onto the skidding tracks. The aspect of the slope angle was considered. Therefore four classes, "plateau", "light slope", "medium slope" and "heavy slope", were selected. The main conclusion of this examination was that the accuracy of a satellite navigation system mainly depends on climatic aspects, slope angle, exposure and different systems of navigation. If all these aspects are optimized in respect to their influence on the signal, the user gets less "position gaps" and accuracy better than 10 % deviation is possible.

Keywords: GPS, GLONASS, GIS, SKIDDING TRACKS, HAWK, TOPCON

Introduction

In the last years the German forestry has been going through a phase of reorientation. The rising international competition as well as the effects of globalization on the wood market has been leading to an increasing use of harvester technology in the forests (Sadelfeld, 2005).

To reduce costs manpower is replaced by the use of modern forestry equipment. The national forest administration of Lower Saxony carried out 55% of its felling volume with harvesters in the year 2004. Up to the year 2008 it should be altogether 70% (Denninger, 2005).

To help foresters with their time-consuming work of marking skidding tracks in forest stands for the fully mechanized harvesting, a new onboard GPS satellite navigation system has been developed. By increasing the mechanization of harvester and forwarder integration into the wood harvest the application of computer aided systems has become more important. The planning of fine logging systems at the PC by geographical information systems (GIS) and satellite navigation systems has already become an international standard. The use of these modern satellite navigation systems in the forest industry could also reduce the costs of the harvester employment. Driving off the skidding tracks due to an inaccurate GPS system can lead to irreparable damage of the soil. Especially in difficult geological conditions, the use of a precise satellite system can minimize the impact of heavy machinery on forest stand.

But the accuracy of these satellite navigation systems has been controversially discussed in the last years. (Kettemann, 1995, Naumann, 2003). Onboard satellite navigation can assist foresters by marking skidding tracks in forest stands. Can an accuracy of 10% deviation in forest stands or even in the "sub-meter-region" be achieved? Also exterior influences of the signal can influence the accuracy (tab.1).

Table 1: The cause of impreciseness of GNSS (Hamberger, 1999)

Error cause	Influence
Satellite orbit	5-50m
Satellite clock	1 m
Receiver	mm...m array
Ionosphere	0.5...>100m
Troposphere	0.01-0.5m
Multipath	m array
Antenna	mm...cm array

The main causes of errors are (Hamberger, 2002):
- Atmospheric errors in the ionosphere and troposphere
- Clock error
- Multi-path receipt, reflections at surfaces of the antenna
- Constellation of the satellites around an exact position

In these context two different satellite navigation systems, the Russian GLONASS and the American NAVSTAR-GPS, as two examples of Global navigation Satellite system (GNSS), have been compared in a diploma thesis concerning their accuracy and usefulness in forestry (tab.2).

Table 2: The comparison of GPS and GLONASS

	GPS	GLONASS
Number of satellites	24	14 (+3)
Flight height	20180 km	19130 km
Frequence	1176,4 – 1575,4 MHz	1602.5 – 1615.5 MHz
Single Accurracy	> 5 m	< 50 m
Type of signal / Bands	L1, L2, L3, L4, L5	L1 (SP, HP)
Max. Satellites	12	12

Global navigation Satellite system

Global navigation Satellite system (GNSS) is the name for a system for positioning on earth and in air by the receipt of satellite signals. GNSS satellites communicate its exact position and time over radio. For positioning the observer must receive the signals at the same time from at least four independent satellites. By determination of the running time and triangulation he derives from it his own position.

GPS – Global Positioning System
GPS is a navigational system that calculates a position from 24 satellites orbiting the earth. The first satellite launched 1978. The Global Positioning System, usually called GPS (the US military refers to it as NAVSTAR GPS - Navigation Signal Timing and Ranging Global Positioning System), is the only operational satellite navigation system.

Satellite Navigation Systems can be used for determining one's precise location and providing a highly accurate time reference almost anywhere on Earth or in Earth orbit. The accuracy of the GPS signal itself is about 5 meters (16 ft) as of 2005 and has steadily improved over the last 15 years.

The GPS system was designed by and is controlled by the United States Department of Defence and can be used by anyone, free of charge. The GPS system is divided into three segments: space, control and user. The space segment comprises the GPS satellite constellation of at least 24 satellites in an intermediate circular orbit (ICO). The satellites circle the earth at a value of 20180 km.

The control segment comprises ground stations around the world that are responsible for monitoring the flight paths of the GPS satellites, synchronizing the satellites' onboard atomic clocks, and uploading data for transmission by the satellites. The user segment consists of GPS receivers used for both military and civilian applications. A GPS receiver decodes time signal transmissions from multiple satellites and calculates its position by triangulation. (Bauer, 2003)

GLONASS
GLONASS (GLObal NAvigation Satellite System) is a radio satellite navigation system. It represents the Russian counterpart to the United States' GPS system and the European Union's unfinished Galileo positioning system. GLONASS is operated for the Russian government by the Russian Space Forces.

The horizontal positioning accuracy is about 55 meters and the vertical positioning is about 70 meters. A more accurate signal is available for Russian military use only. Currently there are 14 satellites flying on three earth orbits in 19130 km height. In 2006 three further satellites will be activated (NAUMANN, 2005).

The goal for the next years is the maximum configuration of 24 satellites. The satellites circle the earth in 11 hours and 15 minutes and are bent with 64.8° inclination to the equator. The control segment consists of four stations, one master station and three transmission stations to the satellites. These stations exclusively are in the area of the former USSR (FARMER, 2002).

Research Area and Technical Equipment

The Research area is a two hectare forest stand in Northern Germany (Harz), forest department Lilienberg. A total of 31 skidding tracks have been applied (fig.1). The research area has a size of 20.7 ha in the department 2239 a1. The main tree species is spruce with an age of 101 years. The upper height is 30,9m (tab.3).

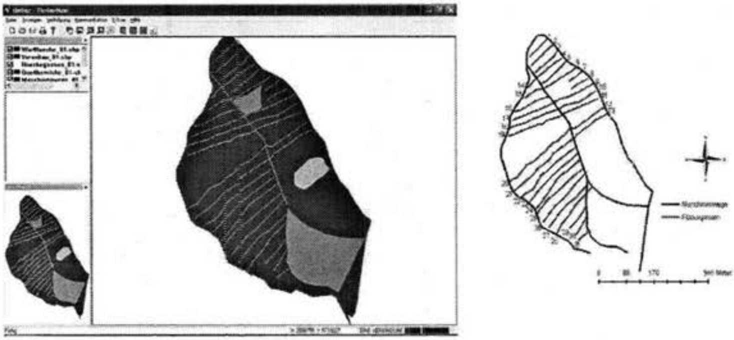

Figure 1: Research area with skidding tracks (red)

Table 3: The forest stand

Tree species	Age	Upper height	BHD	Crown conclusion degree	Stocking degree
Spruce	101 years	30.9 m	34 cm	closed	0.9
Beech (understory)	13 years			closed	0.7

The preparation of the skidding tracks depends on the local conditions. In addition soil damage should be limited as far as possible. The slope angle should not exceed uphill 15% and downhill 30% for forest machines with loading. The width of the skidding tracks should be amounts 4.0 m. The distances between the skidding tracks depend on the age of the forest stand. In this research 20 m was selected.

The investigations were accomplished in May 2005 and in July 2005. The forest stand has various slope angles, represented from plateau situations to heavy slope angles. Altogether four different classes, "plateau", "light slope", "medium slope" and "heavy slope", were examined. No skidding tracks had been marked before.

TimberJack 1470 D

The Harvester was a Timberjack 1470 D (fig.2). This harvester is a typical machine for the forest employment in Germany. As software the "Timber Navi" Software as part of the "Timber Office" software product and the GIS software ArcGIS 9.1 by ESRI were used. The software was tested and used to visualize and compare the accuracy of both systems. The harvester was equipped with a Leadtek Smart Antenna mouse with USB interface. In addition to these two systems corrected data of a mobile differential satellite navigation service (DGPS) was used. This reference was offered by the German ASCOS service.

Figure 2: The Harvester Timberjack 1470 D

ASCOS

In addition to these GNSS a corrected data of a mobile differential satellite navigation service was used. For Germany there are a lot of services that supply corrected data in real time. They can be received over different media. For this investigation the corrected data service ASCOS was used from the company 'eon ruhrgas AG' via a GSM mobile telephone.

For the correction of the data the user can choose between two procedures. The first one is a virtual reference station (VRS) and the second one is the employment of surface correction parameters (FKP) which could be selected. In this examination only the VRS was used. For the VRS variant a bi-directional connection (according to GSM) must be established between the control centre and the user.

The VRS communicates the rough position of the user to the control station. According to the transmitted data a virtual reference station in the direct environment of the user, will be calculated. This is where the user receives the corrected data from.

A goal of this procedure is it to keep the distance between basis station and user as short as possible, because a long distance causes inaccuracies during the positioning (NAUMANN, 2003).

Almanach

As already described the GPS satellites circle the earth at a height of 20180 km, while the GLONASS satellites circle at a height of 19130 km. These constant orbits can be used to predict the position of the individual satellites with a special software program. So the use can determine the position of the satellites for each point of view and time on earth. Out of this data, the control segment publishes an Almanach for each year with GPS and GLONASS satellites.

In this Almanach the information about the orbit of the next three months is stored. The availability of each satellite at each point of the earth can be determined by this information. With an appropriate software (e.g. Occupation Planning of TOPCON) this data can be plotted (fig.3). Thanks to this technology "bad satellite windows" can be avoided.

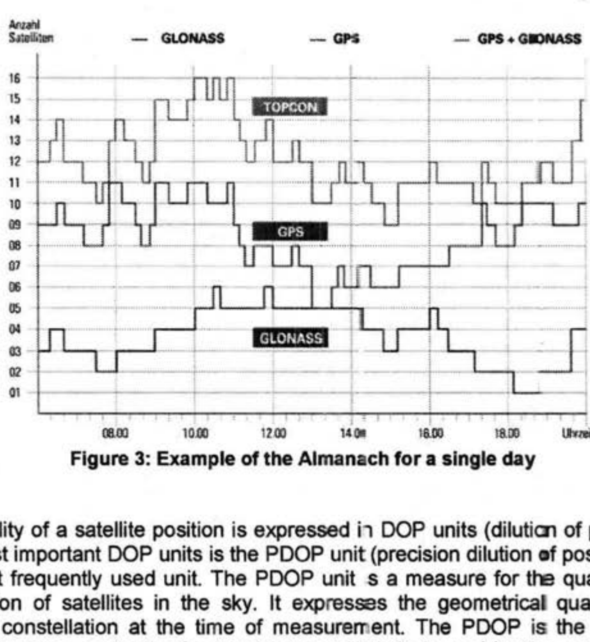

Figure 3: Example of the Almanach for a single day

PDOP

The quality of a satellite position is expressed in DOP units (dilution of precision). The most important DOP units is the PDOP unit (precision dilution of position). It is the most frequently used unit. The PDOP unit is a measure for the quality of the distribution of satellites in the sky. It expresses the geometrical quality of the satellite constellation at the time of measurement. The PDOP is the reciprocal value of volume contents of a tetrahedron, which is formed by the satellites and the user position (fig.4).

In practice this means, the smaller the PDOP value is the more favourable is also the satellite constellation. Since a value of one can be never achieved, values from three to six are good to sufficient. The precision clearly increases with lower values.

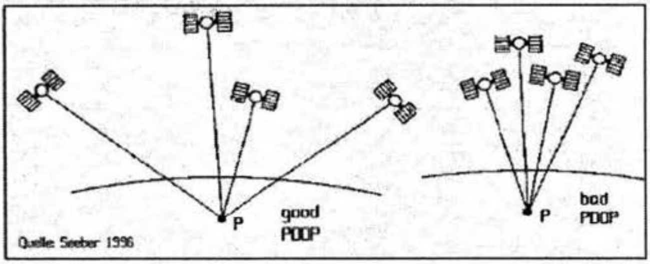

Figure 4: Model of PDOP quality

Figure 5: The Topcon backpack system

The hardware equipment of the backpack solution of the company Topcon consists of the following components (fig. 5):

- GNSS receiver LEGACY-E
- GNSS antenna PGA-1
- Pen PC
- Akku power PAD 160

The Results of the investigation

After the skidding tracks were exactly measured and oriented, the harvester was guided only by the tracking function of the GPS software onto the skidding tracks. The aspect of the slope angle was considered. Therefore four classes, "plateau", "light slope" "medium slope" and "heavy slope", were selected. The harvester was doing his GPS measurement. At the same time the Topcon backpacker system with GPS, GLONASS and ASCOS data was applied to compare these two systems (fig. 2).

GPS on plateau situation
The Harvester began at the southwest end of the skidding track 1 with the processing and moved to the northern direction. The received measured values were good. The maximum deviation was based on point 1357, amounted to 5.43 m. The skidding tracks 2-5 had the same results. On these tracks the same error arose (fig.6).

GPS on light slope inclination
In skidding track 6 the first position gap arouse after 20 meters. This can be explained by a brief signal blackout. The same applied also to the next two skidding tracks. On the tracks 9 to 13 better results were established (fig. 7).

GPS on medium slope inclination
The skidding track 14 was taken from west to the east. The positioning ends after 21 m on the lane. On the way back the measurement reinserted. The same happened to skidding track 15. Better results were established on tracks 18 and 19 (fig.8)

GPS on heavy slope inclination
On this skidding track the position of the GPS signal jumped extremely, in some cases more than 20 meters. The quality of the measurement depends on the availability of satellites. For heavy slope four GPS satellites were not sufficient to determine the position (fig 9).

Topcon measurement
The diagram shows (fig.10) the deviation in meter on the individual skidding tracks. The deviation was measured with the backpack solution by Topcon. On the skidding tracks 1, 2 and 26 is the average value is under 10% deviation. The skidding tracks 3, 4, 5, 20 do not fulfil this condition. The average values of the skidding tracks 3, 4, 20, 26 are settled below the centre, so that the maximum values of these skidding tracks can be interpreted as outliers.

So if you compare the Topcon system that includes the signal from GPS, GLONASS *and* the corrected signal from the ASCOS service, the user will get better results on his measurement; compared to the use of GPS applications only. The arithmetic mean of the of all measurements with the Topcon system was about 3.86 m instead of the single GPS measurement with an average value of 6.11 m (tab.4).

Table 4: Absolute deviation of all measurements

Total measurement	Topcon deviation	Harvester deviation
Mininum	0.00	0.00
Maximum	11.13	26.95
Arithmetic mean	3.86	6.11
Variance	8.02	24.23

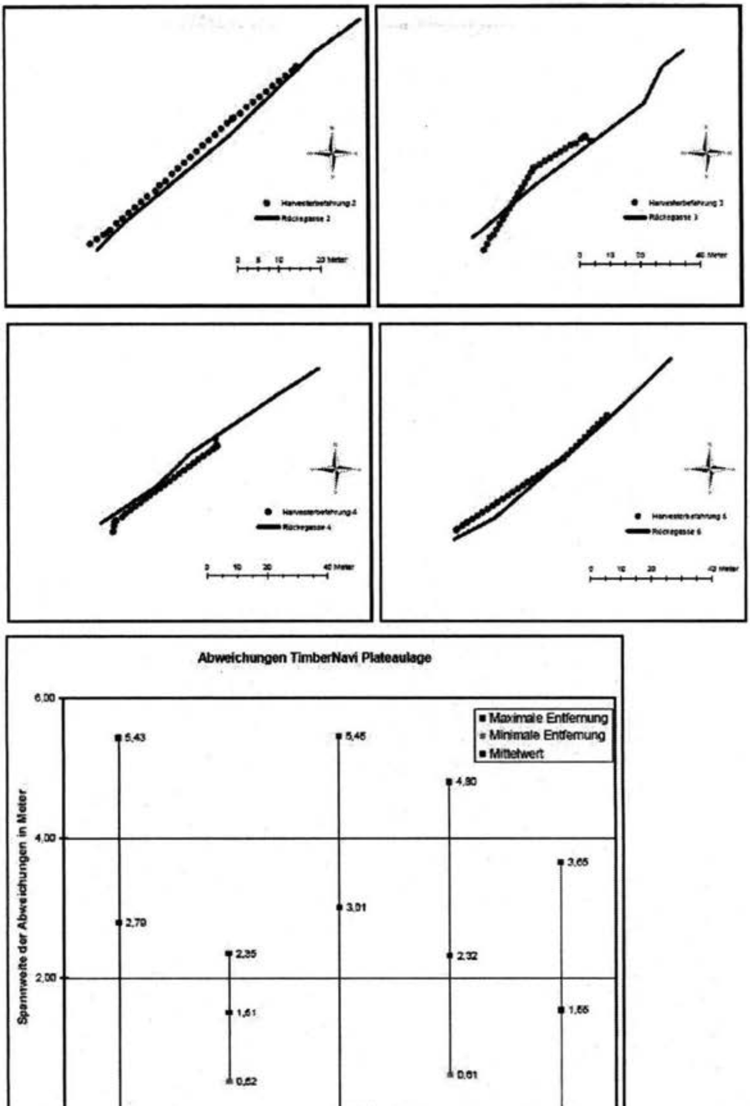

Figure 6: Examples of GPS measurements on plateau situation (tracks 2-5)

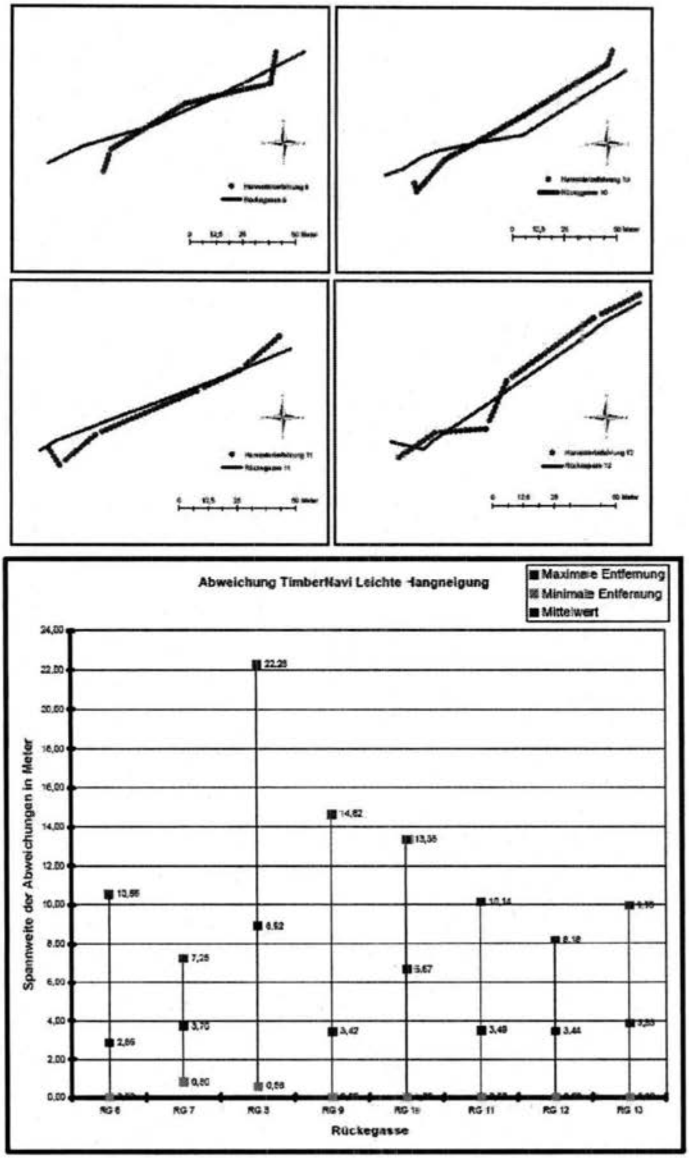

Figure 7: Examples of GPS measurements on light slope situation (tracks 9-12)

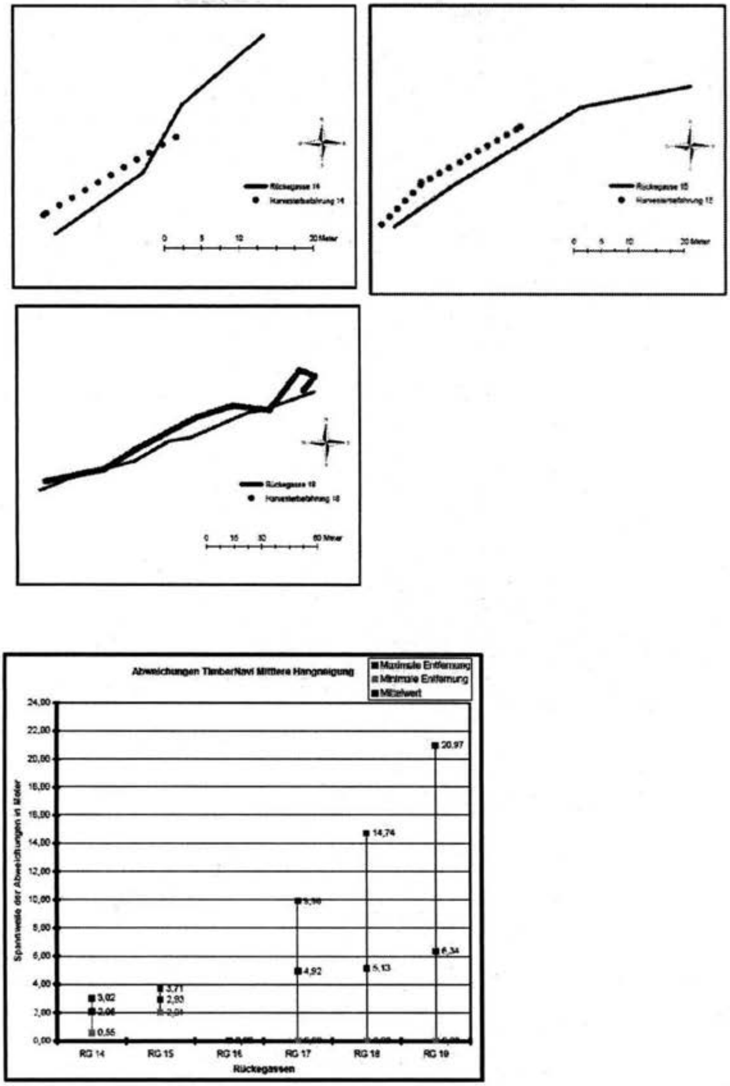

Figure 8: Examples of GPS measurements on medium slope situation (tracks 14, 15 and 18)

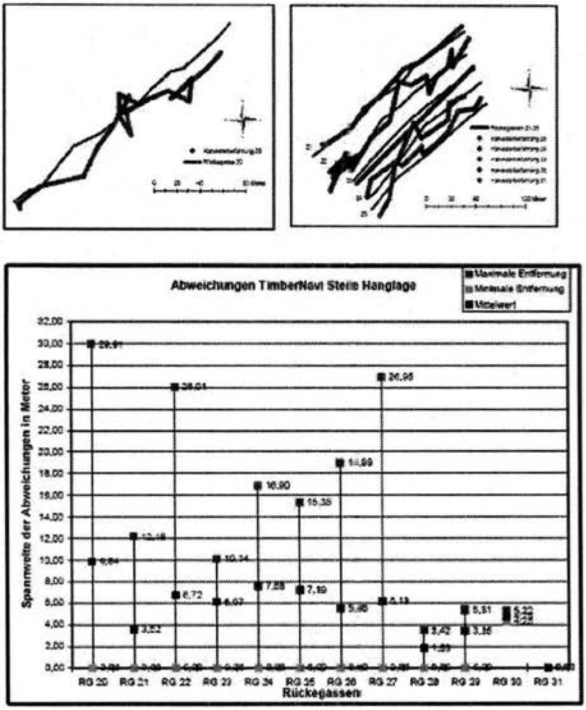

Figure 9: Examples of GPS measurements on heavy slope situation (tracks 20-25)

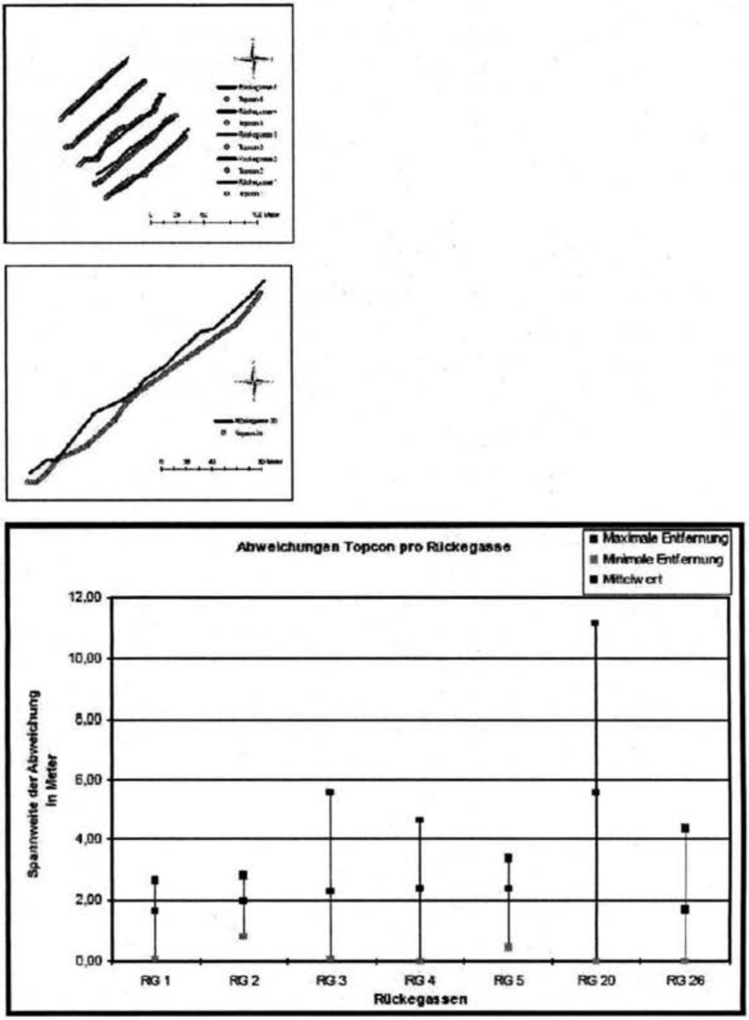

Figure 10: Examples of Topcon measurements

Summary

The main conclusion of this examination was that the accuracy of a satellite navigation system mainly depends on geological aspects, slope angle, exposure and different Global navigation Satellite system (GNSS).

If all these aspects are optimized in respect to their influence on the signal, the user gets less "position gaps" and accuracy with less than 10 % deviation can be achieved (fig.10).

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Website of the company Topcon (www.topcon.com)

EVALUATION OF FORESTRY MACHINERY PERFORMANCE IN HARVESTING OPERATIONS USING GPS TECHNOLOGY

Ronald Cordero, Oscar Mardones, Mauricio Marticorena
Planning Department, Forestal y Agrícola Monteáguila S.A., Chile
E-mail: ronald.cordero@forestal.cmpc.cl

Abstract
A study aiming at defining the best technology, and its limitations, in Global Positioning Systems, for monitoring machinery involved in the various forestry processes. Hence, a Thales-brand GPS device was integrated with a KS-73 PC, with an AMD Elan, 66Mhz processor. This unit was installed on harvesting machinery, specifically on cut-to-length (Harvester-Forwarder) and full-tree (Fellerbuncher-Grapple Skidder) systems. The results obtained, join the graphic-spatial component with its alphanumeric counterparts. By capturing the position where the machines were operating, it is possible to generate surface progress grids, which combined with inventory grids, result in yield information by surface and time unit. Additionally, it is possible to use the graphic information to monitor the compliance with prescriptions and management of the soil resource, among many others.

Keywords: GPS device, monitoring, harvesting machinery, cut-to-length, full tree.

Introduction

GPS technology ability to monitor and track several mobile machines makes it specially attractive for improving forestry, as well as harvesting and transportation processes, by not only optimizing and increasing productivity, but also by ensuring respect and best usage of the soil resources. Some experiences in the area of forestry operations may be reviewed in Ryans (2002), Taylor *et al.* (2001), Holley (2001) and Turcotte (2003). The old question "what are the various forestry equipment doing now?" may be timely answered, as well as the "where?" and "how?". A new tool to minimize costs is in the scope of what is currently called "Precision Forestry". Key operational variables in the productive processes may be kept under control by on-going monitoring and, even better, on-line, real-time access to the performance the equipment is experiencing. Therefore, Forestal y Agrícola Monteáguila S.A., part of the CMPC holding, responsible for supplying *Eucalyptus* pulpwood for the celullose industry in Chile, has initiated a project aiming at incorporating GPS technologies for tracking and monitoring various equipment and machinery involved in the different forestry operations. The main objective is to provide information in time units allowing for a timely forecast, prediction, and correction of actions when necessary, ensuring the correct and efficient use of the soil. Information generated and managed by various players (company, service providers and final customer) will allow for the management of operational variables, and, at the same time, ensuring the compliance with the required productivity levels, and providing traceability to the forest products.

Background

The documented experiences about the use of GPS devices integrated with various pieces of machinery is ample. Thompson et al. (1998) used GPS technology to identify Skidder movements and paths; in such a way to quantify the intensity of path usage of the timber harvesting tracks. An interesting project in the area of time studies developed by Reutebuch *et al.* (1999) for Fellerbunchers and Skidders, among others, shows the positive impact of GPS systems in determining time and yield functions. Although errors observed were high in some instances, technology has improved enough from that year to overcome these negative issues.

Ryans (2002) used GPS to monitor silvicultural operations, such as site preparation and commercial thinning operations, proving the technology was already cost-effective (Trimble Geo II). The disadvantages of the existing units, mentioned in this document, such as the limited capacity to store and transfer data, the need for operators to be familiar with the technology, limited options for power supplies to the GPS devices and the lack of toughness of the devices to withstand hard work have been currently overcome.

Holley (2001) shows the practical application of the real-time harvest concept, and the use of ESRI's ArcPad software, makes the provision of navigation and mapping solutions complying with the needs of real-time harvesting a reality; for example, awareness about the stand and property boundaries, buffer zones, etc.

Turcotte (2003) used GPS and sensors applied in the transportation and road construction areas to capture data about the condition of the forest road network by rigging forest trucks with GPS units. The information collected allowed to know where improvements to the road network were required, in order to effectively schedule maintenance operations.

Methodology

The study started by exploring the technology currently available in the market for Global Positioning Systems (GPS), subject to meeting the following basic requirements: autonomous precision under 5 meters, allowing for the differential correction with base stations, large data storage capacity, ability to use the machine's power supply, programmability, wireless data transfer capabilities, graphic representation of data on screen and, lastly, low cost.

In this way, a Thales-brand, Navigation A12 OEM GPS device, was integrated with a Embedded KS-73 PC (Figure 1).

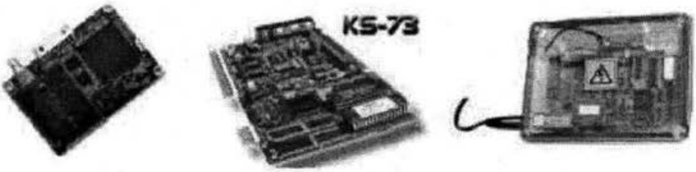

Figure 1. Thales-brand GPS device, KS-73 PC and final GPS-PC integration.

The GPS unit is a 12-channel device, with an autonomous horizontal accuracy of ± 5 meters, with DGPS (differential correction) capabilities and external antenna. The PC's main features are: AMD ELAN 486, 32-bit processor and 66 Mhz CPU, with a high versatility, ideal to interface with machinery, LCS controllers and touch screen, 32 MB RAM, chip hard disk, SRAM back-up battery and real-time clock.

The unit was integrated and configured to operate on 24-V and 12-V machines and their power supply, and with a total cost no exceeding US$2,100.

The integrated unit was installed on two clearcut systems for 12 and 13 year old *Eucalyptus* stands. The first harvesting systems is cut-to-length, consisting of a Timberjack 1270B Harvester and a Timberjack 1710D Forwarder. The second harvesting system is full-tree, consisting of a Tigercat 720C Fellerbuncher and Tigercat 620 Grapple Skidder (Figure 2).

The sites selected were two stands in the VIII Region, involving volcanic and clay soils (Figure 3). The monitoring period covered 27 days, although not complete for each of the involved teams. The stands were the harvesting systems performance was monitored all have flat topography, with slopes ranging from 0% to 20%. The installation of GPS systems involved an external antenna in order to assure a better satellite coverage.
Although programmable, data were collected at 10 second intervals, where position were recorded, as well as altitude, speed and time.

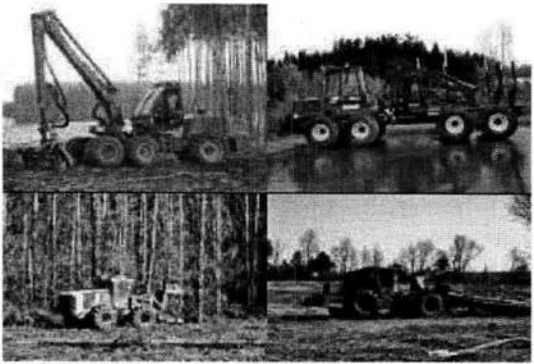

Figure 2. Timberjack 1270B Harvester, Timberjack 1710D Forwarder, Tigercat 720C Fellerbuncher and Tigercat 620 Grapple Skidder.

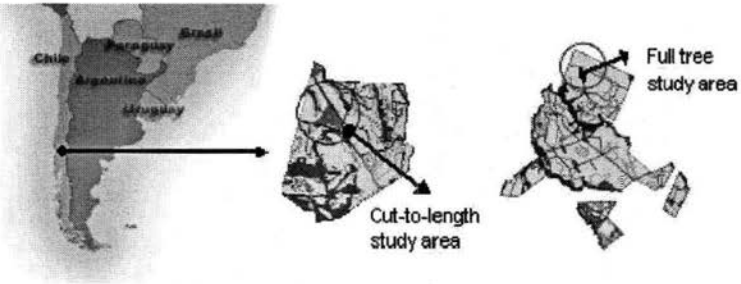

Figure 3. Study areas in the VIII Region of Chile.

Results and Analysis

In the cut-to-length system, a total of 84,362 records were collected for the Harvester operation over a 17-day period. Data were graphed into a chart in order to measure the daily progress on the surface area (Figure 4). According to the speeds registered, it is possible to differentiate when the machine should be in operation (productive time) and when it is not performing productive work. As the GPS device is directly connected to the machine's power supply, it is certain to register when the machine is effectively in operation, since data collection does not rely on whether the operator has turned the GPS device on or off. For the Harvester operating period, it was found the unit was operating 81.3% of the shift time; and out of this time, 88.2% of time the machine was effectively harvesting (Table 1).

According to the daily values (Figure 5), it is possible to note the days with the highest and with the lowest production correspond to Tuesday and Friday, respectively. The above is critically significant for monitoring whether there is any trend over the various days of the week in order to make timely corrections.

Another piece of relevant information is obtained by cross-referencing the coverage with the surface progress, as generated from the GPS-collected data and the iso-volume information resulting from the forest inventory grid (Figure 6). For the case above, Table 1 summarizes the progress in cubic meters produced per day, based on the inventory information. The above exercise is useful when later comparing the base volumes from forest inventories versus the field measurements during harvest, or versus the volume collected by the harvester computer.

Road care, by monitoring harvester paths, or the eventual damage to culverts and ditches by entering the stand through non-authorized locations (Figure 7), or the care to not disturb areas not considered in the production plan (Figure 8), also represent effective management tools.

Harvester operation is particularly affected by slope, among other factors, and the operator must change the felling and processing strategies accordingly (Figure 9). As a result of the above, it would be useful to work on the spatial scheduling of harvesting operations by defining clear graphical goals, such as shift progress, efficient consumption of fuel based on topography, among others.

For the Forwarder, a total of 13,696 records were collected over 4 days of operation. With those data, just like in the case of the Harvester, a surface progress and volume production grid was generated based on the same iso-volume information used in the above exercise (Figure 10). During the survey period, the Forwarder was operating for 38 hours, 35.4 of which were effectively logging operations. Although the survey period was short, it is possible to establish an hourly production of 35.8 cubic meters with a 67.9% of machine up-time (Table 2).

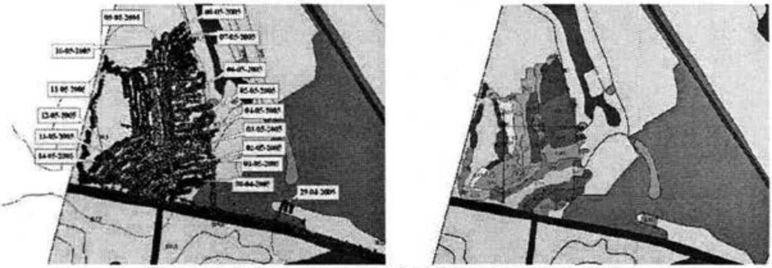

Figure 4. Daily progress and surface area harvested.

From the information generated it is possible to establish the approximate location and length of wood piles (Figure 11), which is really useful if graphic allocations for transportation are intended when trucks do not have GPS technology. On the other hand, this information may lead to spatial management of standing timber stocks, by knowing how they evolve, how long timber lies on the stand, what products are there and where they are located, what type of access is available (summer or winter road). With the same graphic information, it is also possible to measure the compaction effect of logging equipment, through a point-density analysis (Figure 12). From the "Precision Forestry" standpoint, the above analysis is relevant, since it lead the soil ripping decisions, as well as allowing to accurately know how the fragile soils were cared for and the compliance with the harvest prescriptions.

The survey of the full tree harvest system provided the same quality information (Figure 13, 14 and 15). A total of 40,189 records were collected over 13 days of operation (6 days Fellerbuncher and 7 days Grapple Skidder).

Table 1. Statistics for Harvester operating period.

		Time (hours)				Percentages [%]		Production	
Day N°	Day	Operation	Harvest	Movement	Halting	Operation	Production	[ha]	[m3]
1	Friday	5.2	4.8	0.2	0.2	57.8%	92.3%	0.42	165.2
2	Saturday	10.5	9.0	0.3	1.2	58.3%	85.7%	0.49	200.1
3	Sunday	9.8	8.4	0.7	0.7	54.4%	85.7%	0.50	204.9
4	Monday	14.7	13.7	0.7	0.3	81.7%	93.2%	0.78	323.7
5	Tuesday	18.5	17.0	1.3	0.2	102.8%	91.9%	0.83	341.6
6	Wednesday	15.0	13.7	0.7	0.6	83.3%	91.3%	0.70	285.8
7	Thursday	12.8	11.2	0.8	0.8	71.1%	87.5%	0.53	204.7
8	Friday	19.2	17.9	1.2	0.1	106.7%	93.2%	0.97	386.3
9	Saturday	16.5	15.2	1.2	0.1	91.7%	92.1%	0.73	290.7
10	Sunday	16.3	15.1	0.9	0.3	90.6%	92.6%	0.82	333.9
11	Monday	16.1	14.9	0.9	0.3	89.4%	92.5%	0.79	319.7
12	Tuesday	16.6	15.6	0.9	0.1	92.2%	94.0%	0.76	307.3
13	Wednesday	14.0	13.5	0.5	0.0	77.8%	96.4%	0.64	258.8
14	Thursday	15.1	12.8	1.2	1.1	83.9%	84.8%	0.58	235.4
15	Friday	9.6	3.2	0.4	6.0	53.3%	33.3%	0.07	28.0
16	Saturday	17.0	14.3	0.8	2.1	94.4%	84.1%	0.65	262.6
17	Sunday	7.1	6.2	0.7	0.2	78.9%	87.3%	0.36	145.0
Total		234.0	206.5	13.4	14.3	81.3%	88.2%	10.62	4,293.7

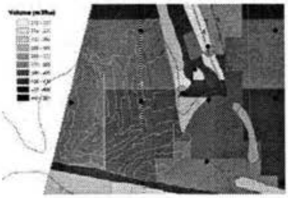

Figure 6. Daily harvester progress crossed with inventory grid.

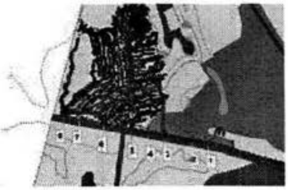

Figure 7. Numbers of harvester entering

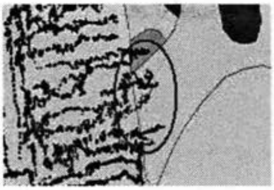

Figure 8. Areas to be not harvested

Figure 9. Felling lines changing due to the slopes

Both the Fellerbuncher and the Skidder operation require, in the real world, shorter times or intervals for data collection. 10-second intervals, as the initial GPS setup, proved to be uneffective in accurate determining the progress over the logged area, thus, not being able to collect information associated to logged volumes per time unit. With shorter intervals the bunches the Fellerbuncher cuts and their subsequent logging should be displayed easier.

The Skidder is recognized by its high impact on the soil (compaction and load dragging). Therefore, it is very valuable to monitor the compliance with harvest prescriptions, as well as the correct usage of the logging tracks (Figure 13), thus providing certainty about where the rehabilitation and soil-ripping silviculture operations should be prioritized.

In addition to monitoring the units involved in harvesting, testing the GPS accuracy was also performed as well as the signal quality in the various sites. As a control for the accuracy possible to accomplish with the used GPS device, and to obtain the differentials of positions caused by local projection, some control points on a road axis were taken with a Trimble GEO XT GPS device, which were collected with a post-process error rate lower than 1 meter. With the above data, the positions provided by the monitoring GPS when the Harvester was moving over the terrain were compared, and it was concluded that the autonomous error in the positioning is lower than 5 meters, in general (Figure 16); all of the above, of course , depending on other factors, such as satellite setup, weather conditions, vegetal cover effect, etc.

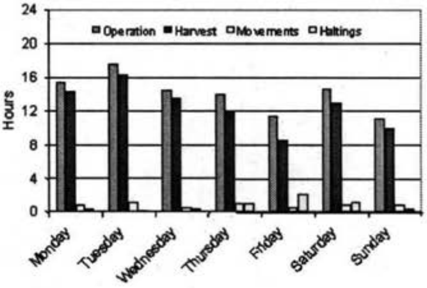

Figure 5. Harvester average week performance

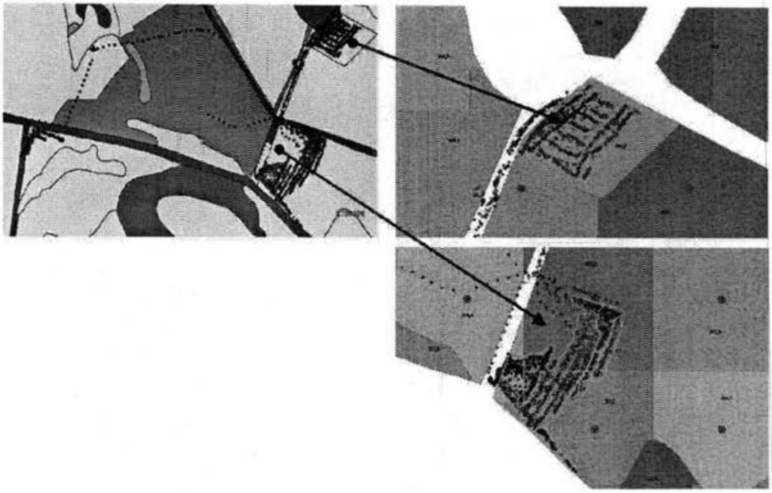

Figure 16. Forwarder surface progress and volume production based on inventory grid.

It must be noted that the GPS device integrated into the monitoring system allows to work in differential model. The present study did not perform that, but it is possible to correct data, either in real-time or in the post-processing, in order to reach error margins close to 1 meter in positioning.

Another significant aspect in GPS evaluation is the number of channels; that is, the maximum number of satellites where information can be captured from, in connection with any position at any given time. The higher the number of satellites, or channels, available to GPS, the higher the accuracy of the position collected. Accurate positioning requires 4 satellites, at a minimum. The Thales GPS device used for monitoring the harvesting equipment has 12 channels. Measurements for the various machines were performed, and their analysis concludes that the Fellerbuncher registered, on average, values round 6 satellites, just like the Harvester; whereas in the case of the Grapple Skidder the average is 8 satellites and 9 satellites for the Forwarder (Figure 17). Also, a smaller standard deviation was observed in the case of the Grapple Skidder and Forwarder when compared to the Fellerbuncher and Harvester. This may be the result of the more open environment the logging equipment operates, whereas the felling units will always have a tree curtain interfering with the GPS signals.

Another quality indicator for the GPS-collected information is PDOP (positional dilution of precision), which indicates loss of accuracy in the positioning (Figure 18). The lower the values of PDOP, the better position quality, with a maximum acceptable of 6. The PDOP value distribution for the various equipment shows that they are all below 6, with average values ranging from 2.4 and 2.5 for the Fellerbuncher and Harvester, respectively, and from 1.5 to 1.8 for the Forwarder and Grapple Skidder. According to the technical features, it is possible to state that values around 2 represent a very good data collection condition.

Table 2. Statistics for Forwarding operating period.

	Time (hours)		Percentages [%]		Production	
Day N°	Operation	Forwarding	Operation	Production	[ha]	[m3]
1	5.0	4.1	62.0%	83.1%	0.57	211.2
2	14.7	13.8	92.0%	93.5%	1.24	469.4
3	7.0	6.5	43.6%	93.5%	0.56	208.7
4	11.4	11.0	71.1%	96.7%	1.07	378.8
Total	38.0	35.4	67.9%	93.1%	3.44	1,268.1

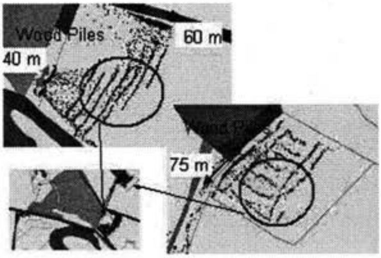

Figure 11. Location of wood piles in forwarding operation.

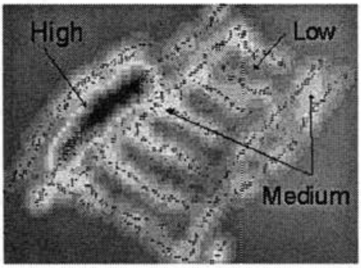

Figure 12. Forwarder compaction effect

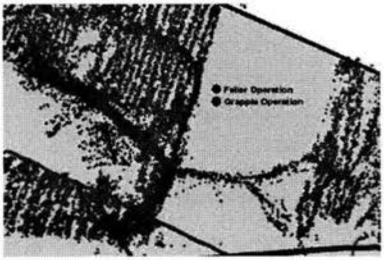

Figure 13. Full tree harvesting system monitoring

Figure 14. Feller progress crossed with Inventory grid.

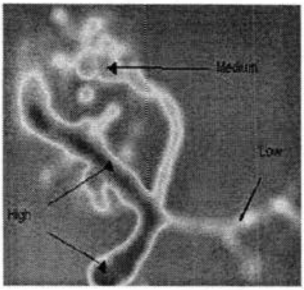

Figure 15. Grapple Skidder compaction effect

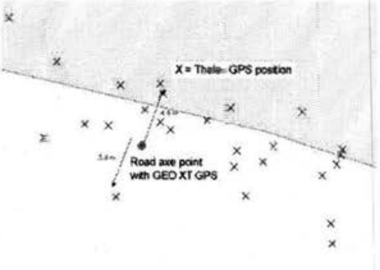

Figure 16. Accuracy test control

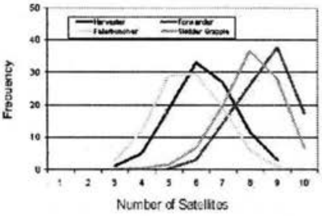

Figure 17. Satellite reception by machine

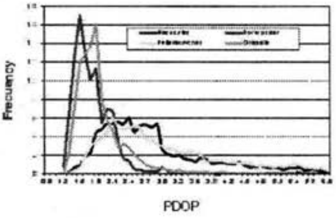

Figure 18. PDOP distribution by machine

Conclusions

The technological integration of the Thales GPS device with the KS-73 PC technically fulfilled current and future expectations for machine monitoring in forestry operations, allowing for incorporating additional features and programs, thus representing an advantage over other similar products existing in its category. The feature it has for allowing customized programming of the unit is critical when different systems and machines have various requirements. This study detected the need to apply different data collection intervals on cut-to-length machinery versus full-tree logging equipment. Since the unit allows for customized programming, only adjusting its capabilities in accordance with the new requirements will be needed. Due to its good autonomous accuracy levels and differential correction capabilities make it attractive for forestry use.

Developing systems suitable for managing and processing large volumes of information and integrating spatial display of them will be important. Demand based on the above will not be meaningless, and that will precisely be the new path this study will approach, in conjunction with solving the automatic and wireless data transmission issues.

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PRECISION FORESTRY AND INFORMATION

- Information Management a forgotten task? -

Christoph Kätsch
Department Forestry & Wood Science, Stellenbosch University, South Africa
E-mail: christop@sun.ac.za

Abstract

The informational base of decisions, which has been widely accepted as being of paramount importance for the enterprises success, is often seen under quantitative aspects only. This holds true for forest enterprises which often rely on large sets of information compiled with high costs. Most of these data are never used in decision making because of irrelevance or poor quality. Information quality in the widest sense often remains unseen or unevaluated although information with low quality can cause even worse decisions compared to those decisions taken under a lack of information.

This paper aims to raise awareness on the issue of Information Quality Management in forest management. It proposes a comprehensive approach for Information Management including the whole information flow from the Data-Level, Information to Knowledge. The tool set proposed so far includes on the one hand side more informal tools which a commonly summarized as information management tools. On the other hand methods of formal information assessment are proposed and discussed. The paper finally proposes a joint effort of all relevant disciplines in forestry science towards common research and development in the field of forest information quality management.

Keywords: Information quality, Information Management, Information Assessment

Introduction

Information has been recognized as being of similar importance as the basic production factors in producing enterprises. It plays an important role in planning, implementation and controlling production processes while supporting the management by providing relevant data on how to dispose of all relevant production factors. Forestry and forest production with all its specific features relies in particular on relevant and accurate information. Depending on the forestry system, large amounts of data need to be compiled, analysed and transformed into information.

Obviously the issue of information useful in running forest operations will cross one's mind when talking about Precision Forestry. In fact most of the papers presented during this and the preliminary conferences here in Stellenbosch report on new and different approaches to produce and to deliver relevant information to the different segments of the forestry production. Keywords like remote sensing, Geographic Information Systems (GIS) and Decision Support Systems (DSS) stand for some of the technical fields forestry research focuses on around the globe since years. All of them aim to produce or to provide better information in the widest sense and there cannot be any doubt, that they contributed much to today's knowledge and helped to reduce uncertainty in forest production substantially. Nevertheless the informational base for managing forest production remains controversial. Compared to other producing industries forestry has to deal with an extraordinary degree of uncertainty on future developments in the forests, a fact which makes the need for relevant information of high quality even more understandable. Beyond this the object "forest" eludes itself from exact mensuration. Several, very different "construction sites", slow reaction times and long lasting production processes which are mostly controlled by natural factors increase uncertainty significantly.

Beside the nature-given factors determining forest production, more "home-made" factors regarding an insufficient provision and use of information should be mentioned. Scientists as well as practitioners often complain that sophisticated new methods and applications for producing information developed by forestry science and other disciplines are integrated or used very reluctantly in practical forestry applications. This fact is well documented for European forestry in several research projects in the last decade but it holds true for many other fields of application in different disciplines as well.

The deeper analysis of this observations brought out, that basically three reasons can be hold responsible for this assessment. First it might be, that information provided by the new method or technology is irrelevant for the use in the day to days decision making, second managers have no confidence in the information and third the information is seen to be too expensive. At least the first two reasons mentioned have to do with an often unseen or underestimated issue: Information Quality.

The benefits from using information depend in particular on its quality. Wrong or insufficient information may become quite costly, if decisions based on it lead into a wrong direction. Unfortunately costs caused by poor information quality are mostly unknown but may reach substantial height and it is obvious that decision making based on wrong or unreliable information is even worse then having no or limited information available.

Information provided by information systems is often seen from a quantitative perspective only. As many information as possible should be available in order to prepare decisions and to minimize the risk, caused by uncertainty about relevant factors and future developments. While concentrating on the quantitative aspects the problem of Information Quality is often not seen.

Present and future developments concerning the forestry sector will produce more and more pressure on the industry to deal with the problem of Information Quality. On the one hand side globalisation leading to a more and more linked and meshed economic environment will increase needs for information about external factors like markets, customer requirements and competitors. On the other hand more and more information is produced by external service providers causing additional concerns on information quality. Albrecht (1999) therefore predicted "The issue of information quality is a sleeping giant, and its effect could dwarf those of product and service quality combined"

This paper aims to raise awareness of the problems related to information management with a specific focus on information quality in forestry. It presents some foundations on information quality management on different levels and proposes a concept for future research in this field. Due to the very complex issue of forest information it will not be possible to present turn-key-solutions for this issue but to present some ideas on how this issue could be addressed in future efforts for Precision Forestry.

The quality of information

For better understanding the issue of information quality it seems to be appropriate to clarify some of the basic concepts of information management and the relation to data and knowledge. Figure 1 shows the continuity from the "character" up to "knowledge".

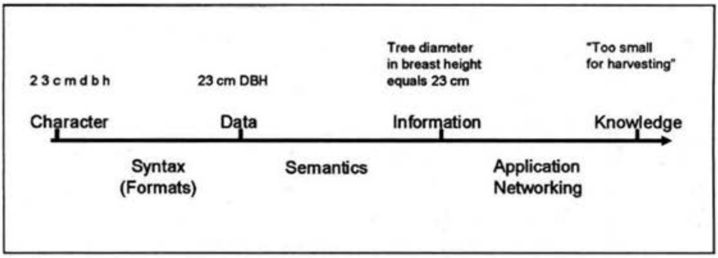

Figure 1: From character to knowledge

Characters forming the base of any information are combined according to a given syntax leading to data. Data normally describe specific properties of entities for example the diameter in breast height of a tree which indicates the thickness of the tree stem at the height of 1.3 m. This data becomes information as soon as it is interpreted for a specific purpose or if it is used in a specific decision problem. Once the information is certified and linked with other information of the relevant sector it becomes knowledge.

The whole transformation process from "character" to "knowledge" can be error prone and of low quality if one of the elements is incorrect, not relevant or not understandable due to poor presentation.

According to NOHR (2001) Information Quality can be defined as the sum of all requirements expected from information in order to fulfil specific information needs. Information that is fit for the use by information customers can be seen as highly qualified information. The quality of information is of course a multidimensional issue including a set of criteria describing very different properties of information.

The most important criteria are:

- *Accuracy*: Accurate information describes properties or the state of relevant objects according to the reality. If the entity can be described with measurable variables the degree of accuracy can be described easily.
- *Reliability*: The user of information should be convinced that any information available is correct in the widest sense. Even if a high accuracy is given for any variable it might be less reliable because of the measurement procedure used.
- *Relevancy and process orientation*: Information of high quality should meet objectively given information needs. Although this criterion seems to be quite understandable, it is one of the more difficult ones. In particular in forest management decision making is often based on individual approaches of information use.
- *Timeliness*: Information that is not available in time is useless and therefore of very low quality.
- *Completeness*: Incomplete information which misses several and crucial parts may be misleading. Normally decisions are based on complex sets of information which add up to a comprehensive picture of the situation to be considered.
- *Presentation*: This criterion deals with the fact that information needs to be presented in a suitable manner. As infomation needs to be interpreted in order to prepare decisions appropriate presentation is an important quality issue.

Although the criteria mentioned above are not listed according to a hierarchy, they will be of different importance in different enterprises. Nevertheless some of the problems experienced with information quality seem to be very similar across all industry sectors. Based on a study carried out in the United Kingdom (ROLPH et al. 1994), managers experience biggest quality problems with the relevancy and topicality of information and its completeness whereas problems with accuracy or reliability of information have been evaluated as being of minor importance.

When assessing information quality according to the criteria listed above, the origin of the information has to be considered. First information which is generated within the enterprise so-called "constructive information" and second "receptive information" which comes from outside the enterprise may have different quality problems. Whereas constructive information is based on more or less clear and understandable data sources, the source for receptive infomation is mostly unknown, making quality criteria like "reliability" more important than others. This externally generated information will play a more and more important role within a globally oriented economy. Beyond this "Out sourcing" which is more and more applied in forest enterprises will increase the flow of "receptive information" into the forest information systems as well.

The quality of information in forest management

The issue of information quality is not unknown to forest managers. Problems with poor accuracy, low precision, incompleteness and missing relevancy or topicality are often mentioned when practitioners argue about forest management plans.

Questions regarding the information requirements in forest management have been discussed quite intensively since decades. Very controversial views to this issue have been presented in dozens of publications all around the globe and it seems that these discussions will continue or intensify with growing economic pressure concerning all components of forest production systems. In particular in forestry systems with high complex silvicultural approaches such as mixed uneven-aged forest stands, practitioners often argue quite intensively which information is required for what purpose (SEKOT 1991, KIRCHMANN 1995, GADOW ET AL. 1995, KÄTSCH 1996, 1998). Even in discussions with South African forest plantation managers one may hear very different opinions about the costly exercise of forest inventories.

For getting a better understanding of these findings and for pointing out the major differences between forestry production and other production sectors it might be helpful to recall the basic structure of the production processes to ones mind. The Figure 2 shown below demonstrates the general production planning and control process in the so-called Y-model.

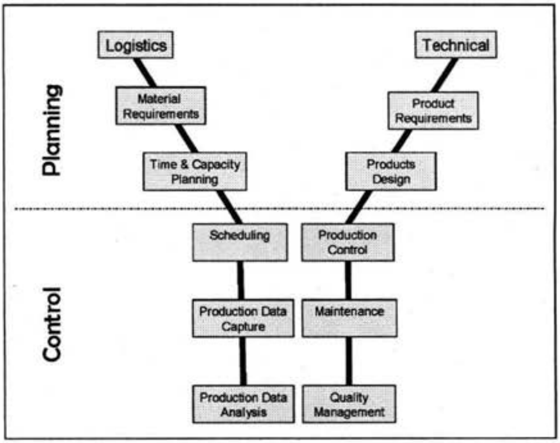

Figure 2: The two lines in the production logistics process

Basically the process contains a logistics line on the one hand side including planning and control of the use of production factors in the process. On the other hand the technical process in all its phases is listed. The planning phase is done separately on the logistics and on the production line whereas both lines are closely linked during the implementation and control phase.

From the informational perspective it is important to realize that the manager running a factory producing clearly defined and easy to assemble products can concentrate on planning and controlling the internal and external logistics of the production processes - which might be a very demanding and complex task - while the technical production process is controlled by machines, robots and computers. These machines use data processors which are in analogy to information systems often called "Non-Information-Systems" because data are not transferred into relevant knowledge or information by the humans involved in the process. The data are directly used in controlling the production process according to predefined rules.

A forest manager has to deal with both, the logistics on the one hand side and the technical production planning, implementation and control on the other hand. On both lines large amounts of information are necessary in order to enable decision-makers to find the right direction of measures to be taken during management.

Basically problems with information quality are similar to those found in other producing enterprises but a major difference lies in the technical part of the system. The technical information is required to control a widely nature-based production with slow reaction times and multiple factors determining growth while interacting in different ways with each other. Producing timber or non-timber products in standard quality and quantity remains a fairly difficult process as mayor growing factors cannot be controlled in the same way as a production machine of a car manufacturer. Even agricultural systems which allow direct inputs by fertilising or irrigation are easy to control compared to a planted or natural grown forest.

Investigations carried out in order to evaluate the use of information in forest management basically led to three major information quality problems:

- the problem of relevancy and topicality of information
- the problem of accuracy, precision and reliability
- the problem of presentation and accessibility of information.

By far the biggest problem experienced so far deals with the question of relevancy and topicality of information. Most of the forest managers questioned in interviews complained that too many and irrelevant information on the technical part of the process are produced during planning and implementation of forest operations.

More serious consequences can follow after the use of inaccurate or simply wrong information. Information about timber volume, tree diameters, growth and yield are often seen as being inaccurate and imprecise und therefore useless. Indeed one may ask, what benefit from the information about the standing timber volume in a compartment is expected, if the real timber volume differs more ther 25% from the estimate. An example from European beech forests may underline this (Figure 3).

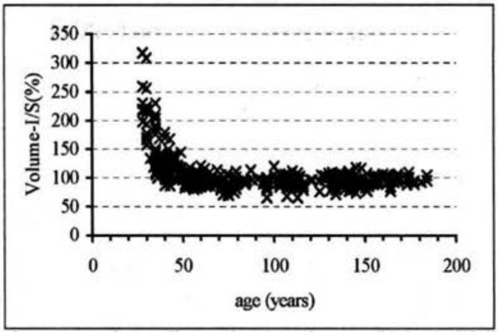

Figure 3: Accuracy of standing volume estimates (Volume I/S (%)) using standard yield tables for European Beech stands in Lower Saxony (Kätsch 1993)

The timber volume per ha estimated by using standard yield tables was compared with highly intensive volume measurements on sample plots. The 100% line indicates the case when both methods led to the same result. In average the differences amount to about 10% but for younger single stands the differences reached nearly 300% (KÄTSCH 1993).

Even worse results are reported when future yields of compartments or plantations are estimated. This has nothing to do with poor management but simply with the fact, that some of the factors determining forest growth cannot be measured and not used for predicting further developments in the forest. PALLET (2005) for example recently mentioned this fact when discussing the meaning of soil and climate information in precise pulp timber production.

Information quality on the logistics side seems to be less critical. According to international publications it is mainly the problem of relevancy which has been discussed quite controversially. In particular for the planning phase different concepts concerning material needs or the financial issues of the whole process have been presented.

With increasing involvement of external service providers in forest operations the amount of receptive information has increased dramatically. The forest manager has to rely on information given by contractors without knowing the exact source of data, the methods employed for measurements and so on. This may cause very specific problems with information quality.

The list of problems may be prolonged several times and there cannot be any doubt that forest management has to deal with severe problems regarding information quality in the widest sense. As a result of this, forest managers often do not rely on the information available and subsequently do not use it anymore.

Concepts for managing Information Quality

Until today no universal concept for managing information quality is available. As the whole issue of information quality is a multidimensional one with very different criteria involved depending on the specific production system, a single, universal concept will never be available. Nevertheless the basic tasks in information quality will be the same.

When thinking about a concept for Information Quality Management two basic facts should be considered:

1. The above mentioned fact that information has become a production factor indicates that this factor requires management as the other production factors do. Managing information includes the generation, the use and the evaluation of information from the quality perspective as well as from the economic side. The issue of Information Quality is a management task which should be considered as such
2. Compared to other products, information has one specific property which makes it quite difficult to evaluate or to compare its quality. Whereas the quality of products such as cars, computers or timber can be assessed in advance by doing a "test drive" or similar, information quality is only visible after it is used. In a short product lifecycle system it may be possible to assess information quality after using the information but when rotation times last 7 to 35 years in south African plantation forestry or 200 years in the northern hemisphere forests it will be nearly impossible to do this kind of information quality control.

Due to this complexity and the extraordinary meaning information has in modern forest industry a multidimensional approach on quality management should be considered including the whole transformation process from data to knowledge according to the transformation chain shown in Figure 4. Data Management, Information Management, Information Design and finally Knowledge Management cover all aspects of Information Quality by providing formal and informal methods of information assessment. The whole process of IQM which is running bidirectional has to be carried out for every business process which has been identified as being of crucial importance for the enterprise's success. The quality of information flowing through every process is analysed carefully leading to a set of quality criteria, indicator sets and quality goals.

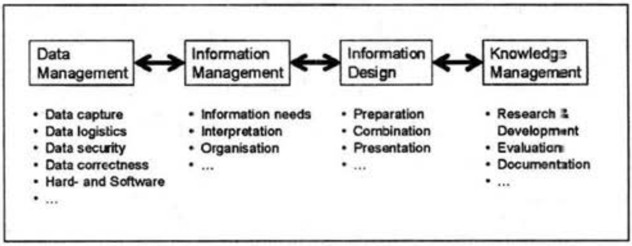

Figure 4: Multi-dimensional approach in Information Quality Management (IQM) (according to NOHR 2001)

The holistic toolset provided by the IQM-Concept should include formal concepts of information assessment which will allow evaluating the contribution of single information or groups of information to enterprises success. The guideline for these formal methods is the criterion of relevancy which has been identified as being a crucial requirement for information of high quality as it includes other criteria like accuracy as well. Information is relevant, if its provision helps to minimize the uncertainty in a specific decision problem. In addition the costs for gathering and presentation of the information should be smaller then the benefit achieved by having the information available. Figure 5 demonstrates the problem which has to be solved. The x-axis represents different sets of information while on the y-axis the monetary dimension of the problem is shown. The information set where the difference between the expected monetary benefit from information and the costs for collecting it reaches its maximum is defined as being optimal.

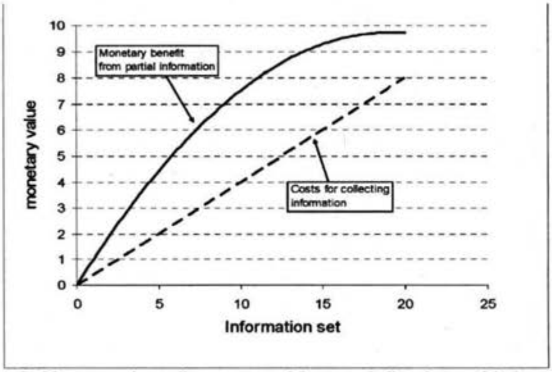

Figure 5: Monetary benefits expected from a defined set of information

Modern informatics provides several formalized methods based on mathematical decision models. Until today basically two different approaches have been developed so far.

The first group includes methods for information assessment founded on the decision theory (see Janko 2005). It is based on the assumption that information has a monetary value according to the monetary benefits which is caused by its use in a decision problem. If no additional benefits are expected, the specific information is not relevant and should not be gathered. Another approach based on the information theory (Shannon 1948). It evaluates the so-called entropy of information, which can be seen as an indicator for the degree of uncertainty in a decision problem. Both methods are based on assumptions about conditional probabilities for benefits from information use which are expected in a specific decision problem. Without going into detail the following example based on an example given by Reucher et al. (2000) may clarify the approach:

A forester has to decide about thinning a pine stand planned to produce high-quality saw timber. Two alternative concepts a_1 and a_2 both linked with specific benefits are possible. The benefits expected from the thinnings may differ according to a good, a medium and a poor result achieved by the thinning. A poor result after concept a_1 has been applied for example may lead to a monetary loss of -550 monetary units whereas a poor outcome of a_2 would result in a loss of -180 monetary units.

		Results PV	
Concept	Good (g)	Medium (m)	Poor (p)
a_1	780	300	-550
a_2	420	270	-180

The forester knows from his experience what results normally are to be expected when a thinning is carried out. Normally good (g) or medium (m) results are to be expected with 70% probability. This knowledge R is expressed as conditional probability:

$$R = \{PV = g \vee PV = m[0,7]\ \}$$

In order to minimize uncertainty the forester plans to do a more intensive inventory providing him with two additional information packages IP_1 and IP_2 including the standing volume I_1 and the stand density I_2.

By knowing this additional information probabilities for the thinnings outcome will be as follows:

$$IP_1 = \{PV = g \mid I_1 = g[0,95], PV = m \mid I_1 = m[0,85], PV = p \mid I_1 = p[0,99]\}$$

$$IP_2 = \{PV = g \mid I_2 = g \vee I_2 = m[0,65], PV = p \mid I_2 = m \vee I_2 = p[0,90]\}$$

By employing an algorithm proposed by REUCHER ET AL. (2000) the monetary benefits for a_1 and a_2 are estimated:

Knowledge	Expected benefit u from a_1 (Monetary units)	Expected benefit u from a_2 (Monetary units)	Information value (Monetary units)
R	$U_{min}(a_1)=45$; $U_{max}(a_1)=381$	$U_{min}(a_2)=135$; $U_{max}(a_2)=240$	
R+IP_1	$U_{min}(a_1)=45$; $U_{max}(a_1)=381$	$U_{min}(a_2)=135$; $U_{max}(a_2)=240$	0
R+IP_2	$U_{min}(a_1)=253$; $U_{max}(a_1)=353$	$U_{min}(a_2)=200$; $U_{max}(a_2)=232$	118

It is obvious, that the information package IP_1 does not contribute to the final results whereas information package IP_2 improves the possible outcome significantly. Its value can be estimated by calculating the difference between the minimum benefit expected with the information available ($U_{min}(a_1) = 253$) and the corresponding value without the information ($U_{min}(a_2) = 135$). As long as costs for gathering this information are lower than the information value it should be collected and used in the decision process.

The problem of the method demonstrated lies in defining the probabilities for the different conditions that may appear in a decision problem. What are the probabilities, that the pine stand will develop itself into a specific direction and how will they change when more relevant information is available?

The second group uses an indirect approach by evaluating changes in jobs and tasks to be carried out by members of the organisation after the introduction of several information sets. A well known example which has been implemented in several industries is the "time saving – time salary model" which is based on the evaluation of savings achieved due to the release of workers caused by the introduction of important information or information systems (SASSONE 1987).

Obviously none of the formal methods of information assessment mentioned have been used in forest information management. In order to move on towards precision forestry it might be worthwhile to evaluate the use of these methods and its benefits for the forest information supply.

Conclusions

The problem of information quality in the widest sense is well known in forest management. Some aspects of this problem – in particular questions of accuracy and precision of data collected through forest inventories and mensuration - have been addressed in several research projects but a comprehensive approach dealing with this issue is missing so far. In particular questions of relevancy and topicality of forest information presented by costly information systems have not been investigated to an adequate degree although high costs for feeding and running information systems often form the base for controversial discussion about the benefits of several information sets.

In order to minimize costs while maximising the benefits derived from highly qualified information forest informatics along with other disciplines like forest mensuration, forest inventory and forest economics should concentrate in a joint effort on developing suitable tools for managing the issue of information quality. As proposed in this paper a multidimensional and comprehensive approach can be used combining more informal methods of information management with formal methods of information assessment. The more informal methods may help to understand and to analyse information quality by structuring the entities involved in the forest production processes whereas formal methods can help to assess the value of information objectively. Like many decision methods the logical base of some models available seems to be quite understandable but it remains difficult to translate the forestry problem into the parameters required.

It is clear, that a sophisticated fully operational management tool for information quality lies far ahead. Forestry production will remain a mostly nature driven process with many unknown and unpredictable factors which can not be controlled like a computer controlled production machine. Most of the information describing the actual state of a forest will remain uncertain due to very complex structures and limited possibilities to get a complete picture of the forest to be managed. In complex silvicultural systems the individual approach of the forest manager based on his personal specific experience and an individual set of information may remain the best adapted method. Nevertheless the critical analysis of information quality should become an important part of forest management.

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FOREST OPERATIONS MANAGEMENT: TOWARDS MOBILE COMMUNICATION

Esko Mikkonen
Department of Forest Resource Management, Helsinki, Finland
E-mail: Esko.Mikkonen@helsinki.fi

Large worldwide operating forest industry companies use modern information and communication technology (ICT) in forest operations management nowadays. Many of the smaller companies are introducing these systems as well. The necessary condition for the use of these systems is a well developed communication infrastructure of the country. Similar systems are applied elsewhere, too, but they may not be as sophisticated as these.

The basic data of the forests is continuously gathered and monitored through inventories both national, provincial, company and private woodlot owner's levels. The data may be available in digital form which allows use of modern GIS systems. The data is based on satellite and aerial images as well as field surveys, so called multi source data. This is important for managing companies' own forests and national forests.

Operative harvesting plans are based on this basic data. Maps and other relevant marked stand's information are shown on the screen of an on-board computer of a harvesting machine. The harvester optimizes the utilization of the stems according to bucking-to-order scheme send wirelessly to the machine. Environmental aspects are monitored through on-line follow-up of the location of the machine alarming the operator of the hazards of exceeding the cutting area borders, protection zones etc. Forwarding follows many times immediately after the logging and the location information of the piles is send to the database. The performance record of the machine is stored in the memory automatically.

After logging the information is sent to company's district office, which organize the optimal long distance transportation schedules given by the optimization routines. The truck fleet can be monitored on-line with GPS or mobile telephone cellular network and rescheduled easily. Text and MMS messages provide big help in mobile communication.

These systems have intensified the use wood procurement resources and cut the costs of operations considerably. Another advantage is that environmental risks of traditional activity, harvesting, can be minimized and thus increase the acceptance of direct commercial use of forests.

This paper gives an example of how information technology is used in Finnish conditions and discusses the pitfalls of applications.

Keywords: Forest operations, wood procurement, management, mobility, communication, information technology

Forest Operations' Information Needs

If one looks at the activities of woodland division of a forest industry company or an independent wood procurement organization they seem to consist of many tasks that have an effect directly or indirectly on the outcome of the operations and thus need to be taken into consideration when managing these activities. Need for precise information is huge.

In modern wood procurement information and communication technology (ICT) plays an essential role. The tools provided by the ICT are geographic information systems (GIS), global positioning systems (GPS), world wide web (WWW), mobile phone or cellular phone networks such as NMT, GSM and UMTS to mention a few.

Wood procurement is basically a logistic process which can be managed with the above mentioned tools. A proper and strong management requires measurement of the efficiency of the organization. This means that planning of activities as well as monitoring is needed on every level of management. Planning can be strategic, tactical or operative.

Management structure can be hierarchic, functional, matrix or team-work type organization. The modern solution seems to be in most cases functional, team work based organization. When dealing with its interest groups different levels of partnership may be applied by the companies. This varies from purely owned operations to complete outsourcing which is the name of the game today.

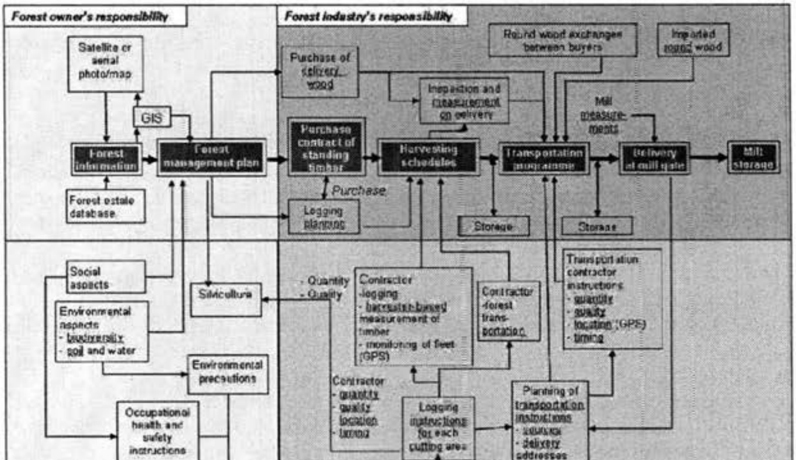

Figure 1. Typical supply chain.

The purpose of wood procurement in supply chain is to fulfill the raw material need of an individual mill or the entire company (figure 1). It forms the framework for the forest operations management. The arrows in the figure show the relations between the activities and auxiliary activities. Auxiliary activities are needed to help carry out the actual forest operation more cost efficiently. Such an activity is wood measurement, for instance.

Harvesting in these examples is supposed to be carried out using shortwood or cut-to-length (CTL) systems which is typical in the Nordic countries. Of course, similar type of structures can be found in any wood supply systems.

The forest operations management starts with an annual strategic wood procurement plan based on pre-orders of the mills drawn from market development estimates for products. From that information a tentative wood purchase plan as well as preliminary transportation plan is being developed. These plans allocate the volumes of different assortments needed to the procurement districts and calculate the other resources required to carry out the task. At this stage just a small portion of the stands to be cut is known, most likely only the geographic area where they are supposed to come. This is due to the fact that the raw material needs to be bought from the free timber market in the form of pre-marked stands. Only a small portion comes from companies own forests in Finland.

In the countries where the state owns the forests and sell harvesting concessions the approach might be different as regards planning. As time goes by these plans are revised quarterly to the tactical plans. At this stage the stands have been bought and the information is available. In the sales contract the forest owner and wood buyer agree upon the length of period during which the harvesting must be completed.

The information gathered for these plans does not necessarily need to transferred quickly, it can be collected from various databases. Of course better mobility in data collection makes the process much faster and efficient.

In the next step monthly and weekly operative plans are developed including the harvesting and transportation schedules for the stands to be harvested. For these plans and operational decisions mobility in data collection and usability is a must.

Buying of timber from free market is the most important activity in conditions where the public supply of timber is insignificant. In a team based organization this activity is carried out by a specialist who knows the local conditions very well.
The information on the stand characteristics from sales contract is transferred into the information system of the company for further planning activities. The reliability of this information is crucial, because all the following management measures are based on this.

Forest owners' forest management plans are very important source of information for this purpose. However, they are confidential and controlled by the forest owner. So, many times this in information is fed into the company's systems in the timber sale situation only.

Own forests are a minor source of wood for Nordic companies but world wide this is rather common. However, companies have long term forest management plans for their own forests. These utilize nowadays modern planning tools such as GIS. From this data source the actual harvesting schedules can be defined and executed. Companies tend to use their own forest resource to balance the timber flow. One typical trend today is to outsource the forest property and forestry to separate companies due to the low return on investment expected from traditional forestry. Owing the forests would decrease the return on investment figures of the actual forest industry business.

Planning and management of operations in mobile environment

As was presented earlier, the raw material flows from the forest to the mills and management information basically to the reverse direction.

Strategic planning is carried out both at company's woodland division and district levels. At this stage mobile information collection is not a necessity.

Tactical planning concerns basically logistics, how to get the raw material most efficiently to the mills. These plans are made at districts' level except for imported wood which is handled at woodland department level. These plans are up-dated quarterly. At this stage mobile information collection is not a necessity either.

Operative plans consist of the actual instructions by whom, how and when the operations must be completed.

Figure 2. An example of the structure of communication network in wood procurement.

Once the company has got the authority to cut the stand owing to sales contract, and the information is passed to the planning system, the operations management i.e. harvesting and transportation plans are prepared. These include the assortment to be made, the destinations for them, schedules of the actions and other necessary plans such as precautions for the environmental risks. These are then adjusted to the other stands' information purchased from the same area to optimize the use of resources available. The plans are then converted to day-to-day instructions for the contractors available for the task.

Monitoring of the operations produces daily and weekly reports of the progress of operations. If something goes wrong, the team can quickly interfere in the situation by smoothly adjusting instructions. The most handy way is to use mobile options both in collection and use of information.

Harvesting of the stands is almost completely mechanized with harvesters and feller-bunchers in company operations in the Nordic countries. To some extent chain saws are used especially in thinnings and special wood logging as well as self-sufficient forest owners' harvesting. Regardless of the level of mechanization, shortwood system is applied. Off-road transportation is carried out by forwarders, which carry the load to the road side. Skidding is very exceptional operation in the Nordic countries.

The companies have outsourced their forest operations to contractors almost to 100 %. This means that the contractors have to go mobile in their operations management which means extra investments.

ICT goes mobile

Modern wood procurement relies heavily on quick and reliable transfer of information. Tools are GIS, GPS, mobile phones, text messages and wireless communication. There is a lot of information technology in a modern harvesting machine. They are equipped with an on-board computer that in addition to wood measurement functions also monitors the state of the machine operation itself.

From the operations management point of view the correct wood measurement and cross-cutting instructions are essential. At this point a wrong decision might destroy the value of the timber. This is because a customer oriented approach is used. Bucking instructions for individual trees are defined by the bucking-to-value tables or bucking to order tables from the saw mill or plywood mill using the logs. These tables are transferred to harvesting machines wirelessly almost daily, according to the need of the customer. Because of the variety of assortments and sometimes large need for special wood, a group control system for the management of a fleet of harvesters is developed.

Production and productivity figures can be followed continuously as well as the location of machine through GPS. Once the location of the next harvesting site and the stand characteristics in addition to the assortments to be made are known the contractors work independently. They only report daily to the team's office the state of the work end the finishing of the site. This information is used to define the transportation readiness of the assortments. Coordinates of the piles are also available for the route optimization routines of transport scheduling programs.

A well functioning mobile communication network is a must for efficient data transfer between the harvesting equipment and supervision of the work.

Pros and cones of expanding mobility

The companies seem to pursue to as light as possible own organization. This has brought outsourcing into the management of operations. If someone can offer a better cost efficiency than company's own operation would provide they are willing change. For instance, the measurement of wood at the mill is outsourced to the specialized companies, only the information is transferred to the end users.

As mentioned earlier, modern organization for forest operations management is based on teams that act on certain geographic area. Otherwise teams are quite independent; they report their performance to the district office and select the means to reach the goals set by the next organization level.

Supply chain for industrial wood has come faster and shorter in the way that already at the stump the address of the assortments is known. The delivery is as quick as possible and the running capital is kept as low as possible.

We will see even better management in the future once automation advance. This allows even higher productivity, remote monitoring of the operations and the better utilization of raw material and, at the same time, protecting the valuable production environment, the nature.

Increasing mobility serves very well these developments. Time is money, also. Even still more expensive than the old systems, the total savings can be substantial, however, due to increased efficiency and the flexibility to react quickly in a changing situation.

There several systems on the market place for the mobile communication and they don't usually communicate with each other. This might cause extra costs.

Certainly, there are some pitfalls in increasing mobility also. The risks in securing the data increase. If the data is stored in mobile equipment and not transferred immediately, risk of losing it due to mechanical or electrical failure will increase. Certainly the human errors are there, too

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REMOTE SENSING AND CURRENT FORESTRY INFORMATION NEEDS IN SOUTH AFRICA

F. Ahmed
School of Environmental Sciences, University of KwaZulu-Natal, South Africa
E-mail: Ahmed@ukzn.ac.za

Abstract

Remote sensing has been seen as an alternative to the ground survey for forest inventory. Methodologies have been developed since the 1970s to explore the potentials of remote sensing data. Since then, forestry information needs have expanded to include non-timber and environmental aspects. The development of remote sensing methodologies has not been able to meet the information needs at the operational level.

The purpose of this paper is to illustrate the information needs for utilizing remote sensing in South African forestry. The analysis focuses on finding the niches of the information needs and the remote sensing operational applications. The recent developments in remote sensing technologies for retrieving forestry information are reviewed and the potential of remote sensing technologies to offer an alternative to traditional ground-based assessment of forest resources and their use in a variety of forest-related applications are explored. Results indicated that the development of remote sensing methodologies requires the considerations of meeting the information needs, evaluation of infrastructure of the production and delivery of remotely sensed data, and balancing the costs and benefits of retrieving forest resource information at required levels of precision. There are enormous possibilities for the application of remote sensing in forestry that could be adequately investigated and supported. The vast potential of remote sensing in forestry must be learnt and effectively utilized.

Keywords: Remote sensing, forestry information needs, precision.

Introduction

Remote sensing has been seen as an alternative to the ground survey for forest inventory. Methodologies have been developed since the 1970s to explore the potentials of remote sensing data. Since then, forestry information needs have expanded to include non-timber and environmental aspects. The development of remote sensing methodologies has not been able to meet the information needs at the operational level.

Forests control much of ecosystem's dynamics by acting as carbon source and sink, habitat to organisms, and natural controlling media for hydrological cycles. Increasing population growth and associated demands on nature is leading to alarming rate of destruction of forests (Howard, 1991). Moreover, growing and harvesting plantation forests for various end products have been a very important economic activity. Perhaps, this is the main reason why proper management of forests that encompasses inventorying is being necessitated in many places (Howard, 1991).

Historically foresters were among the first ones to make use of remote sensing techniques. Forestry is concerned with the management of forest for wood, wood products, forage, water, wildlife, and recreation. Because the principal raw product from forests is wood, plantation forestry is especially concerned with timber management, maintenance and improvement of existing forest stands, and fire control. Forest inventory using aerial photography was first used in the early 1920s (Howard, 1991). Since then the use of aerial photographs spread rapidly throughout the world. A large number of remote sensing techniques, other than aerial photography, have since been developed. The systems presently available offer a wide range of capabilities.

Remote sensing as a new technology, has proven to be able to meet the demand of data about environmentally related issues in high quality, at fairly low cost, and with an expeditious response (Katsch and Vogt, 1999). Although medium resolution satellite remote sensing is considered one of the most effective and efficient technologies for the primary acquisition of spatially related data, the fairly coarse ground resolution makes these satellite images hardly suitable and feasible for small scale inventories and surveys. The most recent developments of sensor technology, particularly regarding the spatial resolution of the sensors as well as their ability to generate images of the surface of the earth, will undeniably broaden the applications of remote sensing. Currently in the remote sensing community there is a divided research focus on the potential of very high spatial and spectral resolution data for the estimation of forest physiology, as well as structural and biochemical response (Peddle and Johnson, 2000).

There are approximately 2 million hectares of commercial forest in South Africa (DWAF, 1997). Over the last two decades, South Africa has made the transition from a net importer to a net exporter of forest products with an industry of international size and competitiveness. In terms of its contribution to the national economy the sector currently: meets about 90% of domestic demand for forest products, contributes 1.8% to the country's GDP, and employs approximately 124,000 people 25% in saw milling, 38% in the pulp and paper industries and 37% directly in plantations (DWAF, 1997). The figures now stand at R12 billion in contributions to GDP and 170000 jobs (Chamberlain *et al*, 2005). Effective management of commercial forests in South Africa would ensure the sustainability of one of South Africa's important renewable resources.

Maintaining the sustainability and long-term quality of South Africa's forests through effective management is a subject of interest for a variety of private and government groups. Unfortunately, current limitations in field survey techniques with regard to high costs, subjectivity, and low spatial and temporal coverage severely limits decision making by forest resource managers (Ahmed, 2005).

Recent advances such as high resolution and hyperspectral imaging (Curran, 1989, Donoghue, 1999; Underwood *et al*, 2003) combined with new processing techniques (Scarth *et al*, 1999, Rowlinson *et al*, 1999; Ghebremicael *et al*, 2004) offer exciting potential to deliver faster, more accurate and more objective information than has been previously envisaged.

However, a number of uncertainties remain around cost effectiveness, precision, robustness of information and its suitability to address practical, forest industry needs (Behra and Roy, 2002; Rowlinson *et al*, 1999, Rosenqvist *et al*, 2003). There is also uncertainty around where these technologies fit into, replace or complement the overall suite of existing tools available to the forest industry.

With the very rapidly changing pace of remote sensing technology, it is imperative to try and understand the strategic role of remote sensing as part of a cost effective suite of technologies to address the operational needs of the South African forest industry; and determine the potential to address practical problems that can offer increases in efficiency compared with current forestry practices.

The purpose of this study is to illustrate the information needs for utilizing remote sensing in South African forestry. Attempts will be made to assess the information needs of forestry as inputs into forestry management databases and their required level of accuracy and to identify potential application areas of remote sensing technologies in forestry in South Africa.

Interviews and workshops with forest information users (government departments and forest industry) were held. An extensive literature survey on the recent developments in remote sensing technologies and their applications in forestry was also undertaken.

Forestry Information Needs

Remotely sensed data have a key role to play in forest plantation management. Since the last few decades, more information has been needed on forested lands than before (Katsch and Vogt, 1999). In the fifties of this century, forest inventory focused on timber production information. In the late 1980s, the information on global warming, biomass, and multiple utilisations of forest resources were required in addition to the timber production information. Table 1 outlines the forestry information needs as classified by the functions of forests.

Table 1: Forestry information needs classified by the functions of forests:

Timber Production	**Variable / data type**
Trees (stand)	Wooded area (ha or % of terrain), Species composition (dominant sp., stand type), Structure (high forest, coppice etc.), Age (class), Stocking (trees/ha), Diameter, Height, Quality, Health, Damage (fire, storm), crown cover, canopy closure, basal area, volume, aboveground biomass, leaf area index (LAI), and mean annual increment (MAI)
Ecological Factors (site)	Soil types, Vegetation types (ground or lesser vegetation), Topographic (elevation, aspect, slope), Climate.
Management	Ownership (state/private), Objectives, Protection status
Forest protection	**Variable / data type**
Stand	Forest area (actual/potential ratio), Species Composition, Structure (horizontal, vertical)
Site	Soil, Vegetation types, Topography (elevation, aspect, slope), Climate
Stability	Forest condition, Quality, health
Management	Value of protected infrastructure, Water resources, Objectives
Ecosystem	**Variable / data type**
Carbon Cycle	Woody and herb biomass, Soil organic matter, Climate
Biodiversity - Ecosystem	Vegetation type, Vegetation cover, Pattern of vegetation, Naturalness; management history, age, exotic species, Management objectives, Forest condition (rate of change)
Biodiversity - Species	Species composition (including rare species), Species richness (indicator species), Pattern (corridors / networks), Threats to sp. diversity; human disturbance, pollutant deposition, exotic species
Sustainability	Management objectives / history / planning and Land use change

Forestry information users are environmental organizations, government forestry departments, research institutions, forestry industry, and forest owners. The forestry industry and forest owners require information at the tree or stand level and the national (or international) institutes need information at the local, national, or regional level. In order to meet the needs, it is clear that the information collected from forests should be at the stand level to meet the different level of information requirements. Accurate stand level information is needed for management planning from the forest owners, forest industry, research and academic institute, and national ministries.

The information needs listed below (Table 1) are not exclusive, but they represent the main information needs for various purposes. Information needed for timber production, forest protection, or ecosystem analysis varies in scale or resolution and frequency, and hence requires remote sensors of appropriate spectral, spatial and temporal resolutions.

The main results of the forestry user requirement assessment were: the main use of the forestry information was for forest monitoring and research. Forest management planning was also an important use of the information. In terms of data collection methodology, ground survey was commonly used. Earth observation data were not commonly used by most users to obtain the needed information. A large number of variables were identified by the users to be important (Table 1).

The results also suggested that the information needs from forestry are demanding and that an infrastructure for processing remotely sensed data is essential for retrieving information from the data at the operational level. Also the balance between costs and benefits of utilizing remote sensing techniques compared to the ground surveys has to be evaluated.

An increasing demand for sustainable forest management has been declared in international conferences. The list of criteria and indicators showed the needs for a comparable set of quantitative and qualitative information on forests to facilitate the international co-operations.

The recent development of the United Nation framework convention for climate change needs the information on forests to evaluate the carbon cycle and potential carbon sinks (UNFCCC, 1998). The Kyoto protocol requires the information on sources and removals by sinks forestry activities limited to '...net changes in greenhouse gas emissions resulting from direct human-induced land use change and afforestation, reforestation, and, deforestation since 1990' (Kyoto Protocol, 1998). Based on the descriptions in the Kyoto protocol South African forest information needs are: spatial information (land-use types and distributions), temporal information (time series data on forest cover changes), and statistical information (land area and biomass data)

Disregarding the fact that the terms of afforestation and reforestation are not clearly defined, it appears that the information needs are more demanding since the spatial and temporal changes of land cover and land use are needed.

The results show that aerial photographs are used to map forest covers and boundaries and interpreting quantitative data at the stand level for forest management planning purposes. Satellite imagery is not widely used in forest inventories in South Africa as a number of uncertainties remain around cost effectiveness, precision, robustness of information and its suitability to address practical, forest industry needs.

Comparing the currently available remote sensing instruments, most information needs could be satisfied only by the high-resolution sensors (Ahmed, 2005). Table 2 shows the feasibility of using optical (multispectral) remote sensing of different spatial resolutions in forestry, which is based on a set of nomenclatures, of retrieval forest information from remote sensing, based on expert opinions and the available research results.

Table 2: Feasibility of remote sensing in forestry applications (Adapted from Köhl and Päivinen, 1996). Feasible: over 80% of the pixels correctly classified; possible feasible: 50-80% correctly classified; and not feasible: under 50% correctly classified.

Attribute	Area (ha)	High resolution sensors (e.g. aerial photo camera)	Medium resolution sensors (e.g. Landsat TM)	Low resolution sensors (e.g. NOAA/AVHRR)
Forest area	1	Feasible	Possible feasible	Not feasible
	100	Feasible	Feasible	Possible feasible
Stand structure	1	Feasible	Possible feasible	Not feasible
	100	Feasible	Feasible	Not feasible
Vegetation type	1	Feasible	Possible feasible	Not feasible
	100	Feasible	Feasible	Not feasible
Diameter	Tree	Not feasible	Not feasible	Not feasible
	stanc	Possible feasible	Possible feasible	Not feasible
Volume	1	Feasible	Not feasible	Not feasible
	100	Feasible	Feasible	Not feasible
Woody biomass	1	Feasible	Not feasible	Not feasible
	100	Feasible	Feasible	Not feasible
Drain/removals	1	Feasible	Possible feasible	Not feasible
	100	Feasible	Feasible	Not feasible
Damage	1	Feasible	Possible feasible	Not feasible
	100	Feasible	Feasible	Not feasible
Health	Tree	Feasible	Not feasible	Not feasible
Topography	0.5	Possible feasible	Not feasible	Not feasible
	1	Possible feasible	Possible feasible	Not feasible
Arrangement of patches	1	Feasible	Possible feasible	Not feasible
	100	Feasible	Feasible	Not feasible
Soil type	1	Feasible	Possible feasible	Not feasible
	100	Feasible	Feasible	Not feasible

It can be seen from Table 2 that it is practically not feasible to extract forest attributes (except forest area at 100 ha) using low resolution optical sensors. It is feasible to determine almost all forest attributes using high resolution imagery with a minimum mapping unit of 1 ha. However, tree diameter cannot be determined using high resolution imagery. While tree diameter and health and volume of timber cannot be estimated using medium resolution imagery, other forest attributes can feasibly be extracted from such data.

Potential Applications of Remote Sensing in Forestry in South Africa

The diversity of remote sensing instruments, both optical (covering the visible and infrared portions of the electromagnetic spectrum) and microwave (Radar) and Lidar, currently available provides data with coarse-to-fine spectral resolution and other characteristics suitable for the quantitative analysis of forests (Peterson and Running, 1989). The mapping scale and accuracies obtained by each sensor are dependent on the spatial and spectral resolutions of each sensor (Ahmed, 2005).

Remote sensing technology applications in forestry take different forms. Most applications have focussed on species identification and classification of forests that make use of the capability to acquire spectral information. Specific applications include: mapping of forest types, assessment of stand structure and forest damage, change detection, forest growth and productivity and foliar and canopy chemistry.

The potential applications of remote sensing in forestry, relevant sensors, processing techniques, and extractable forest information are reviewed in Ahmed (2005). The following is a summary of immediate potential applications in forestry:

Assessment of Stand structure

There is potential to assess structural features of forest using remote sensed imagery and hence provide useful indicators of forest condition at high temporal and spatial resolutions.

It is also possible to examine the utility of remote sensing using neural network for assessing, predicting and mapping important forest structural features (e.g. stem density and basal area).

The utility of satellite data to quantify such forest structure characteristics as crown cover, canopy closure, stems per hectare, tree diameter, basal area, volume, tree height, tree age, aboveground biomass, leaf area index (LAI), and mean annual increment (MAI) could be investigated. This could also incorporate testing a variety of space borne and air borne sensors (high spatial resolution data with image pixels smaller than the dimensions of individual tree crowns) that may allow the delineation of individual trees that, in combination with automatic delineation algorithms, may also offer a mechanism for broad scale assessment of tree crown attributes. Existing algorithms could be tested and perhaps new ones developed.

Assessment of forest damage

The potential use of remote sensing data in the assessment of forest damage, due to *Sirex*, is also worthy of investigation as the spectral signature of stressed trees may indicate not only the degree of stress but also the type of stress.

Medium and high resolution imagery could be processed using Tasselled Cap Transformation and Enhanced Wetness Difference Index to map the infestation and damage caused by *Sirex* in pine stands. Existing Tasselled Cap

Transformations and Enhanced Wetness Difference Indices could be tested and perhaps new ones developed. In addition, once the infestation and damage caused by *Sirex* have been accurately mapped, remote sensing information and GIS climatic/ environmental data could be used to identify, monitor, and anticipate the spread of infestations.

Change detection

Although the spatial resolution of multispectral satellite imagery is far less than that of traditional aerial photography, satellite-based remote sensing offers some important advantages. The ability to identify forest operations in the field and to be able to check against the forest database is critical.

Remote sensing technology has been repeatedly used to detect changes in forestry environments. This has involved both coniferous and tropical forestry, but generally on a regional to global scale. There is a need to develop and test change detection frameworks and algorithms to monitor forest plantation operations at the stand level. This would probably involve the use of high resolution multi-temporal imagery and a multitude of techniques e.g. textural analysis and sub-pixel classifications. New change detection algorithms could possibly be developed.

Forest Growth, Productivity and Water Use

Model predictions of seasonal variation in leaf biomass and productivity rates (using remote sensing) show promising correlation to temporal variation in e.g. NDVI. More work is needed to verify model predictions and improve the correlation of spatial variations in e.g. LAI and productivity to remotely sensed measures.

There is potential for using remote sensing data to provide an alternative means (tested and validated models) of estimating forest productivity in the long term and complement existing approaches aimed at estimating water use of forest crops at stand level, e.g. *Eucalyptus*. It will also be of interest to develop algorithms for the estimation of LAI from remotely sensed vegetation reflectance.

Foliar and Canopy Chemistry

Estimates of the chemical concentrations (e.g. chlorophyll-a and chlorophyll -b; nitrogen; lignin; water content) of forest canopies can be made using hyperspectral data. Estimates of particular chemical elements such as nitrogen can be used for precision forestry practices; fertilization can be applied only to areas with nitrogen deficiencies. The data has applications in the areas of forest health and vigour, water stress, and disease.

Radar in Forestry

There is a need to test the utility of Radar imaging in estimating aboveground biomass, delineating of vegetation cover, and monitoring temporally dynamic processes (e.g. forest operations). The relative efficiency of ERS-2, Radarsat-1, and ENVISAT ASAR is worthy of evaluation. More value could be added if the impact of fusing the above radar data with optical sensors (e.g. Landsat TM) is also assessed.

Lidar in Forestry

There is a need to test the utility of Lidar in estimating selected forest canopy parameters: e.g. aboveground biomass and leaf area index (LAI), tree height, basal area, total biomass, and leaf biomass. Existing processing algorithms for single tree crown identification and those based on the height of all laser pulses within the area covered by the ground truth data could be tested and new ones developed. The potential of combining (fusing) lidar data with other sensors (e.g. Landsat ETM+) to cover a wider area could also be pursued.

Results indicated that the development of remote sensing methodologies requires the considerations of meeting the information needs, evaluation of infrastructure of the production and delivery of remotely sensed data, and balancing the costs and benefits of retrieving forest resource information at required levels of precision.

Conclusions

It seems that a potential convergence of forestry needs and remote sensing products may be at hand. This potential convergence is possibly the result of two independent, but vitally important, factors: the changing forestry business, and the changing remote sensing business. Forestry is now viewed as a biological asset that must be managed to maximize return on investment, rather than as a cost centre that must be managed to reduce costs. Managing forests creates the need to make economically efficient decisions, which creates the need for information, which could generate larger and more consistent markets for digital remote sensing products. On the other hand, the remote sensing development community began to see the forest canopy and the trees rather than noisome interference. While it is absolutely true that the remote sensing development communities need to understand forestry more thoroughly, it is equally true that forest managers need to investigate and fully understand what new remote sensing technologies can provide.

A range of remotely sensed imagery is now available to forest managers in South Africa. The combination of different wavelengths, spectral and spatial resolutions and active and passive systems together with the relevant processing techniques open up immense possibilities for the provision of up-to-date forest information. It is now technically possible to identify individual trees, estimate their size with some accuracy and create a three-dimensional model of a forest using Lidar. It is technically possible to explore the physical and chemical structure of trees using Hyperspectral imagery.

There are unenumerated possibilities for the application of remote sensing in forestry that could be adequately investigated and supported. The vast potential of remote sensing in forestry must be learnt and effectively utilized.

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SIMULATING HARVESTING PROCEDURES TO EVALUATE DIFFERENT WORKING SYSTEMS BASED ON DISCRETE SINGLE TREE EVENTS

Martin Hemm, Martin Ziesak, Walter Warkotsch
Chair of Forest Work Science and Applied Informatics, TU Munich, Germany
E-mail: hemm@forst.tu-muenchen.de

Abstract

The basic idea is to apply industrial simulation software in the wood-supply-chain and modify it in order to develop an optimisation and decision support tool for the right choice of the operating system and the assortments produced. Simulation software is designed to analyse, plan and control material handling systems. In forestry it assists the user to find the most efficient machine combination depending on stand and terrain characteristics. Results show that it is possible to use industrial simulation software to model and analyse different kinds of operational scenarios in forestry based on discrete single tree characteristics. Precise economical and technical impacts of different logging processes can be shown. First simulation models delivered results on productivity, costs and energy consumption. By analysing and comparing the output of different models, the simulation software can be used as decision support system.

Keywords: wood-supply-chain, logistics, simulation software, stand models

Simulation?

With the development of computer technology, simulation has been more and more widely used in many fields of our society. Simulation techniques not only play very important roles in scientific study, but also occupy relevant places in education, military, entertainment and almost any fields that we can imagine.

The Oxford English Dictionary (1989) gives the following definition of simulation:

"The technique of imitating the behaviour of some situation or process (whether economic, military, mechanical, etc.) by means of a suitably analogous situation or apparatus, especially for the purpose of study or personnel training."

The Glossary of Geology (1997) gives a definition of simulation especially appropriate for scientific simulations:

"The representation of a physical system by a device such as a computer or model that imitates the behaviour of the system."

These definitions provide a basic idea of simulation. By the help of simulation software and particular created models an ordinary computer can be transferred into a "virtual lab" where different kinds of experiments get analyzed. It is advantageous to work with this special lab, because it has no restrictions, no direct influence on real operations and almost no resources get lavished. But there are further reasons to use simulation rather than real life experiments:

Costs
Building physical models (prototypes) possibly is an expensive way to receive new results on certain questions. Mostly it is much cheaper to build abstract models on the computer and analyze them. Good examples are planes or skyscrapers where it is difficult to produce prototypes. All important data on technical qualities like air stream, acoustics, vibrations or heat distribution get optimized by the help of simulation.

Exposure
When experimenting with dangerous systems simulation – if possible - should be applied to prevent people and environment from harm.

Observability
In some cases observing real life systems is just difficult or not at all realizable (e.g. inaccessibility, varieties in scale). In contrast during a simulation all influencing factors are observable and the runtime can be enhanced or reduced if necessary.

Interference
At a lot of real life systems interference and respectively experimenting is not possible. By simulating these systems the scientist is able to analyze every aspect of it by varying each parameter at will. There is also no problem to rerun the simulation infinite times.

Interruptions

During the simulation of an existing system interruptions or breakdowns can be caused by request. A good example is the automobile industry where the production has been already optimized to a high level. Even small interruptions in the workflow cause high expenses for the producer. Therefore any modification proposal gets tested by using simulation before the whole process will be paused and adjusted.

History of simulation

For computer scientists the history of simulation starts in the forties of the twentieth century. It was the time when the first real "computers" were built. These machines possessed a modifiable memory unit and could be programmed totally free. They were used for weather, celestial bodies or electric circuitry simulations.

Within the upcoming decades the further development of more and more powerful computers was aroused by challenging simulation tasks and their ever growing need for bigger process and memory capacities. In large part these tasks or projects were conducted by the United States government, especially at the Department of Defence.

Till the eighties simulation was mainly used for special problems, the so called "grand challenges" which required mainframe computers and which promised to deliver results of eminent scientific, technical, economical or social matter.

Today computers are an everyday commodity including a multitude of different application areas from word processing and data management to worldwide communication via internet. For this reason using simulation as a working tool is not a privilege of huge scientific projects anymore but became an instrument available to everyone.

German forestry

Before pointing out the modus operandi of building a simulation model of harvesting operations the main features of forestry in Germany are to be introduced.

Germany possesses about 11 million hectare of forest areas held by private owners (43 %), the state (33 %), corporate bodies (20 %) and trust (4 %). The main tree species are spruce (28 %), pine (24 %), beech (15 %) and oak (10 %). Since more than 250 years the foundation of German forestry is the idea of sustainability, which consists out of three basic principles:

1. maintaining the ecological processes in forests (the formation of soil, energy flows, and the carbon, nutrients and water cycles).

2. maintaining the biological diversity of forests.

3. optimizing the benefits to the community from all uses of forests within these ecological constraints.

These are the main directives of all forestry actions in Germany and Central Europe and of course these restrictions affect the way of acting in the forests. For example in Germany clearcuts are not allowed except for small scaled faces (< 1 hectare) and most logging operations are planned for silvicultural regimes, i.e. single trees have to be cut in order to provide space for the remaining ones and to improve the quality of the stand.

German forestry and its challenges

Enterprises in the forest sector today have to compete on a global timber market. To fulfill the requirements of their customers and to compete with international timber prices it is necessary to reduce operational and transport costs in the timber harvesting process.

The challenge of German Forestry today is to maintain a market oriented timber supply and to become a proactive industry instead of a reactive one. With growing investments into machines, economical aspects are going to be even more important in the future for the positioning of an enterprise on a global timber market. Low operational costs and high technical productivity of the machinery will become increasingly necessary for forest operations. Improvement of the integral logistics management can only be achieved by taking a close look at all elements of the production chain (Warkotsch, Ziesak 1998).

The main task of forest logistics is to manage the material and information flow in all segments of the wood supply chain. In order to be able to respond to the industrial dynamics it is important for the forest enterprises to know precisely their production layout and stand inventory at any time. Planning processes within the operational system that are based on an up-to-date inventory of the raw material could be optimized by using supporting tools like simulation software. Due to the silvicultural approach in Germany approximate information about the spatial location of the selected trees is necessary.

Research methodology and applied simulation technique

An evaluation of different forestry-based calculating and planning tools from various countries gave an insight into already existing software applications. In a study made by Hemm (2002) seven simulation programs for supporting the planning process of forestry operations were tested. The investigation included software packages from Canada, Finland, Sweden, Chile and USA. Most of these simulation tools are designed for regional silvicultural specifics and local harvesting problems, which makes it difficult to use them in Germany without any necessary modifications. Due to these results, the Department of Forest Work Science and Applied Informatics decided to create a new tool, which should assist in finding the most efficient machine combination for harvesting and logging processes.

The next step of the research study was to evaluate simulation software that could be adapted to complex systems such as the forestry production chain. Eight different software packages were compared and evaluated in a multiple goal analysis by means of a catalogue of criteria containing several specific forest requirements. The requirements of the programs on production layout, manufacturing process and products were tested and in the end a program named "AutoMod", developed in the United States by Brooks Automation Inc. was chosen (Bruchner 2000).

AutoMod is parameter-driven and requires computer language based programming as well as visual interactive programming by means of a manufacturing simulator (Banks 1998). Within this discrete simulation a material handling system can be defined with all its physical components in an editing environment in which the logic is also programmed. The simulation can then be run in a simulation environment creating a detailed 3-D real-time visualization of the system (Banks, Carson, Nelson 1999).

Modeling process

A harvesting operation model requires three principal components:

1. **stand area** including positions of forest roads and extraction line system,
2. **stand** including information on position, species, dbh, height and assortments of every single tree,
3. **harvesting and transport systems** including information on capacity, costs and consumption.

The combination of these three components results in a model which can be used as decision support tool for planning harvesting operations and machine employment.

Modeling the stand area

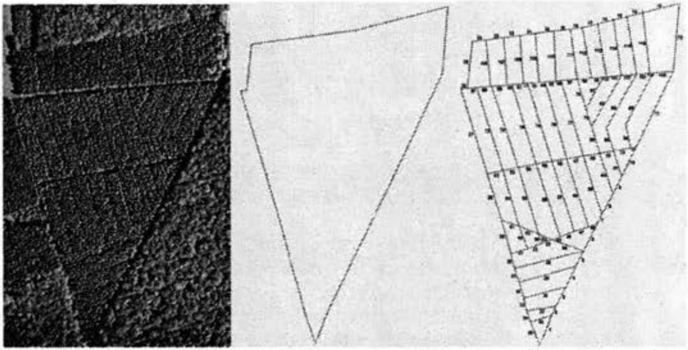


Figure 1: Aerial view, borderlines (GIS), numbered forest roads and extraction line system (GIS) of the test stand

The starting basis of a stand model displays the area on which the trees are growing. At least the borderlines of this area have to be available in a digital format. Therefore the relevant information can be extracted out of a digital terrain model of a test stand (figure 1).

By the help of a geographical information system (GIS) the borderline coordinates get extracted and converted to a local coordinate system in the AutoMod software. They are basis and orientation guide for the integration of the forest roads and the extraction line system. The AutoMod model is working in a two-dimensional environment, because due to the lack of adequate data the development of a three-dimensional one has not been finished until today.

To reproduce the realities of the stand area as real as possible it is necessary to gain coordinates on starting, ending and intersection points of a forest roads or extraction lines in a format suitable to use in a GIS (e.g. Gauss-Krueger-Coordinates). These information can be found by analyzing aerial photographs, maps and of course by collecting it during on site inspections. When all the data is complete it gets merged in a GIS and later on converted and transferred into AutoMod which is the last point of the stand area building process.

The roadways in the model have special attributes, which make it possible to define the roads either as extraction line or as forest road. On the roadways there have been placed control points at regular intervals of one meter. The control points are marks for the machines driving on the roadways, where they can stop and start processing. Next to the forest road four depots are created in which the logged assortments get stored.

Modelling the stand

To build a stand consisting out of single trees there are lots of information needed to assure a realistic image in the model:

- approximate number of trees
- stand age
- information about species, position, dbh and height of every single tree
- information on the intended silivicultural treatment and information on whether a tree has to be cut out or not
- information on quality, diameter, length and volume of the logs and respectively assortments that will be produced during the simulated harvesting operation

At best this data should be provided by the user of the software. That means he should have access to data bases which contain information about every single tree of the stand he likes to model by the help of AutoMod. For example this information could derive from analyses of aerial photographs or systematic samples.
Due to the fact that the stand data is not available in the favoured quality yet the Department of Forest Work Science has developed another strategy to gain it. It has to be pointed out that this way of working is just the best alternative to the more precise stand information that cut be collected by measuring every single tree. If data of this quality would be available it could be used in AutoMod to generate every stand without any problems!

In this project the stand is modelled by using a stand simulator called "SILVA", developed at the Technical University of Munich (Pretzsch, Biber and Dursky, 2002). The research focuses on a stand of eleven hectare size located in Western Germany. Cruise data is taken from systematic samples placed in this certain stand. Then, on the basis of the cruise data the stand is reproduced in SILVA and a tree list is generated by the program, including information about tree number, tree species, dbh and height as well as x- and y-coordinates for every single tree (figure 2).

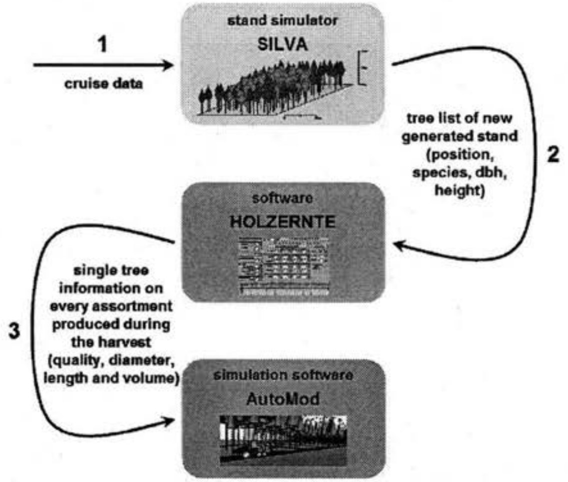


Figure 2: Derivation and integration of the stand and assortment data by the help of SILVA and HOLZERNTE

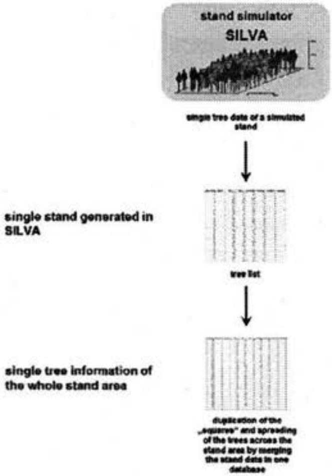


Figure 3: Combination of the stand data of the small SILVA-stands in one database including

This data, listed in a MS Excel table gets transferred to AutoMod and the stand generated by SILVA is reproduced as production plant in the AutoMod virtual reality environment (figure 3).

Unfortunately SILVA just produces quadrangular stands with a maximum area size of one hectare. The squares which are build in Silva get "cloned" and spread across the stand area afterwards by using MS Access queries (figure 4). This method assures that the area gets covered with trees. The program automatically eliminates the overlapping trees by marking them at the respective data base as "not relevant".

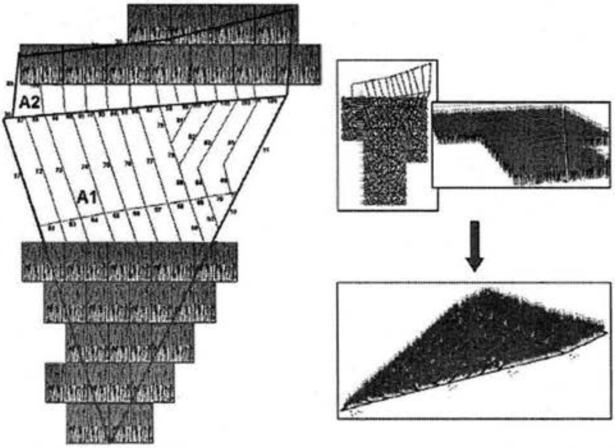


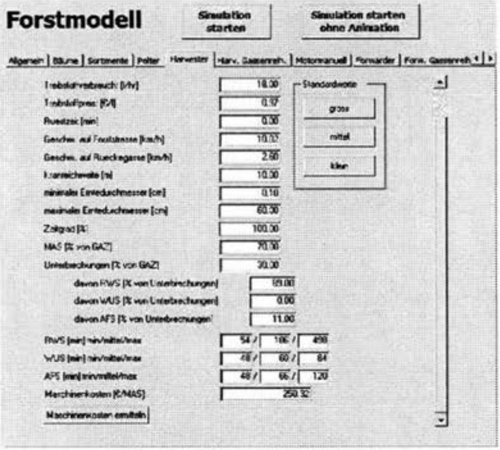
Figure 4: Allocation of the trees across the stand area and elimination of the overlapping trees

But the information, which is necessary to calculate productivity during the simulation is still missing: the number of assortments of each tree and their attributes.

To solve that problem a calculation software called "HOLZERNTE", developed at the FVA Freiburg, Germany, was applied (Hradetzky, Schopfer 2001). Input data for "Holzernte" is the list of trees to cut during the planned harvesting operation. On the basis of this input data the user is able to define the pile he wants to accumulate. HOLZERNTE then calculates the assortments and their attributes for every specified pile. At the end of the calculating process, a MS Access table including the assortments and attributes is generated. This table gets connected with the single tree information in AutoMod, which again is done by using queries. Provided with all necessary tree data the model of the eleven hectare big stand can be generated in AutoMod.

Modeling the working systems

After modelling the production plant, the next step is to simulate the production processes. Therefore two harvesting (harvester, chainsaw workers) and three primary transportation (forwarder, skidder, horse) scenarios have been selected. An interface or "frontend" has been generated, which the operator can use to define relevant machine parameters (figure 5). These parameters can be varied for every new simulation run.



Treibstoffverbrauch [l/h]	18.00
Treibstoffpreis [€/l]	0.97
Ruestzeit [min]	0.00
Geschw. auf Forststrasse [km/h]	10.00
Geschw. auf Rueckegasse [km/h]	2.80
Kranreichweite [m]	10.00
minimaler Erntedurchmesser [cm]	0.10
maximaler Erntedurchmesser [cm]	60.00
Zeitgrad [%]	100.00
MAS [% von GAZ]	70.00
Unterbrechungen [% von GAZ]	30.00
davon RWS [% von Unterbrechungen]	89.00
davon WUS [% von Unterbrechungen]	0.00
davon AFS [% von Unterbrechungen]	11.00
RWS [min] min/mittel/max	54 / 106 / 498
WUS [min] min/mittel/max	48 / 60 / 84
AFS [min] min/mittel/max	48 / 66 / 120
Maschinenkosten [€/MAS]	250.32

Figure 5: Harvester frontend

Table 1: System parameters of the harvester adjustable by the user

parameter	definition
fuel consumption [l/h]	adjustable by user
fuel costs [€/l]	adjustable by user
preparation time [min]	adjustable by user
velocity on forest road [km/h]	adjustable by user
velocity on extraction line [km/h]	adjustable by user
crane range [m]	adjustable by user
minimum and maximum felling diameter [cm]	adjustable by user
rate of labor utilization	adjustable by user
proportion of real working time on total working time [%]	defines the MTBF
MTBF (mean time between failure)	Describes the time between two breakdowns of the harvester. The duration depends on the proportion of real working time on total working time which gets defined by the user.
MTTR (mean time until repair)	Describes the length of the breakdowns by the help of a triangular function with minimum, most likely and maximum values.
machine costs [€/pmh15]	calculated by user

In the following section you will find short explanations of the most important parameters of the harvester, which are the basic requirements for simulating the harvesting and logging processes (table 1):

Each simulation run starts with the compilation of the model. The trees, roadways and machines are generated in the virtual reality environment of AutoMod (figure 6).

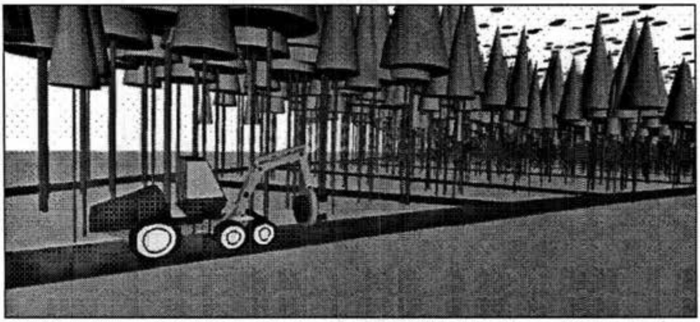


Figure 6: AutoMod virtual reality environment showing harvester processing a stand

After having finished its preparation process, the harvester starts driving on the extraction line to the nearest tree to be cut. It stops on the control point, which is the closest to the tree. There it starts to cut and process the tree and takes down the logs next to the extraction line before moving to the next tree. During this working process a breakdown may occur. In that case the machine stands still at its current position until the repair is finished. The simulation run ends, when all marked trees are cut and processed by the harvester (Ziesak, Bruchner, Hemm 2004).

At the end of each run AutoMod creates an output window. In columns the results of the harvester which are calculated during the simulation are shown (figure 7).

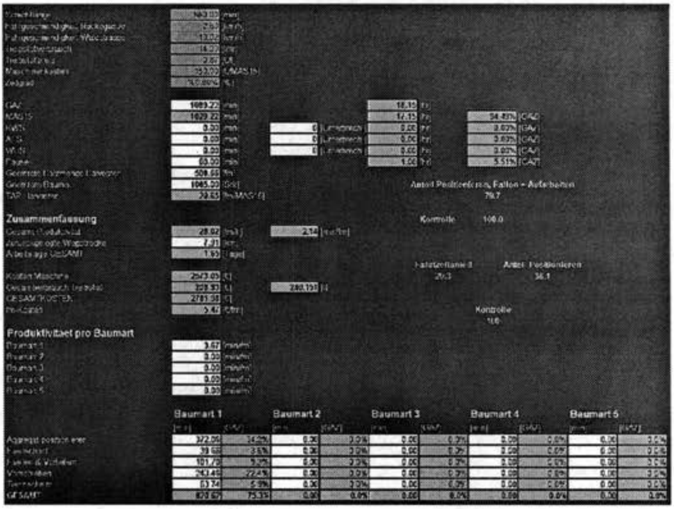


Figure 7: Output window in AutoMod showing the results of the harvester

The output-interface delivers the results of one run. Thereby amongst others the following parameters get calculated for the harvester after each simulation run:

- total working time [h] and [dys]
- net process time [pmh]
- duration and frequency of breakdowns [h] and [qty]
- volume harvested [m^3]
- number of trees harvested [qty]
- productivity [m^3/pmh]
- covered distance [km]
- machine costs [€]
- fuel costs [€]
- total costs [€]
- cost per m^3 [€/m^3]

In AutoMod it is possible to do multiple runs with different settings in the input-interface and in this case multiple output-interfaces are produced. That for example allows the user to compare the output of different scenarios with different types of harvesters and get a decision support.

The procedure shown for the harvester basically works the same with the other four systems. It is also possible to combine several systems:

- harvester + forwarder
- harvester + skidder
- harvester + chainsaw worker + forwarder
- chainsaw worker + skidder
- chainsaw worker + horse

Verification of the model

In reference to build models for simulation purposes the term "verification" is defined as a process of determining whether or not the products of a given phase of the software development cycle meet the implementation steps and can be traced to the incoming objectives established during the previous phase.

Until today all of the five production processes have been tested by conducting many different experiments in order to proof that these modelled systems are working correctly. To reach this target for the harvester the values of each parameter shown in table 1 have been varied within a predefined range. As an example the experiments with the parameter "crane range" will be explained:

experiment set-up

During the experiments altogether three different models are used. The stand area and the trees placed on it have not been changed at all. These models only differ in the kind of their extraction line systems. All three systems are idealized, i.e. that the single lines have a determined distance between each other. The values of these constant distances are 20 meters, 30 meters and 40 meters. Figure 8 shows the three different models:
At table 2 the characteristics of the stands are presented:

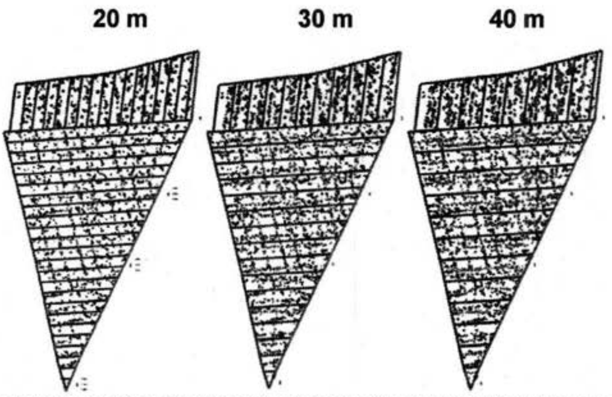


Figure 8: Three models with different extraction line systems featuring a constant distance of 20 m, 30 m and 40 m

Table 1: Characteristics of the three different stands

	distance between extraction lines = 20 m	distance between extraction lines = 30 m	distance between extraction lines = 40 m
total number of trees in the stand [qty]	7331	8065	8378
number of trees to be cut out [qty]	1085	1190	1245
percentage of trees to be cut out [%]	14.8	14.8	14.9

execution of the test

In every model seven simulation runs are conducted in which the crane range of the harvester is changed in one-meter-steps from seven to thirteen meters. Especially the results of the following values are interesting to discuss here:

- number of trees that could not be reached and cut out [qty]
- driving distance [km]
- productivity [m3/pmh]
- percentage of times for positioning the crane and driving on labor time [%]

results

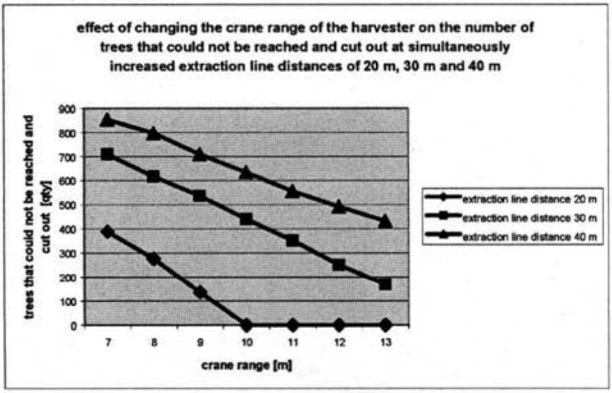


Figure 9: Effect of changing the crane range of the harvester on the number of trees that could not be reached and cut out at simultaneously increased extraction line distances of 20 m, 30 m and 40 m

The results of these simulation runs show that increasing the range of the crane from seven to thirteen meters allows the harvester to grab more and more trees (figure 9). For example at an extraction line distance of 30 m and a range of seven meters 710 trees still lie outside the catchment area of the machine, in contrast at a range of thirteen meters it just are 169. This effect can be shown at all conducted experiments. At a range of 10 m and an extraction line distance of 20 m like in reality all trees selected for thinning can be processed.

Concerning the increment of the extraction line distances in combination with the enlargement the number of trees to be cut out rises about 160 in total. By enlarging the space between the extraction lines on a constantly dimensioned stand area more space emerges for the trees to grow on, because the number of extraction lines gets reduced.

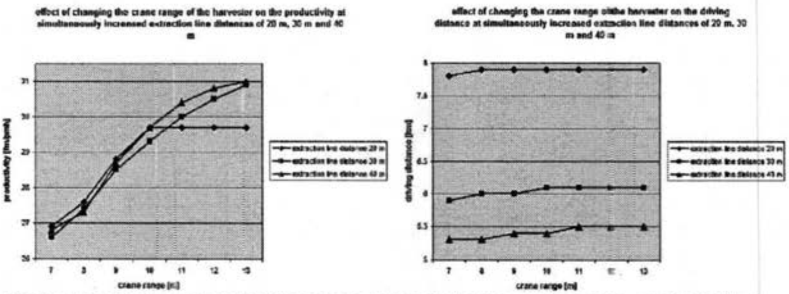


Figure 10: Effect of changing the crane range of the harvester on the productivity + effect of changing the crane range of the harvester on the driving distance at simultaneously increased extraction line distances of 20 m, 30 m and 40 m

By enlarging the crane range the productivity of the harvester accelerates (figure 10). This behaviour can be explained by the fact that more and more trees can be reached and processed. Thereby the proportion of productive work on the trees to "unproductive" times for driving on the lines and roads rises. Additionally the increment of the extraction line distances causes a reduction of roadways. Compared to the times the machine needs for processing the trees the times for driving get less. At an extraction line distance of 20 m the driving route has got an average length of 7.9 km. At 30 m distance there are 6.1 km to drive and at 40 m the harvester just has to go 5.5 km. Because irrespective to the extraction line distance there are still "enough" trees for thinning at the stands, the productivity gets influenced by the reduction of the extraction lines in a positive way. But if there was not an adequate number of trees to cut out the productivity influenced by the proportionally big number of not reachable trees could decrease.

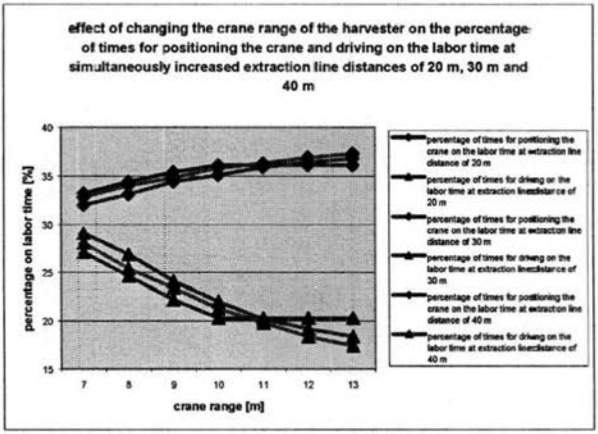


Figure 11: Effect of changing the crane range of the harvester on the percentage of times for positioning the crane and driving on the labor time at simultaneously increased extraction line distances of 20 m, 30 m and 40 m

The proportion of the times for positioning the aggregate at the tree and the driving of the harvester can be seen at figure 11. With an increasing crane range more and more trees can be reached by the machine. Thus the times for positioning are rising up automatically, because this action always is part of every harvesting cycle. As mentioned before this increment affects the proportion of productive times (processing a tree) to unproductive ones (driving). The effect of shortened extraction line routes also has been explained in the paragraph above.

Of course, the described experiments can not cover the whole range of features the model offers. They are just presented to give a little insight in the work that has been done during the last three years on the Department of Forest Work Science and Advanced Informatics of the TU Munich. But it becomes apparent that the model – shown by the example of the harvester – is able to represent realities regarding stand areas, roads and extraction lines as well as single trees and working systems in a way its performance and calculated results are usable to support the planning and conducting of harvesting operations in practice.

Validation of the model

The verification proved that the model executes the specified logic and performs all actions as expected. Furthermore the whole process of building the model once more showed how the quality of the results depends on the data that has been used to create it.

POHL (2006) was able to reproduce a really existing stand by measuring approximately 400 trees that were cut out and hauled by one harvester and one forwarder during an especially planned harvesting operation. She observed the operation and recorded every single event in time studies. The results were satisfactory, but it just has been one study. For the future more of these time studies should be made in order to correctly validate the model. Unfortunately this always is combined with great finance and temporal effort.

Conclusion

Industrial simulation software can be a flexible tool for modeling production processes in the wood supply chain. To model different timber harvesting scenarios it is necessary to create a model of a forest enterprise which represents the production area as close to reality as possible and provide actual inventory data about material, machines and stand conditions. The main purpose is to create an instrument for planning and controlling all production processes (Hemm 2005).

The developed harvesting model can be used as decision support tool. The results calculated during several simulation runs contain detailed data on economical, ecological and technical aspects, which are useful for a forest enterprise to see the positive and negative effects of different harvesting systems and logging operations on their budget and the environment.

It is the first time a model calculates in such a detailed way on the basis of single tree information.

However the handling of the software and the available data on stands and working systems offers space for improvement. Also the integration of three-dimensional conditions needs to be realized inside a future model

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PRECISION FORESTRY AND THE MULTIPLE PATH PRINCIPLE

Klaus v. Gadow
Institute of Forest Management, Georg-August-University, Göttingen, Germany
E-mail: kgadow@gwdg.de

Abstract

Natural and planted forests represent an important renewable reservoir of raw materials for the wood processing industry and a remnant wilderness of high recreational and spiritual value in the urbanized societies. To meet the demands of society, foresters have been developing standard treatment schedules which are assumed to be optimal for a given set of site and market conditions. However, these ideals usually turn out to be largely theoretical and often rather useless. Species choice and silviculture are influenced by changing demands and changing environmental conditions. This necessitates continuous adaptation and renewal of silvicultural prescriptions, often several times within one rotation. The objective of this paper is to present a new approach for adaptive management of forest ecosystems. The Multiple Path Principle has been designed to balance different demands, to buffer the negative effects of intermediate policy changes, to coordinate spatial objectives, to integrate varied forms of expertise, to assess the real attributes of all spatial units within the landscape and to reduce impractical planning horizons to a realistic time window. The Multiple Path theory assumes that a forested landscape is an aggregation of spatially defined land parcels of varying size and shape. Each parcel is characterized by a specific tree population with a given set of attributes. The Multiple Path model is based on the understanding that not only one, but a variety of treatment schedules or "management paths" may be potentially suitable for each individual land parcel. Each path has a value and is characterized by a succession of specific management activities, unexpected hazards and growth. Examples are presented to illustrate the concept.

Keywords: Multiple path principle, Growth models, harvest event, hazard, thinning models.

Silvicultural norms

In many regions of the world people depend on forests for their livelihood and well-being. Natural and planted forests represent an important renewable reservoir of raw materials for the wood processing industry and a remnant wilderness of high recreational and spiritual value in the urbanized societies. To meet the demands of society, foresters have been developing standard treatment schedules which are assumed to be optimal for a given set of site and market conditions. In even-aged rotation forest management systems the "ideal" schedule is characterized by a particular combination of planting espacement, thinning succession and rotation age. However, this ideal usually turns out to be largely theoretical and often completely useless. Species choice and silviculture are influenced by changing demands and changing environmental conditions. This necessitates continuous adaptation and renewal of silvicultural prescriptions, often several times within one rotation.

In an uneven-aged forest with selective harvesting, the ideal silvicultural standard is often defined by some assumed diameter distribution or species composition. This "guide curve" approach may simplify management, but usually there is no proof that it is either economically sound or ecologically reasonable (Cancino and Gadow, 2002). A particular forest stand may be subjected to several changes of silvicultural policy within its life (Amling, 2005; Koch, 2005). Because of the inflexibility inherent in the forestry business, the practical implementation of a new standard regime may take a long time. Therefore, the application of a limited number of standard management regimes appears to be an outdated approach. This is particularly evident in regions with highly variable forest structures, long production periods and a history of repeated changes of silvicultural policy (Heyder, 1984).

The objective of this paper is to present a new approach for managing forest ecosystems, known as the Multiple Path Principle. The Multiple Path Principle has been developed to link different spatial and administrative levels in a hierarchy of forest design, to balance different demands, to buffer the negative effects of intermediate policy changes, to coordinate spatial objectives, to integrate varied forms of expertise, to assess the real attributes of all spatial units within the landscape and to reduce impractical planning horizons to a realistic time window.

Seven Principles of Adaptive Forest Management

Because of the long production periods, timber growing is characterized by the typical symptoms of inflexibility. Forest policies and silvicultural priorities may change, but the results of such changes usually become apparent much later. Thus, a basic challenge for the science of forest management is continuous adaptation to changing environmental and social circumstances, under inherently inflexible conditions. To be effective, adaptive management must recognize seven important principles.

The Hierarchy Principle

The map of a forested landscape shows a mosaic of geographical units which are known as stands or compartments. The attributes of neighbouring stands are often quite dissimilar and this characteristic adjacency feature defines the particular pattern of a man-made landscape. Each stand is characterized by a unique treatment history, distinctive properties and specific treatment requirements and each harvesting event at stand level has an immediate effect on the landscape as a whole. It affects many aspects, such as sustainable biomass production, total income, total carbon stock or total nitrogen uptake. On the other hand, there are constraints at the landscape level which will prohibit the application of certain silvicultural treatments in a particular stand. The inseparable link of the landscape and the stand level calls for a design which joins the spatial and administrative hierarchies.

The Balancing Principle

The demands of society determine the objectives of forest management. These demands are diverse and often wide-ranging and they usually have to be satisfied simultaneously. This "balancing" problem of forest management has been addressed in numerous studies dealing with multi-criteria analysis. The value of a specific management path depends on the relative weights of the relevant decision criteria and on how well they are achieved.

The Buffering Principle

The balancing problem is aggravated by the fact that economic conditions are not constant and that the cycles in which they change are often far shorter than the lifespan of the trees. Thus, the "buffering" principle of forest management recognizes the fact that species choice and silviculture are influenced by changing demands and changing environmental conditions which require continuous adaptation to new silvicultural policies. This adaptation is usually very slow and buffering in this context means that the constraints of the limited flexibility which is an inherent feature of timber growing are recognized. Transition forest management has become the rule rather than the exception in Europe.

The Spatial Principle

Another major challenge of forest management has to do with the spatial-temporal organisation of forests within natural, urban or agricultural landscapes. Forest land typically consists of a mosaic of spatial units known as stands or compartments. Each stand has unique attributes and the characteristics of neighbouring stands may differ substantially. The "spatial" Principle requires that harvesting activities are coordinated, not only in a temporal, but also in a spatial context. This will allow concentration of heavy equipment for limited periods of time. Spatial coordination may also involve establishing a network of compartments with special conservation status, spread over an entire landscape.

The Integrating Principle

Because of the long-term environmental and social implications of timber management, forest research has always had to transcend boundaries. Forest scientists had to join up with other disciplines, typically the biological, mathematical and social sciences, to ensure that new and specialized research results are applied to forest management problems. This "integrating" Principle necessitates bridging gaps between related disciplines and incorporating their specific know-how. According to Sayer and Campbell (2004), such integration may not yield scientific breakthroughs, but it can help to generate options and to resolve problems.

The Reality Principle

The design of a forested landscape is necessarily based on data which describe the current state of the mosaic of land parcels. It is not possible to predict tree growth or to make decisions about future harvesting activities if nothing is known about the different forest stands within the landscape. Taking account of reality is essential and one of the most important principles of forest management, one that has been violated many times, is the "reality" principle. It says that idealistic silvicultural programs which describe a theoretically optimal sequence of activities from planting to the final harvest (like in the graph on the right), may look good on paper. However, in most cases it is simply not possible to apply such programs in reality.

The Time Window Principle

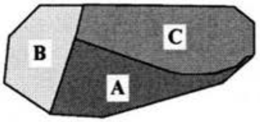
Forest stands have a history of past management, which cannot be changed, and their future development cannot be predicted indefinitely. Thus, the traditional discounted cash flow calculations of a hypothetical forest, from planting to rotation age, are not really relevant because they are based on idealistic assumptions and often on impractical planning horizons. The time window is a limited period of time, starting at t_0 with the real attributes of each individual stand within a forested landscape and ending at t_1, after a period for which future management paths can be predicted with reasonable accuracy. The economic value of a management path is mainly determined by two factors: the discounted cash flow within the time window and the stand attributes at the end, i.e. the stand value that is handed over to the following time window.

Adaptive Management and the Multiple Path Theory

Forest Management can reduce uncertainty and the likelihood of unexpected events by anticipating the future in a systematic way. It can also improve the chance that future developments will agree with specified objectives. The Multiple Path model assumes that a forested landscape is an aggregation of spatially defined land parcels of varying size and shape. Each parcel is characterized by a specific tree population with a given set of attributes. The Multiple Path model is based on the understanding that not only one, but a variety of treatment schedules or "management paths" may be potentially suitable for each individual land parcel. Each path is characterized by a succession of specific management activities, unexpected hazards and growth. Each path has a value which is defined in terms of a given set of objectives. An introductory example may illustrate the concept.

Figure 1 presents some relevant details of a simplified forested landscape with three stands, A, B and C. The map shows the location of the stands. In compliance with the reality principle, the current stand attributes, including the areas, tree species, ages, dominant tree heights, stems per hectare and basal areas, are listed in the table.

A time window of 10 years has been defined. Three paths were designed for stand A and two paths each for stands B and C. Relevant path details include the terminal volume, i.e. the growing stock at the end of the time window, and the net present value (see Table 1). These values were generated using the Software BWin (Nagel et al., 2002).



stand	stand area (ha)	tree species	age (years)	dom. height (m)	stems per ha	basal area (m2/ha)
A	5,0	beech	140	32	120	36,0
B	4,0	spruce	60	27	650	28,5
C	5,5	spruce	130	36	250	43,0

Fig. 1. Map of a forested landscape with the geographical locations of three stands, A, B and C; the current stand attributes are listed in the table.

Tab. 1. Path details for stands A, B and C; the terminal volume is the growing stock at the end of the time window.

path	description	T terminal volume (m^3/ha)	NPV net present value (€/ha)	T total (m^3)	NPV total (€)
A1	Z-tree thinning	150	100	750	500
A2	final harvest	80	120	400	600
A3	do nothing	260	-10	1300	-50
B1	Z-tree thinning	260	100	1040	400
B2	low thinning	300	90	1200	360
C1	Z-tree thinning	280	150	1540	825
C2	final harvest	20	230	110	1265

Tab. 2. Values of T and NPV and assoviated utilities for the 12 different path combinations.

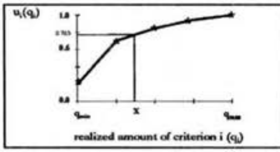
combination	T (m^3)	NPV (€/ha)	u(T)	u(NPV)	U
A1B1C1	3330.0	119.0	0.872	0.620	0.721
A1B1C2	1900.0	149.3	0.328	0.928	0.688
A1B2C1	3490.0	116.2	0.901	0.590	0.714
A1B2C2	2060.0	146.6	0.432	0.897	0.711
A2B1C1	2980.0	125.9	0.792	0.691	0.731
A2B1C2	1550.0	156.2	0.100	1.000	0.640
A2B2C1	3140.0	123.1	0.832	0.662	0.730
A2B2C2	1710.0	153.4	0.204	0.973	0.665
A3B1C1	3880.0	81.0	0.971	0.231	0.527
A3B1C2	2450.0	111.4	0.658	0.542	0.588
A3B2C1	4040.0	78.3	1.000	0.200	0.520
A3B2C2	2610.0	108.6	0.698	0.514	0.588

In a Z-tree ("elite-tree") thinning the main competitors of the valuable target trees are harvested; a low thinning removes the suppressed trees. The buffering principle applies in all cases. One objective is to realize a high carbon sequestration at the end of the time window, another is to attain a high net present value. These objectives are met at various degrees by the different path combinations. For example, for the combination A1B1C1, the terminal growing stock is equal to 750+1 040+1 540=3 330m³. The per ha net present value for this combination is equal to (500+400+825)/14.5=119.0€. Table 2 presents these values for each of the 12 combinations. To comply with the balancing principle, an additive utility function may be specified of the form (Pukkala, 2002):

$$U=\sum_{i=1}^{n} a_i u_i(q_i)$$

where *U*=utility for a given path combination; *n*=number of decision criteria; a_i=relative weight of criterion i $\left(0\le a_i\le 1;\sum_{j=1}^{m} a_i=1\right)$; q_i=realized amount of criterion i for a given path combination (€; m³); and $u_i(q_i)$=partial utility function for criterion i $(0\le u_i(q_i)\le 1)$.

The partial utility functions for the two criteria can be derived by subdividing the range between the maximum and minimum observed criterion value into 4 classes of equal width. The 5 class boundaries are then lined up in 5(4)/2=10 pairs. The partial utility function is derived using Saaty's (1980) method of paired comparisons. Fig. 2 shows an example of a partial utility function, the utility value for any arbitrary value *X* can be determined by linear interpolation. The 5 class boundaries for the terminal growing stock and their corresponding utilities are also shown in Figure 2. A linear function was assumed for the NPV criterion.



T	1550	2380	3210	4040
u (T)	0.10	0.64	0.85	1.00
NPV	78	156		
u (NPV)	0.20	1.00		

Fig. 2. Left: graph of a general partial utility function; the utility value for any arbitrary value X can be determined by linear interpolation. The 5 class (and 2 for NPV) boundaries for the terminal growing stock and their corresponding utilities are shown in the table on the right.

The total utilities are presented in Table 2, using the function $U=0.4\cdot u_1(T)+0.6\cdot u_2(NPV)$.

The best combination is A2B1C1, closely followed by A2B2C1. Additional conditions may ensure that a variety of legal, operational or economic constraints are satisfied for the landscape as a whole. This is a very simple example of adaptive forest management. The purpose is to illustrate the concept and no attempts were made to involve the integrating principle by including the experience of related disciplines (how much nitrogen is taken up by the different paths to reduce groundwater contamination; how do the paths affect genetic diversity, habitat requirements or near-naturalness?). It is easy to see that the traditional approach of prescribing an ideal management path from planting to the final harvest would be unrealistic and impractical. Thinning schedules are adapted such that they make sense, not only in terms of long-range policies, but also in recognition of the current state of each individual stand.

Precision requirements

To be able to generate a set of feasible treatment paths for a given initial stand condition requires accurate estimates of tree growth, possible hazards and harvest events. Predicting the effects of a particular harvest event requires that a match is found between forestry terminology ("high" or "heavy" thinning) and the algorithm that simulates the removals and the structure of the remaining stand after the harvest. Data about tree growth and hazards are gathered in longterm growth studies. Harvest event data are obtained by analysing actual thinning events in relation with the corresponding forestry terminology that was used to describe such events.

Tree Growth

A key to successful forest management is a proper understanding of growth processes. Foresters need to be able to anticipate the consequences of a particular harvest operation and about the dynamic change of less tangible characteristics of a forest, such as the stability and resilience in an environment affected by industrial pollution or the aesthetic value of a given forest structure. Many of the world's managed forests are even-aged. Even-aged forests include regular populations of trees with very similar attributes where simple modelling approaches are adequate. Selectively managed continuous cover forests feature more irregular populations including trees of different dimensions and different growth patterns requiring more sophisticated methods. The most appropriate modelling technique is determined by the level of detail of the available data and by the level of resolution of the required forecast. Thus, a stand model will be used if average population values and area-based information is available. An individual tree model would be more appropriate when some relevant attributes of the trees and their competition status are available. Most useful are hierarchical growth models featuring different levels of resolution within one compatible system. Overviews of current growth modelling techniques are provided by a number of authors, including Vanclay (1994), Gadow and Hui (1999), Pretzsch (2001), Porté and Bartelink (2002).

Hazard potential and risk

Due to the long-term planning horizons and the great variety of natural, economic and operational hazards affecting forest ecosystems, uncertainty and multiple risk are typical aspects of forest management. Damage is loss expressed in monetary terms. The damage potential includes all the potential threats within a given hazard domain. Risk has been defined as the expected loss due to a particular hazard for a given area and reference period. Disregarding the cost of capital, the expected loss (r) may be calculated as the product of the damage (*s)* expressed in monetary terms and its probability (*p*), $r = s \cdot p$. The probability of a tree being damaged by wind may increase with increasing tree size, whereas the damage itself is the result of an increase in the harvesting costs and a decrease in the log price. Risk assessment is a formal procedure for quantifying risk with regard to the damage potential, including all the possible threats within a given hazard domain. Thus, risk is not the same as uncertainty. The damage potential often depends on the development stage of the trees and on the silvicultural treatments (Kouba, 1989; Yoshimoto, 2001).

Thinning models

Most important in the temporal and spatial development of a managed forest are the harvesting operations, which are often carried out at regular intervals. Harvesting decisions are normative and intrinsically fuzzy. The fuzzy character of a thinning is exemplified by vague expressions (high thinning, low thinning), by the personalized nature of the decisions and by the fact that exact measurements of tree attributes are usually not available. Various combinations of thinning-relevant attributes may be used to quantify removal probabilities, depending on the kind of forest and the specific objectives of the thinning operation. Typical thinning-relevant attributes in a non-spatial situation are the tree species and variables defining the relative size or the economic value of a tree. The modification of a diameter distribution caused by selective harvesting may be quantified in a variety of ways.

Especially challenging are spatial thinning models. A spatial thinning model permits a choice of useful criteria, such as the structural attributes of a specific grid cell within a forest, or the neighbourhood constellation of a tree (Daume et al., 1998; Albert, 1999). Using a logistic regression, Hessenmöller (2002) estimated the probability of a beech tree with known breast height diameter being selected for removal for different thinning weights. Schröder et al. (2005) are able to mimic different silvicultural methods, such as gap selection and strip harvesting.

Generating Management Paths

Generating management paths for individual stands is an important step in the practical application of the multiple path theory. We may distinguish five different methods: a) selective path design; b) rule-based path design; c) standard silviculture with allowed deviations; d) all possible paths for a representative sample; e) all possible paths for a stand.

Selective path design for complex forest structures

The selective design of a management path requires input from someone who is familiar with locally accepted silvicultural practice. The design is based on an assessment and description of the current state of a stand and involves a more or less intuitive and experience-based approach. An example of a decision tree which is used to generate four paths for a 130-year old beech stand is shown in Figure 3.

Additional reasoning and explanations are helpful. This method is often the only feasible one in complex forest structures where selective harvesting is practiced. Special software is helpful for predicting the product yields and the tree growth between harvests. Several senior students have developed application examples for complex forest structures and selective harvesting. Baumert (2004), for example, demonstrated the method for four stands of different age and composition and a time window of 15 years. The standard software BWINPro 6.0, developed by Nagel et al. (2002) and several collaborators, was used in this study.

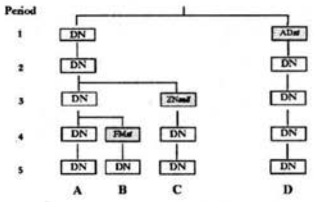
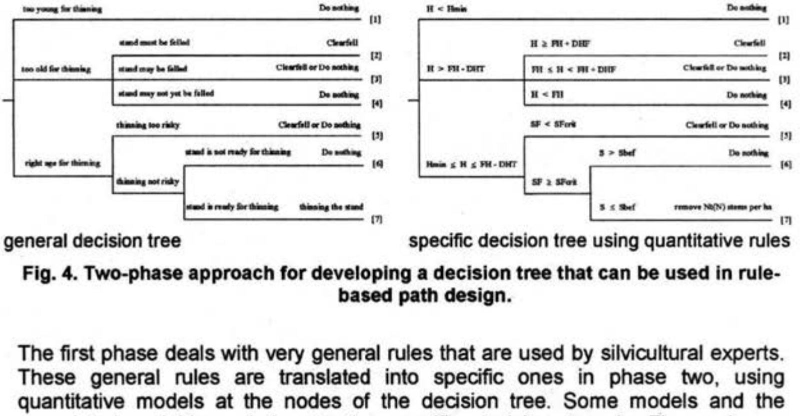


Fig. 3. Example with 4 paths generated for a 130-year old beech stand. DN=do nothing; FMst=heavy thinning, removal of trees in groups (German: "Femel"); ZNmä=moderate thinning, removal of trees who have reached target size (60cm); ADst=heavy selective thinning, removal of target tree competitors.

Rule-based path design for plantation forests

Plantation forests are typically even-aged monocultures managed for profit. The silvicultural prescriptions usually relate to the rotation age, the timing of the first and last thinning, the minimum and maximum stocking levels and the avoidance of risky thinnings. An example of a two-phase approach for developing a decision tree is presented in Figure 4.



general decision tree

specific decision tree using quantitative rules

Fig. 4. Two-phase approach for developing a decision tree that can be used in rule-based path design.

The first phase deals with very general rules that are used by silvicultural experts. These general rules are translated into specific ones in phase two, using quantitative models at the nodes of the decision tree. Some models and the associated variables relating to the specific decision tree in Figure 4, are presented in the box below:

A similar system of rules was developed by Sánchez (2003) for spruce stands, based on the silvicultural standards prescribed by the forest service in Lower Saxony.

In cases, where silviculture is limited to planting and clearfelling, different paths may be scheduled by simply changing the time of clearfelling in a particular stand (Figure 5).

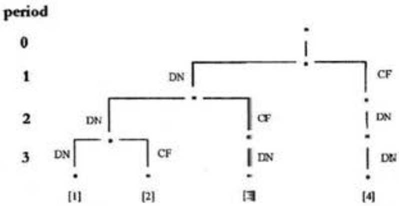


Fig. 5. Example of how different paths may be scheduled by simply changing the time of clearfelling (CF; DN=do nothing) in a particular stand that has reached the minimum felling age.

An example of this approach was presented by Gurjanov and Gadow (2005) for the Lissino forest near St. Petersburg.

Path design based on standard silviculture.

Tab. 3. Standard silvicultural prescriptions for two working circles applied in a forest farm, with allowed deviations; an asterisk and shading indicate the optimum age for activity.

Working circle A *Pine*

age	Activity	timber yield m^3/ha	labour required (mandays)
1	Regeneration: plant 3x3 m		14/ha
4	1. Prune to 1.5 m		2/ha
4	1. Thin 1100 → 650 trees/ha		1/ha
5	2. Prune to 3 m		3/ha
8	3. Prune to 5 m		3.3/ha
12	2. Thin 650 → 400 trees/ha	68.0	0.25/m^3
13*	2. Thin 650 → 400 trees/ha	77.5	0.25/m^3
14	2. Thin 650 → 400 trees/ha	86.9	0.25/m^3
25*	Clearfelling	425.9	0.20/m^3
26	Clearfelling	432.6	0.20/m^3
27	Clearfelling (max. age)	438.8	0.20/m^3

Working circle B *Wattle*

age	Activity	timber yield m^3/ha	labour required (mandays/ha)
1	Regenerate by line sowing, tending, fertilizer & spacing to 6000 stems/ha		58.5
2	Slash, thin to 3000 stems/ha, then to 2000 stems/ha		44.0
4	Thin to 1500 stems/ha, prune		4.5
8	Clearfelling & Bark stripping	20.9	200
9	Clearfelling & Bark stripping	22.7	200
10*	Clearfelling & Bark stripping	24.2	200
11	Clearfelling & Bark stripping (max. age)	25.3	200

In even-aged commercial plantations it may be convenient to design management paths in accordance with standard silvicultural prescriptions. This approach may be illustrated using a forest farm in the Natal Midlands of South Africa. There are two working circles. The working circle Pine includes all stands planted with *Pinus taeda*, the working circle Wattle all stands planted with *Acacia mearnsii*. Standard silvicultural prescriptions were available for each working circle. The prescriptions are presented in Table 3, with allowed deviations.

Relevant details for alternative paths are presented in Table 4 for a wattle stand (E) and a pine stand (F). The output (pine timber, wattle bark) and the input quantities (mandays) are also shown.

Tab. 4. Alternative path details calculated for a wattle stand (E) and a pine stand (F).

description	ha	Variable	Objective function coefficient	Output 1 (pine timber)	Output 2 (Wattle Bark)	Input (mandays)
Clearfelling & Bark stripping year 3 (age 8)	12.7	E1	0.55	0	256.4	2540.0
Clearfelling & Bark stripping year 4 (age 9)	12.7	E2	0.65	0	288.3	2540.0
Clearfelling & Bark stripping year 5 (age 10)	12.7	E3	0.80	0	307.3	2540.0
thin to 400 year 2 (age 12)	8.5	F1	0.75	578.0	0	144.5
thin to 400 year 3 (age 13)	8.5	F2	0.50	658.8	0	164.7
thin to 400 year 4 (age 14)	8.5	F3	0.40	738.7	0	184.7

The objective function coefficients were calculated on the basis of a) the relative importance of an activity and b) the closeness to the optimum age for the activity (see Gadow and Puumalainen, 2001 for details).

Generating all possible paths for a representative sample

In even-aged and very homogenous stands, the data from a small sample can be used to generate management paths for the entire stand. Under the assumption that the time of harvest of a given tree not only depends on its future value increment, but also on the growth-stimulating effects of the remaining trees, Ziegeler and Vilčko (2005) developed a method of path design based on a sample of 6 trees with known positions. How many paths exist if N is the number of possible harvesting events and n is the number of trees at the start of the time window? For each tree there are two possible outcomes:

1. the tree is harvested at harvest event 1, 2, 3, ..., or N;
2. the tree is not harvested.

There are n trees available at the start of the planning period. Each tree may be harvested at any harvest event, but only once. Thus, the sum of the „destinies" within the group is equal to the product $N \cdot N \cdot \ldots \cdot N$ (n times), i.e. equal to N^n.

Let us assume that the representative sample comprises three trees at harvest event N=1. Each one of the trees may be harvested or left to grow. Thus, there are eight (2^3) possible paths until harvest event two and 3^3=27 paths until harvest event three. If the sample includes 10 trees the number of possible paths will be almost 10 million (exactly 9 765 625) assuming three possible harvest events. The effort to calculate competition indices, growth rates and objective function coefficients is high and complete enumeration of all path attributes would be too time consuming. Therefore, this problem requires effective search methods using special heuristics, such as the Genetic Algorithm or Simulated Annealing.

Generating all possible paths for a stand

The methods of path design developed in the studies of Hinrichs (2004) and Seo et al. (2005) are based on the maximum allowed stand density. The number of paths is specifically defined by the maximum number of thinning events, by the number of stand density categories and by the number possible thinning weights at each thinning event:

$$number\ of\ paths = \sum_{i=min\ events}^{max\ events} \{(number\ thinning\ weights) \cdot (number\ densities)\}^{i} \qquad (1)$$

with min events = minimum number of thinning events; max events = maximum number of thinning events; number thinning weights = number of allowed thinning weights at each thinning event; number densities = number of maximum allowed stand density categories during the time window.

For example, altogether 55987 potentially paths are generated if we assume that 6 harvest events with three possible thinning weights and two densities are allowed. A plausibility test makes sure that only those paths are accepted which meet certain restrictions of practicality. The algorithm is implemented in a special software module (known as STAG) and its functioning has been demonstrated using a number of applications, including those in two-species stands of Beech and Spruce. The valid paths can be designed for different long-term strategic goals ("Waldentwicklungstypen") and this represents a major improvement (Hinrichs, 2005). The results confirm the suitability of the model as a key component of a decision support system for optimizing the design of a forested landscape.

Conclusions

If each one of *k* stands may follow *r* possible management paths, then there are r^k possible time space development patterns for the landscape as a whole. Some path combinations may not meet all the landscape constraints and they will be abandoned. The remaining combinations may be ranked according to their attainment of the stand and landscape level objectives. This potential to link the spatial and administrative hierarchies is one of the useful features of the multiple path principle. The optimum combination of paths may be determined using a method known as Accelerated Simulated Annealing (ASA). ASA represents an improvement of the standard Simulated Annealing algorithm. It maintains the advantages of the standard Simulated Annealing search, but the time for finding the global optimum is reduced considerably (Seo et al., 2005).

The multiple path concept represents a general theory that can be applied in any forest region and forest type. It has been found useful in commercial timber plantations, selective management systems and in small and large-scale applications. The seven principles of adaptive forest management are all applicable. Stand level objectives and forest level constraints are automatically combined. Real stand attributes are used and this ensures that the "buffering" principle can be applied. The design of the landscape is spatially explicit allowing the specification of adjacency constraints. The "time window" approach ensures satisfactory levels of accuracy. Evidence of "integrating" the specific know-how of other sciences is still lacking, but there seems to be at least some agreement that forest management needs to bridge the gaps between related disciplines and that all relevant experience needs to be incorporated.

Realistic applications of the multiple path concept are possible in many circumstances where suitable growth and thinning models are available. One may even speculate that the experience gained in managing forested ecosystems may help to devise concepts for manipulating other spatially organized systems, such as agricultural or urban landscapes, or even marine environments.

SI = site index (expected stand mean height at age 20, m);
H = stand mean height (m);
N = stems per hectare before thinning;
BAt = the proportion of the basal area removed;
example 1: $BAt = 0.552 - 0.009932(D)$ for sawtimber
example 2: $BAt = -0.07228 + 7.88/D$ for pulpwood; (Loveday, 1987);
FH = target stand height at felling
example 1: $FH = 2.729 + 1.0625(SI)$ (Marsh, 1987);
example 2: $FH = 23$ (De Villiers, 1988);
DHF = difference between target height at felling and maximum permissible stand height at felling. A stand must be felled if the mean height is equal to or greater than $FH + DHF$;
DHT = difference between stand height at clearfelling and stand height at the last thinning (m);
example: $DHT = 7m$;
Hmin = stand height at the first thinning (m); example: $H\min = 0.1208 + 0.5875(SI)$ (Marsh, 1978);
Hint = height interval between thinnings; example: $H\,\mathrm{int} = -9.1787 + 0.1875(SI) + 0.6454(H)$ (Marsh, 1978);
Nt = proportion of stems per hectare removed in thinning;
example 1: $Nt = \frac{(N - Naft)}{N}$, where $Naft = 1000^2/(Saft \cdot H)^2$ and $Saft = 69.33 - 1.92(SI) + 0.1878(H)$ Marsh (1978);
example 2: $Nt = \frac{\{73.7 - 1.9079(H)\}}{100}$ (Loveday, 1987);
Sbef = S-percent immediately before a thinning; example: $Sbef = 4.131 + 1.016(H)$ (De Villiers, 1989);
Sbef = S-percent immediately before a thinning; example: $Sbef = 4.131 + 1.016(H)$ (De Villiers, 1989);
SF = Stability factor = mean diameter (cm)/mean height (m);
SFcrit = critical Stability Factor; example 1: $SFcrit = 0.85$ *in P. radiata*; example 2: $SFcrit = 1.15$ *in all other pines* (SATGA, 1989)

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MULTICRITERIAL OPTIMIZATION OF TECHNOLOGIES BASED ON FOREST GROWTH SIMULATION

Alois SKOUPÝ, Jaroslav SIMON
Mendel University of Agriculture and Forestry Brno, Czech Republic
E-mail: skoupy@mendelu.cz

Abstract

The paper presents a general procedure for the optimization of forest technologies, based on the latest knowledge in scientific disciplines such as Operational reliability of machines, Technical logistics, and Qualimetry. Methods of assessing machines and technologies are modified in order to enable the selection of most appropriate working procedures in areas with the special status of nature protection as a fulfilment of regulations of the European Community in the field of nature conservation in Czech Republic. An integral requirement is the respect of forest owners and their needs, namely as far as the size of their estates and their economic possibilities are concerned. Combined with the commonly used optimization procedures the proposed method can become a part of decision-making processes supported by expert systems in connection with growth simulations. Synergic effect from the interconnection of all involved information systems should provide integral indicators to facilitate fast and correct decision-making.

Keywords: forest technologies, optimization, quality assessment, forest growth simulation

Introduction

Most works published so far have gradually slipped into the optimization of an actual problem, i.e. usually to the selection of technology optimal for the given workplace by either assessing the technologies available (i.e. already used and employing the already purchased machinery) or the solution was focused on the problem of choice and purchase of machines and equipment for the new technologies.

The paper brings a draft general procedure based on the theory of management and on the theory of machine operational reliability with making use of some technical logistics elements, those from the field generally known as qualimetry in particular.

In the authors' opinion the presented draft procedure will facilitate an actual optimization of technologies, which means not only to choose from the technologies locally available but from the procedures known and used elsewhere and/or to help in the formulation of task assignment for either purchase or development of a brand new technology.

The procedure can become a constituent of an expert system supporting the decision-making process linked up with growth simulations or with mathematic models of forest development. The synergic effect from the interconnection of all information systems involved will enable an entirely new approach to the problem solution providing integral indicators for an instant and correct decision.

Optimization procedure - Proposal

Selection of basic optimization criterion

Problem solution calls for the use of a multiple criteria optimization method which would include not only the economic and technical aspects as it was common in the hitherto procedures, but also the biological, environmental, ergonomic, hygienic aspects, reliability, etc. and labour safety requirements.

In a process of optimization of the given character, the very first decision to be made is that on the used optimization criteria whose individual parameters will have to be quantified. It is also necessary to decide on the method for the inclusion of qualitative indicators that cannot be quantified but rather expressed in another way such as verbal form. The most important step consists however in the selection of the main optimization criterion. The criterion should be cost minimization per unit production, which can be at the same time added –with respect to the type of activity- the requirement of maximum output which can be achieved through proper log-making. Nevertheless, should we include also the other criteria mentioned above, in which parameters cannot be often precisely quantified and hence directly expressed in terms of costs or losses, it is advised to employ a so called integral indicator of quality, which in fact also indicates what technology is most beneficial for the user.

This is applicable at full responsibility also in cases when a precise estimation cannot be made of future yields and losses affected for example by the execution of tending measure when several options or alternatives of the technological solution are to be compared.

Should we be unable to quantify e.g. a future production loss due to soil compation, timber quality loss due to rots infesting trees mechanically damaged at felling or extraction, etc., we can always make use of limiting conditions defined as insurmountable (fixed) limits.

The limiting conditions will not concern only the adverse impact of machines on environment but also the labour hygiene and safety.

Quantitative criteria
Quantitative criteria can be divided into two groups as follows:

- Criteria with a maximum or minimum limiting value (e.g. minimum tractive force, maximum concentration of noxious substances in exhaust gases);
- Criteria with an optimum value where deviation to both sides is considered a disadvantage (e.g. debranching near the stem surface with neither branch stubs being left behind nor the stem suffering damage).

Quality level of the i^{th} criterion for the first group is to be calculated as follows:

$$\mathbf{K}_i = \mathbf{exp}\left(\pm \frac{\mathbf{P}_i - \mathbf{P}_{mi}}{\mathbf{P}_{mi}} \right)$$

where

$\mathbf{K}_i$ = quality level according to the i^{th} criterion
$\mathbf{P}_i$ = parameter of the i^{th} criterion
$\mathbf{P}_{mi}$ = limiting value for the i^{th} criterion

Positive value of the expression in brackets is to be used if the parameter is desired to reach a value higher than the limiting value; it follows that negative value is to be used if the parameter is desired to reach a lower than limiting value. This concept does not place a veto on the use of a machine or technology surmounting or not reaching the limiting value; it will however considerably impair quality level in the overall evaluation. Should we actually wish to prevent the use of the technology in the case that the limiting value is defined as insurmountable (fixed), then we have to use a zero in place of the given criterion quality level.

Quality level of the i^{th} criterion for the second, much smaller group is to be calculated as follows:

$$\mathbf{K}_i = \mathbf{m}_o \, \mathbf{exp}\left(- \left| \frac{\mathbf{P}_i - \mathbf{P}_i^{et}}{\mathbf{P}_i^{et}} \right| \right)$$

where

$\mathbf{m}_o$ = conventional value constant (e.g. $m_o = 0.8$ if performance efficiency required is 80%)

$\mathbf{P}_i^{et}$ = standard value, i.e. conventional value of the optimum

Qualitative criteria

Where the criterion parameter cannot be expressed by any of the above specified methods, it comes to the following verbal classification: Excellent – 1.20; Good – 0.95; Satisfactory – 0.60; Unsatisfactory – 0.30.

In order to be optimized, the quality level must be expressed in such a way that a group of experts from involved industries are inquired about the given criterion in kind of a public inquiry and by them expressed figures are to be used as the only quality figure expressed by arithmetic mean, i.e.

$$\mathbf{K_i = \frac{1}{n}\sum_{i=1}^{n} K_{ij}}$$

where

$\mathbf{n}$ = number of experts

$\mathbf{K_{ij}}$ = opinion of the j^th^ expert

And again – similarly as mentioned above, should the machine or the technology be not included in the selection for an insurmountable (fixed) value of the criterion, then $K_i = 0$.

Regarding the fact that a total quality level of the assessed machine or technology is calculated as weighted harmonical mean, the machine or technology is to be logically disqualified from the selection.

Determining the weights of individual criteria

a) Method of paired comparison

This method is to used to make a mutual comparison of two partial characteristics (criteria) and to specify which of the two compared characteristics is more significant. The assessment is to be made by a group of experts of whom each fills a pre-printed table in such a way that the serial number of the criterion which is – by their judgement- more important is written into the respective windows.
The sought weight of the i^th^ characteristic can be calculated from the following relation:

$$\mathbf{M_i = \frac{\sum_{j=1}^{n} f_{ij}}{n \cdot I}}$$

where

M_i = weight of the i^th^ product's characteristic

f_{ij} = absolute frequency of the occurrence of the i^th^ characteristic serial number in the table of the j^th^ expert

n = number of experts

I = number of opinions issued by one expert

The number of opinions by one expert depends on the number of studied criteria and equals the number of 2^nd^ class combinations from the number of criteria.

$$\mathbf{I = \frac{k \cdot (k-1)}{2}}$$

where

k = number of assessed oil properties (criteria)

Should the method achieve a realistic expression of the mutual weight (significance) of individual criteria, the number of experts to fill the table should be as large as possible (20 as a minimum). The result is therefore affected both by the number of experts and by their subjective opinions. If a suspection exists about the statements of individual experts mutually differing so much that variances among the opinions are not incidental only, the objectivity of results can be checked by using the test of statements fit.

b) Method of paired quantitative comparison

Where the weight of individual criteria is to be expressed not by mere determination of which one of the two is more significant but also what is their mutual ratio a method can be used which is not depending on a large number of experts; one assessor is enough for this method of paired quantitative comparison. Criteria are to be mutually compared according to the scale presented in Table 1.

Table 1 – Scale for the quantitative comparison of criteria

Mutual relation of the criteria	Points (weight) v
Criteria of same significance	1
Criterion of somewhat higher significance	3
Criterion of much higher significance	6
Criterion of much more higher significance	9

The mutual relation between the criteria is to be marked as s_{ij} – i.e. as a relation between the criterion i^{th} and j^{th}. The relation will be expressed as follows:

$$s_{ij} = \frac{v_i}{v_j}$$

where

v_i = number of points (weight) of the i^{th} criterion
v_j = number of points (weight) of the j^{th} criterion

A table is to be constructed according to the number of criteria at a size of m x m with ***m*** being the number of criteria.

Estimated weight value of the i^{th} criterion M_i is to be calculated according to the following relation:

$$M_i = \frac{R_i}{\sum_{i=1}^{m} R_i}$$

where

$$R_i = \left(\prod_{j=1}^{m} s_{ij} \right)^{m^{-1}}$$

and where

m = number of criteria

Calculating the total quality level

As it follows from the above paragraphs of this chapter, the total level of quality can be calculated on the condition that the limiting values of individual criteria (P_{mi}) and their weights (M_i) have been determined.

It is also necessary to set up the quality indicators for each respective K_i criterion – either by calculation or according to the above presented conversion table in the case of verbally expressed criteria. The level of total quality level (K) will be then calculated according to parameters and weights of the respective criteria by means of a relation as follows:

$$\mathbf{K} = \frac{\sum_{i=1}^{m} \mathbf{M}_i}{\sum_{i=1}^{m} \frac{\mathbf{M}_i}{\mathbf{K}_i}}$$

where

M_i = weight of the i^{th} criterion

K_i = wear level (quality indicators) according to the i^{th} criterion

M = number of criteria

In the practical use of results the calculated total numerical value of quality is generally used for a verbal expression of quality degree – see Table 2.

Table 2 – Conversion of quality range to quality grade

Quality range	Quality grade	Quality grade – Verbal description
$K > 1.1$	I	excellent
$0.8 < K \leq 1.1$	II	good
$0.4 < K \leq 0.8$	III	satisfactory
$K \leq 0.4$	IV	unsatisfactory

Integral indicator of quality

A more detailed explanation and a definition should be given on the "integral indicator of quality", which is to provide an aggregative information about the technological solution by a direct specification of money that can be saved or wasted over a long time if we decide for a "correct" or "incorrect" technological alternative today.

The concept of quality:
Quality (optimum quality) is a comprehensive term for the capacity of a product (machine, equipment, technology) to meet requirements of the user and public concern under optimum economic conditions. Quality as a whole is therefore to express both its economic and technical characteristics.

Understanding quality as an entirety of properties of the assessed object, i.e. a totality of parameters according to the assessed criteria, we have to use a system approach to its learning. Any characteristic improved according to any criterion improves quality of the product as a whole and in purely technical terms the product can be further improved up to a very top level of the present state-of-the-art. There are some economic boundaries to the improvement, though. Surmounting of the optimum top technical quality limit is apparently useless and improvement of only a single characteristic of the product may induce inadequately growing production costs and hence an increased purchasing price of the product.

This is a basis for the idea of an "optimum quality" where technical quality level is being assessed in relation to manufacturing and operating costs, which is at the same time a definition of the "integral indicator of quality".

There are two principal conclusions following out from the above facts:

1. There is a tight link between the technical and economic characteristics of the product's quality. A product of high utility value but inadequate price would not be able to fulfil the utility value at an optimal way.

2. A similar tight link exists between the individual partial properties which constitute technical quality. Inadequate development of any product property at a cost of another characteristic may impair the optimum quality of the product as a whole.

Summarizing the above facts, we necessarily arrive at a conclusion that a basis for quality assessment must become the assessment of the level of complex indicators in which changes of any product's characteristic will show. Being assessed separately, any otherwise important partial property of the product cannot express the quality of the entirety. Such an approach is not objective because it is not a system approach.

Possible final evaluation of quality

Regarding the fact that a machine or a technology optimally corresponding with the set-up limiting values and standards will exhibit a quality value of $K = 1$ with a lower and higher level indicating a worse and better result, respectively, the total integral indicator of quality can be expressed in such a way that costs per unit production are multiplied by Indicator K, which makes all aspects studied included in the optimization solution. It is a question of the gradual precision of the method how its inclusion in the optimization solution will eventually show as it is in any case just an optimization with the inclusion of subjective standpoints and opinions of researchers.

Conclusion

Assessment of the quality of used technologies can employ data from the existing economic information systems and data from the application of growth simulations drafted as a computer programme with forest stands being conceived as a set of individual trees whose coexistence can be illustrated as a spatial and temporal dynamic system. The development of individual parameters is modelled at a predetermined time step (5, 10 ... years) with the overall forest stand structure being captured including the data of individual trees. Changes in the stand structure that would result from intentional tending operations (thinnings, juvenile thinnings), regeneration measures, disasters or from growth and mortality *per se* have therefore a decisive influence on a further development of the trees including the stand spatial structure. In such a system, the tree increment is then defined on the basis of growth factors and initial dimensions. Other external variables conditioning the stand growth and structure entering the system are : stand management methods, risks and site conditions. Integral indicator of quality can then help to compare available technologies and/or do a draft modelling of new technologies. The expert system logically includes both biological and environmental limits, providing within the framework of given possibilities an optimal economic effect expressed for example in the minimization of costs, maximization of profit or minimization of loss in the case of negative economic result.

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INFORMATION REQUIREMENTS TO FERTILIZE PLANTATIONS WITH GREATER PRECISION IN A DRY COUNTRY

Ben du Toit
Dept. of Forest and Wood Science, University of Stellenbosch, South Africa
E-mail: ben@sun.ac.za

Abstract

Successful and cost-effective fertilization in plantation forestry hinges mainly on the tree volume response, wood properties and the log price. The first two factors can be optimised if the interaction between water and nutrient availability across the landscape is well understood. Although growth resource availability can be manipulated by silvicultural operations, even larger variations often exist between compartments within plantations and these should be exploited for maximum efficiency in fertilization programmes. Evidence from several South African research programmes are used to illustrate the importance of site-specific fertilization strategies for optimum productivity. In some of these case studies, failure to understand the stand response mechanism to changes in resource availability resulted in poor or erratic responses upon implementation. A new research paradigm is proposed that would incorporate a water availability gradient as one factor in the experimental design. The extrapolation of such results (using remotely sensed physiological stress indicators) could increase precision with planning and implementation of site-specific fertilizer programmes in areas with dry climates.

Keywords: Nutrient availability, water availability, fertilization, leaf area, radiation, quantum efficiency.

Introduction: Fertilization in southern African Forest plantations

Substantial experimentation with fertilizer application in southern African plantations has taken place over the last half century. The most important findings obtained with fertilization of pines, eucalypts and *Acacia mearnsii* has been summarised by Schönau *et al.* (1981); Schönau (1983 & 1989), Donald *et al.* (1987), Herbert and Schönau (1989 and 1990), Noble and Herbert (1991), Morris (1995) Herbert (1996), Carlson (2000), Carlson *et al.* (2000); du Toit (2002), Campion and du Toit (2003b) and Morris (2003). Many of these results have shown that responses to fertilization are usually site specific, even if site management operations (e.g. site preparation, slash management, weed control and thinning) are kept uniform for a given species in a given area. Under similar management regimes, the variability in fertilizer responses is likely to stem primarily from variations in the inherent nutrient supply capacity of soils, and the availability of soil water. There are numerous local examples of stands that did not respond significantly to fertilizer applications, which had been attributed to drought or low rainfall conditions (WRI, 1980; ICFR, 1985, 1986, 1987, 1992). Many of these experiments had been abandoned at an early age, or final results were left unpublished. In most cases, trials were of an empirical nature and the interaction between water and nutrient availability was not specifically studied (Donald *et al.,* 1987; Herbert and Schönau, 1989 & 1990; du Toit, 2002; Campion and du Toit, 2003b). Despite shortcomings with regard to experimental evidence, researchers are often under pressure to make recommendations by extrapolating limited experimental results to large areas of land. This extensive extrapolation has led to erratic results because the complex inter-relationships between growth resource availability and the requirement for additional fertilizer supplements were not well understood. In this paper, we will explore the main drivers of plantation productivity, and use this approach to evaluate responses obtained in several groups of local fertilizer experiments. We then present an argument for changing the conventional experimental approach used in historic fertilization studies, and make recommendations for a new experimental approach.

Which factors exert the greatest influence on the economic feasibility of fertilization?

The high degree of variability in fertilizer element requirements across sites, and the variability in the magnitude of the response makes it important to implement fertilization with adequate precision on a site-specific basis. For example, Australian research on fertilization of radiata pine has shown that the profitability of fertilization is governed primarily by log price and volume response (Knott *et al.*, 1996). The fertilization of plantation forests can also have a significant effect on wood properties. For example, several authors have shown that an increase in growth resource availability to trees (such as fertilization) may increase wood density in eucalypts (Wilkins, 1990; Cromer *et al.*, 1998; Little, 1999; du Toit *et al.*, 2001), which can be economically advantageous in pulpwood crops (Arbuthnot, 1991; Clarke, 2001; Zboňák, 2002; du Toit *et al.*, 2001; du Toit and Drew, 2003). The forest manager usually has little or no control over the log price. However, it is indeed possible to optimise stand growth and wood properties by manipulating the soil water and nutrient availability on a site-specific basis, provided that the fundamental drivers governing the response are well understood (Linder *et al.*, 1987; Pereira *et al.*, 1994; Landsberg and Waring, 1997; Bergh *et al.*, 1999; Stape, 2002; Binkley *et al.*, 2004; Campion, 2005).

Fundamental drivers of forest productivity and their relationship with fertilizer responses

The production ecology equation states that gross primary production is the product of the quantity of photosynthetically active radiation absorbed by the canopy (APAR) and the canopy quantum efficiency (α_c) (i.e. the efficiency of converting this energy into fixed carbon). Since respiration is regarded as (roughly) a constant portion of GPP, the net primary production (NPP) can be estimated from the above variables as well. The fraction of the NPP that is partitioned to stem wood (η_w) is dependent on resource availability and climatic factors. Stem wood production is thus primarily driven by, APAR, α_c and η_w (Linder and Rook, 1984; Linder, 1985; Landsberg and Gower, 1997; Landsberg and Waring, 1997; Binkley *et al.*, 2004). All three of the above mentioned factors can be manipulated through the availability of growth resources (water, light and nutrients). An increase in the availability of water and nutrient supply will enable a forest to deploy a large leaf area with a high canopy quantum efficiency level. In addition, it will partition comparatively small amounts of fixed carbon to root growth as resources are plentiful and easy to obtain (Linder, 1987; McMurtrie and Landsberg, 1992; Bergh *et al*, 1999; Stape, 2002; Giardina *et al.*, 2003; Binkley *et al.*, 2004; Dye *et al.*, 2004). Radiation as such is seldom limiting on low latitude forest sites, but the interception of adequate quantities may be constrained through sub-optimal leaf area indices (brought about by water or nutrient deficiencies) (Linder, 1985; Coops and Waring, 2001; Landsberg *et al.*, 2003; du Toit and Dovey, 2005; Campion, 2005). It follows that the availability of water, nutrients and the interaction between these two factors effectively determine the magnitude of the response to additional fertilizer supplements (Linder, 1987; McMurtrie and Landsberg, 1992; Gonçalves, *et al.*, 1997). Several nutrient and water optimisation trials worldwide have shown (at an experimental scale), how important it is to understand this interaction (Linder, 1987; Linder *et al.*, 1987; McMurtrie and Landsberg, 1992; Pereira *et al.*, 1994; Albaugh *et al.*, 1998; Bergh *et al.*, 1999; Stape, 2002; Campion, 2005). The challenge is to extrapolate this understanding to the plantation scale when formulating fertilizer recommendations.

The forest manager can manipulate nutrient availability through several site management operations (e.g. slash management, burning, weed control, tillage or soil disturbance caused by harvesting machines), and the biggest impacts in short-rotation crops usually occur after during the inter-rotational period (Schönau, *et al.*, 1981; Schönau, 1989; Gonçalves, *et al.*, 1997; Little *et al.*, 2000; Smith *et al.*, 2000; Little *et al.,* 2002; du Toit and Dovey, 2005; Smith and du Toit, 2005). It is thus important to take account of the site management operations in this inter-rotational period when recommending fertilizer supplements to be applied at time of establishment. Silvicultural operations carried out during the rotation (such as thinning or pruning) will affect the leaf area and nutrient dynamics in the stand. It follows that the water and nutrient availability may be altered for trees remaining after a thinning and/or pruning operation. This change in resource availability could affect the quantity and composition of fertilizer supplements needed for optimal growth and it is also likely to affect the magnitude of the response (Brix, 1983; Stoneman *et al.*, 1996; Carlyle, 1998; West, 1998).

Despite the effects of silvicultural operations or resource availability in plantations, it is important to acknowledge that even larger variations in nutrient and water availability often exist between site types or compartments on the plantation scale. This variation is particularly great on the eastern seaboard southern Africa, where we have large gradients of temperature (due to altitude), rainfall, parent material, terrain position, soils and water availability (Roberts, 1994; Louw, 1999; Louw, and Scholes, 2002). These inherent variations within plantation units (coupled to the effect of site management on resource availability) should be exploited for maximum precision and efficiency in fertilization programmes.

Results from case studies showing the importance of site-specific fertilization in South Africa

Case study 1: Fertilization of eucalypts at establishment

The pioneering work of Schönau and co-workers showed that fertilizer requirements at establishment differ with soil type and the degree of site mechanical site preparation or soil tillage (Schönau, *et al.*, 1981; Schönau, 1989; Noble and Herbert, 1991). These results led to the classification of broad site types (e.g. based on climate, soil organic matter, parent material and texture) as well as management options which were used in formulating preliminary fertilizer recommendations (Noble and Herbert, 1991; du Toit, 1995; ICFR, 2000; Campion and du Toit, 2003a). However, subsequent work has shown that nutrient requirements at establishment will differ strongly *within* these broad site types, even under uniform site management conditions.

The case study documented by du Toit and Oscroft (2003) focussed on the Zululand coastal plain, which is dominated by sandy soils of aeolian origin. The authors tested the stand growth response of a single *Eucalyptus grandis* x *urophylla* hybrid to fertilisation with nitrogen (N), phosphorus (P) and sulphur (S) during re-establishment across five dominant soil types on the Zululand coastal plain. All the soils had very low topsoil clay content (3 to 5%) and organic matter levels (0.31 to 0.83%), and all sites could thus be labelled as infertile sandy soils when compared to other forestry soils in southern Africa. All sites received high mean annual precipitation (MAP) by South African standards (average of 1172 to 1452 mm during the trial period) coupled to high mean annual temperatures (21-22 °C). The site conditions are such that the small nutrient pools present are rapidly cycled due to high MAP and temperature conditions (Noble, 1992). A fertility class (infertile, moderate or fertile by Zululand coastal plain standards) was assigned to each soil type, based on the organic carbon content, the degree of base saturation and effective cation exchange capacity (ECEC) of the topsoil (0 to 0.2 m depth). Site management was operations were kept uniform and harvesting residue was burnt on all sites before establishment. Unfertilised control plots in the five trials yielded wood volumes of between 309 and 365 m^3 ha^{-1} at maturity (age six years). Despite the fact that soils were broadly similar (all deep, humus-poor sands), two sets of responses were obtained with fertilisation. Positive interactions between the application of N, P and S occurred on the most infertile sites (Trials C.82 and C.88 in Figure 1), where the response to N, P and S was additive. Fertilisation with 50 g N, 21 g P and 42 g S per tree yielded additional volume responses of between 48 and 50 m^3 ha^{-1} on these sites over a six-year rotation. Fertilizer is placed in close proximity to the newly planted seedlings, and hence is expressed on a per tree basis. When expressed on a area basis, these application rates were approximately 70kg N, 30 kg P and 60 kg S per ha.

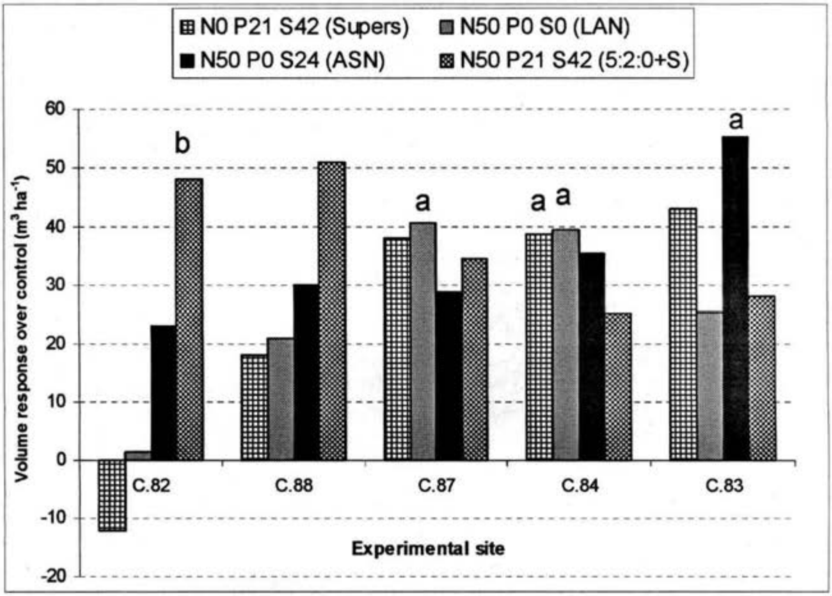

Figure 1. Utilisable wood volume response over the unfertilised control treatments at six years of age for selected fertiliser treatments in the *E. grandis x urophylla* trial series described by du Toit and Oscroft (2003). The numbers in the legend refer to grams of nutrient applied per tree. Letter codes a & b on bars indicate significant differences over the control at p<0.1 and p<0.05, respectively. The volume of C.88 is a projected estimate due to fire damage before harvesting, and hence, no statistical tests were carried out on these data. (Diagram adapted from du Toit and Oscroft, 2003; used with permission of the Institute for Commercial Forestry Research)

Negative interactions between N and P were recorded on sites of moderate and high fertility by coastal plain standards (Trials C.84, C.87 and C.83 in Figure 1). These sites responded optimally to either N or P (applied singly or in combination with S), but the magnitude of the response was generally reduced if N and P were included simultaneously. The additional volume response to individual applications of 50 g N per tree (as ammonium sulphate nitrate), 50 g N (as limestone ammonium nitrate) or 21 g P (as single superphosphate) amounted to 40, 35 and 40 m^3 ha^{-1}, respectively. The results emphasise the high degree of precision needed to obtain maximum benefit from fertiliser applications.

Case study 2: Fertilization of *Pinus patula* at first thinning

Thinning and pruning operations alter the nutrient dynamics and water availability in plantations and hence, the effects of these operations need to be taken into account when trials are planned and when fertilization strategies are formulated. In a case study documented by Carlson (2000), the response of *Pinus patula* to fertilization at first thinning was investigated. Seventeen stands of *P. patula* in Mpumalanga Province (eight years old and having a stand density of 1300 stems ha^{-1}) were thinned to 660 stems ha^{-1} and subjected to fertilization in a factorial arrangement. The factors were N, P, K, Ca (all applied at zero or 150 kg ha^{-1} except for Ca where the upper level was 140 kg ha^{-1}). The mean annual precipitation (MAP) on these sites ranged from 921 to 1513 mm and soils are highly variable. The trials are scattered from the foothills of the great escarpment (lowveld) to the top of the plateau (highveld). The trial sites were subjected to principal components analysis of soil and environmental variables to enable the grouping of similar site types. Despite some outliers, these broad site type groupings coincided fairly closely with soil parent material. The response per grouping differed in magnitude and duration for specific elements that had been applied: Highveld granitic sites yielded moderate responses to P and K supplements while the quartzitic site groups showed no significant responses. The lowveld granitic sites showed very poor responses that were not sustained over time. The sites with shale-derived soils responded strongly to a combination of N, P and K. The escarpment site group (with dolomite and diabase as parent materials) responded most strongly to P and K (Carlson, 2000 and Figure 2).

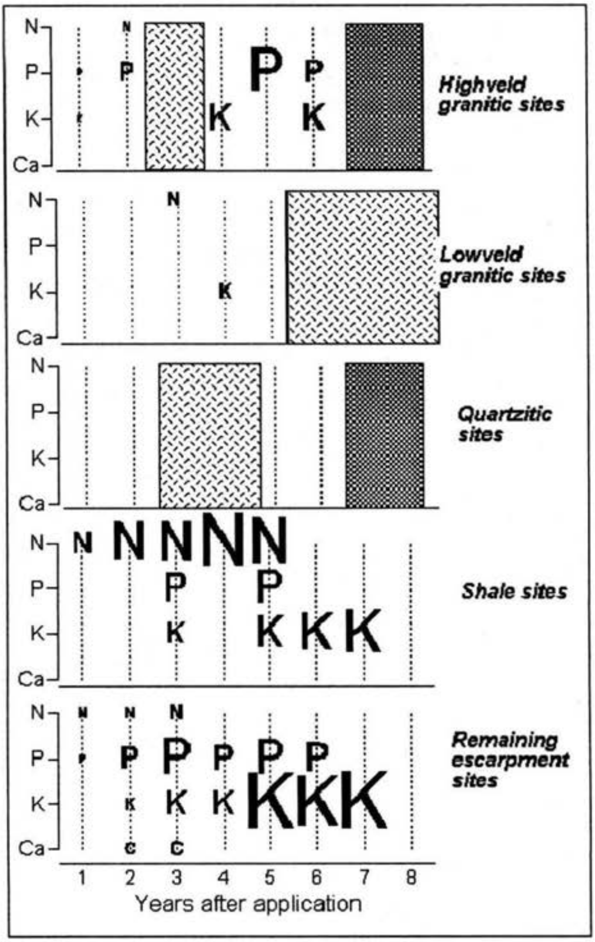

Figure 2. Diagram showing the response of *Pinus patula* over time on various groups of soils to fertilizer nitrogen (N), phosphorus (P), potassium (K) and calcium (C) applied at eight years of age after first thinning. The presence of a symbol indicates a significant response in basal area increment and its relative size is indicative of the magnitude of the response. The dark shading refers to trial being too young for measurements and the light shading is shown where trials have not been measured for a particular year. (Diagram sourced from Carlson and Soko, 2000; used with permission of the Institute for Commercial Forestry Research).

Case study 3: The mechanism of response to increased availability of growth resources

In the introductory section, we have listed a number of South African fertilizer experiments in plantations where the lack of a response has been attributed to a limited availability of soil water. Several nutrient and water optimisation trials conducted world wide have presented the scientific community with strong experimental evidence, showing that the addition of fertilizers to stands in dry climates will only elicit a meaningful response if water supply is sufficient (Linder *et al.*, 1987; Pereira *et al.*, 1994; Campion, 2005). The reason for this response mechanism is presented here by way of a comparison between two published studies. The data was obtained from intensive, process-based experiments in young eucalypt stands which are genetically closely related: Site A is planted to *E. grandis* in KwaZulu-Natal, South Africa (du Toit and Dovey, 2005; du Toit, submitted); and Site B is planted to *E. saligna* in Hawai'i (Giardina *et al.*, 2003). Site A experienced very low MAP during the trial duration while site B is situated in a high rainfall area. We chose treatments that represented low and high nutrient availability in these trials to compare the mechanism of the growth response obtained in the trial: The treatments were slash removed (low nutrient availability) versus slash burnt (high nutrient availability) at site A and unfertilized versus repeated fertilizer application under ambient rained conditions at site B. In the case of each trial site listed above, we compared the change in the elements of the production ecology equation brought about by increased nutrient availability. The results are shown in Table 1

Table 1. Percent change in elements of the production ecology equation for two eucalypt sites (after Giardina *et al.*, 2003; du Toit, submitted). MAP=Mean annual precipitation; LAI=leaf area index; APAR=absorbed photosynthetically active radiation; α_c = canopy quantum efficiency.

Site	Mean MAP during trial period (mm)	Stand age during trial (years)	Mean increase in LAI with high fertility treatment ($m^2\ m^{-2}$)	Increase in above ground woody mass with high fertility treatment ($t\ ha^{-1}\ a^{-1}$)	Change in production ecology variable brought about by increased nutrient availability	
					APAR	α_c
A	810	0 to 3	0.76	15	+ 18%	+ 13%
B	3500	2 to 4	1.73	100	+ 13%	+ 33%

On site A, the increase in above ground woody biomass production was small and it resulted predominantly from increases in APAR. The data presented here is the average change over the three year measurement period, however, it was brought about by a **temporary** change in leaf area index. The leaf area index of the treatments (and APAR levels), converged by three years of age and remained similar thereafter (du Toit and Dovey, 2005; Figure 3). The canopy quantum efficiency was affected by a lesser degree than APAR by the increase in nutrient availability, probably because of forced stomatal closure during times of water stress. In stark contrast, increases in nutrient supply on the wet site (B) brought about large improvement in production, through large changes in canopy quantum efficiency (α_c) and lesser changes in APAR. This can most likely be attributed to the lower water stress experienced at the wet site and the fact that the stand already had a high LAI (4.73) in the unfertilized state. Any further increases in LAI would have resulted in small additional gains in APAR as descried by the logarithmic relationship between APAR and LAI (Linder, 1985; Landsberg and Waring, 1997).

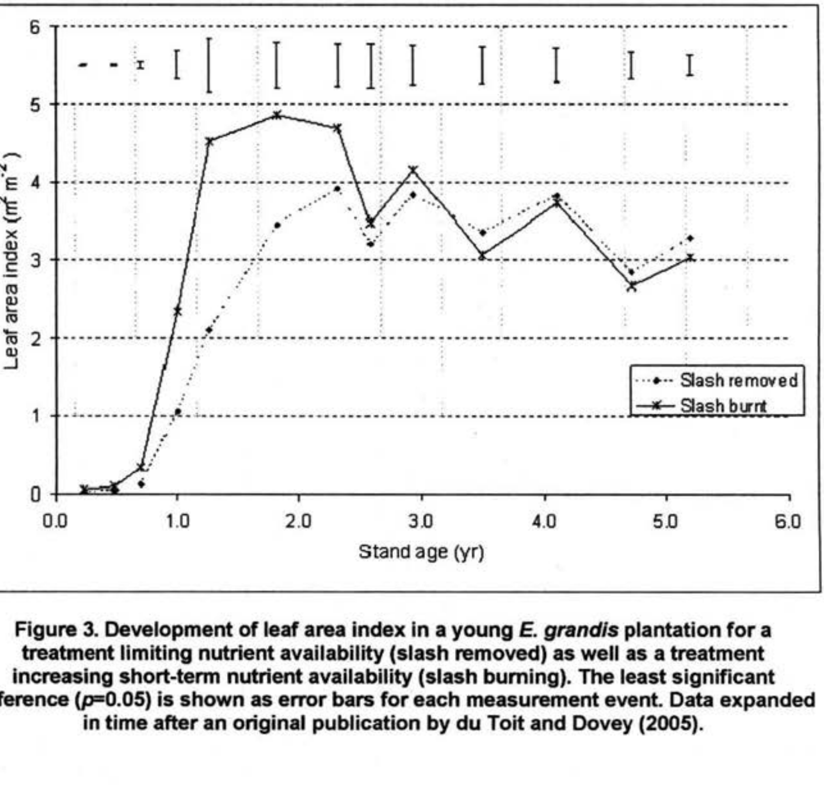

Figure 3. Development of leaf area index in a young *E. grandis* plantation for a treatment limiting nutrient availability (slash removed) as well as a treatment increasing short-term nutrient availability (slash burning). The least significant difference (p=0.05) is shown as error bars for each measurement event. Data expanded in time after an original publication by du Toit and Dovey (2005).

Discussion and Synthesis

The fertilizer response in case study 1 was highly site-specific. The use of quantitative soil properties that describe nutrient pool sizes (base saturation and organic matter content) or nutrient holding capacity (ECEC) was not very satisfactory, although it did enable us to construct a coarse fertility gradient that could be used to differentiate between response types. More disturbing was the fact that we could not really explain the negative interaction between applied N and P in the relatively fertile sites, while, at the same time, individual applications of these elements yielded significant positive responses. It is likely that a more intensive study of the nutrient dynamics following harvesting, establishment and fertilization could have shed light on the response mechanisms observed. Another shortcoming of the trial series was that we did not adequately monitor soil water availability. Fortunately, all trials received above-average rainfall over the trial period, suggesting that water availability was not such a major constraint. However, in the introductory paragraphs, we have referred to several other experiments in this same region where the non-response of fertilizer experiments during drought periods could not be explained conclusively, making the extrapolation of trial results difficult.

Case study 2 again highlighted the large differences between broad site types and importance of being able to make site-specific fertilizer recommendations. The trial sites in this case study were spread over a wide and variable region. The magnitude of the experimental undertaking meant that only two levels of fertilizer could be tested per element (one of which was a zero application level). This precluded an accurate estimation of the interactive effect between fertilizer elements at several rates of application. Accurate monthly weather data was not collected on the trial sites. However, the long term mean ratio of actual to potential evaporation (a useful indicator of the site water availability) was determined for each trial site. However, this variable was confounded with parent material (e.g. all trials in one parent material grouping were also constrained by water availability. This meant that the reason for responses to fertilization (or lack thereof) within site groupings remained unclear. Researchers could not discern whether certain site groups failed to respond due to lack of soil water or lack of nutrition. This problem highlights the importance of selecting trial sites in future trial groups across nutritional and soil water availability gradients. Such an approach will assist the researcher to differentiate between responsive and non-responsive sites in a specific site grouping and understand the constraints (water or nutrient supply) that may have prevented a meaningful response.

The conclusions drawn from the contrasting eucalypt sites in the third case study show the importance of addressing the interaction between water and nutrient availability when experimenting with fertilizer supplements. It also explains the mechanism of the response in terms that are physiologically meaningful. In moist or wet environments, fertilized stands are likely to respond with modest responses in LAI and comparatively large increases in α_c (assuming the species is well matched to prevailing site temperature conditions). The process-based model, 3-PG (Landsberg and Waring, 1997) is generally regarded as a good simulator of stand physiological response mechanisms, being based on extensive experimental evidence (Dye, 2001; Landsberg *et al.*, 2003; Dye *et al*, 2004). A sensitivity analysis was conducted on variables in this model and α_c emerged as one of the most sensitive parameters (Esprey *et al.*, 2004; Esprey 2005). A moderate increase in α_c is thus likely to result in comparatively large growth responses. There is also a fair body of evidence to suggest that η_w will also be increased with increased availability of growth resources, further contributing to maximise stem wood production (Linder and Rook, 1984; Landsberg and Waring, 1997; Stape, 2002; Giardina *et al.*, 2003; Binkley *et al*, 2004).

In the dry environment of site A, the response to fertilizer is dominated by changes in leaf area, and consequently, changes in APAR. An increase in leaf area index implies that the stand will need to transpire more water whilst speeding up growth. The fact that the stand on site A could only support an increased LAI during the early phase of canopy development, but returned to levels similar to the low fertility treatment after canopy closure, was attributed to water scarcity limiting the duration of this response from year three onward (du Toit and Dovey, 2005). This suggests that increased nutrient availability (through slash management or fertilization) has a small window of opportunity to increase light capture and tree growth on dry sites, before the canopy reaches maximum size and water scarcity limits the response. A similar mechanism governs fertilizer responses after thinning: If both water and nutrient availability are increased at the same time, maximum responses are observed (Brix, 1983; Stoneman *et al.*, 1996; Carlyle, 1998; West, 1998). In drier environments it is likely that thinnings at adequate intensity can temporary increase water availability, which will give fertilized treatments the opportunity to rebuild leaf area faster after the thinning event. However, once optimum leaf area for that site had been regained, it is likely that fertilized treatments will effectively grow at the same rate as unfertilized controls. We can conclude that the response to added fertilizer to a stand with sub optimal water supply is complex, because it is likely to be limited to specific windows of opportunity (e.g. during canopy development or after thinning). Furthermore, the capacity of the stand to respond to increased nutrient availability will be severely limited if the stand does not have the ability to substantially increase its canopy quantum efficiency. In order to understand the response mechanism and to extrapolate fertilizer trial results in dry environments, it is critically important to quantify the water availability during the entire treatment and monitoring period. Several factors could contribute to limit water availability: low rainfall, high evapotranspiration rates, highly concentrated or seasonal rainfall patterns and/or soils with low water holding capacity (specifically shallow, coarse textured soils). Water balance models have been constructed to deal with these complexities (e.g. Roberts, 1994).

"Hindsight is an exact science". It is not the author's objective to excessively criticise historical research efforts as it is not known under which financial, manpower and equipment constraints previous researchers had to work. However, to make progress, we need to ask the critical question: Where did the historic fertilizer trial approach in South Africa fail to deliver optimum results? It is generally accepted in agriculture and forestry that a simple factorial trial is a good experimental technique to test interactions between applied nutrients or other site management factors. It is the authors opinion that the basic concept of the trials were sound, and that they contributed substantially to furthering our knowledge base. However, the groups of fertilizer trials had fairly limited use in assisting with the extrapolation of experimental results for implementation in practice. The problems regarding extrapolation lie predominantly in two areas: (1) Due to the empirical nature of many historical experiments in South Africa, researchers did not quantify the gradient in nutrient availability across trials. Baseline fertility levels were uncertain and researchers failed to accurately describe (or fully understand) any changes to this baseline brought about by either fertilizer treatments or accompanying silvicultural operations that alter nutrient supply. A certain set of conditions and treatments elicited a given response but the mechanism was unclear, i.e. the system was treated like a "black box". In South Africa, Noble and Herbert (1991) made some progress towards classifying soils into broad classes or organic carbon content which may be linked to the sites responsiveness to N fertilization. However, they could not conclusively show that the rate of N mineralisation in field is well correlated to forest soil organic carbon levels since they did not measure nutrient dynamics in field. In contrast, the data presented by Carlyle *et al*, 1998, working in Australia, showed that **N** mineralisation of the mineral soil (determined *in situ*), could be linked to laboratory incubations. This type of finding is useful as an indicator of site responsiveness to applied nitrogen. In mitigation, we must add that during the last decade, South African silvicultural research has seen an increase in the number of trials where some form of a process-based understanding was pursued in order to understand the effects of site management on resource availability and tree growth, e.g. (Smith *et al.*, 1997; Little, 1999; Dye, 2001; Smith *et al.*, 2001; Louw and Scholes, 2002; Little *et al.*, 2002; Dye, 2004; Esprey *et al.*, 2004; Campion, 2005; du Toit and Dovey, 2005) among others. (2) Failure to accurately quantify the interaction between water and nutrient availability in historic experiments meant that the results could not be extrapolated with certainty to any area with variable (but generally limiting) water supply. Even if we acquire a very good understanding of the effect of treatments and operations on nutrient supply (point 1 above), but fail to understand the interaction between nutrition and water availability across the landscape, it will be near impossible to implement site-specific fertilizer applications. There is thus a need to incorporate a water and fertility gradient in new trials which would facilitate an extrapolation of the results to compartments or sub-compartments on the plantation scale.

Conclusions and recommendations

Southern Africa is a dry sub-continent and the evidence presented in this paper shows that a pre-requisite for site-specific fertilizer programmes is an understanding of the effect of water availability on increased nutrient availability. It is necessary to incorporate a water availability gradient as one factor in fertilizer trials. This has been achieved on an experimental scale at a few locations (through irrigation treatments), but such costly experiments cannot be replicated across several site types. The interception and diversion of rainfall (by spreading canvas or building "roofs" below the canopy in certain treatments) could be considered (e.g. Bertills and Näsholm, 2000, p115), but these have several limitations of their own, such as changes to soil temperature and biology, and being expensive. A cheaper, more practical and more representative method would be use soil depth (possibly even in combination with varying rainfall across a landscape) as a vehicle to bring about a water availability gradient. Schafer (1988a & 1988b) found that soil depth was the single greatest factor governing productivity of both *Pinus elliottii* and *Pinus pinaster* plantations in the southern Cape (i.e. the southern portion of the Western and Eastern Cape provinces). It would be feasible to lay out several small trial clusters (each containing treatments altering fertility) in close proximity to each other, located on a gradient of soil depths (the latter affecting water availability) to test the water by nutrient interaction. A group of these clusters (simulating a nutrient and water availability gradient) could be extremely useful to extrapolate results to a complex biophysical environment where water availability is highly variable.

If a water by nutrient availability gradient can be utilised in a trial design, the second vital ingredient for successful extrapolation of results (in the author's opinion) is an understanding and quantification of the changes brought about by treatments, i.e. through quantifying water and nutrient availability. The construction of a water balance is relatively easy (Roberts, 1994) and indices of nutrient availability and uptake could be developed for use in nutrient availability modelling. In recent years, several advances have been made in linking soil water supply to meaningful physiological variables, such as LAI or stress indices, often through remote sensing techniques (Coops and Waring, 2001; Coops *et al.*, 1998 & 2001). If information on the water balance and baseline site fertility levels could be linked to easily measurable variables such as LAI, or other indices from hyper-spectral data, highly efficient and accurate extrapolation of research results across the landscape could become a reality in dry climates.

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AUTOMATIC GENERATION OF TREATMENT PATHS FOR MIXED FOREST STANDS OF SPRUCE (PICEA ABIES) AND BEECH (FAGUS SYLVATICA)

Lars Hinrichs
Institute of Forest Management, Göttingen, Germany,
E-mail: lhinric@uni-forst.gwdg.de

Abstract

The individual forest stand, which is characterized by different site conditions and treatment history, is the elementary spatial unit in a forested landscape. Therefore, landscape and stand level planning are inseparably connected. A particular stand development is defined by a succession of harvesting operations and their ecological and operational effects. Such a succession is known as a management *path*. An important task of forest management research involves describing and evaluating treatment paths for individual stands with the aim of developing a realistic design for the landscape as a whole. This paper presents an approach for automatic generation of treatment paths for mixed forest stands, based on the development of the basal area and the relative share of two tree species, beech and spruce. Growth of individual trees is estimated using the simulator BWINPro. The management paths are guided by a stocking relative to the maximum density, which defines the thinning times and weights. The model is implemented in a special software module (known as *STAG*) and its functioning is demonstrated using two mixed stands of beech and spruce. For both stands the valid paths for two long-term strategic goals ("forest development types") and otherwise equal constraints were calculated. The results confirm the suitability of the model as a key component of a decision support system for optimizing the design of a forested landscape.

Keywords: Forest management, automatic generation, treatment path operational domain, thinnings, maximum basal area, species proportion, forest development types, multiple path concept

Treatment paths

The geographical formation of a man-made landscape is characterized by land use patterns and ownership boundaries. The individual forest stand, which is characterized by different site conditions and treatment history, is the elementary spatial unit in a forested landscape. Accordingly, forested landscapes are described and managed on the basis of their spatial subdivision into individual stands. Every stand is defined by its geographical position and by given attributes like age, density, species composition, site quality and tree dimensions. These attributes form the basis for decisions, which concern not only the stand itself, but also the forested landscape or the forest management unit as a whole. Thus, landscape design and stand level planning are inseparably linked and ultimately, the development of a forested landscape is defined by a given combination of stand treatments (Gadow, 1991).

Every stand development is determined by a sequence of forest operations and the resulting effects on the ecosystem and the operational success. This unique succession of operations is described as a *treatment path* or *path*. One task of forest management planning is to describe and evaluate treatment paths for stands with the objective of designing an overall plan for the forested landscape as realistically as possible. To describe a path for the time period t_0 t_1.three important aspects must be taken into account (see fig. 1):

- the forest operations (E_i) at the time of i
- the natural growth (ΔW_j) in period j,
- unforseen hazards ($\mathbf{r}_j$) in period j.

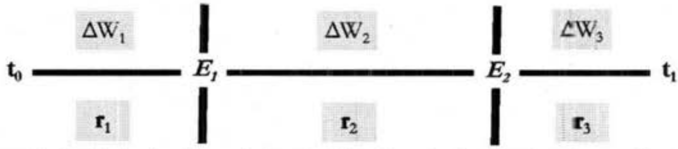


Figure 1. A path for the time window t_0 - t_1 is characterised by forest operations (E_i) at a given time i, as well as natural growth (ΔW_j) and unforeseen hazards (r_j) in period j.

Thus, the outline of a path is a process which assesses the effects of given forest operations on the future stand development. In the jargon of economy the quantity of the paths forms a decision field which is indicated by the features operational domain *A*, state space *Z* as well as by a objective function g (Bamberg and Coenenberg, 1994).

For every operation a from A and every state z from Z the decision field gives the consequences to g (a, z) which are connected with the coincidence of the operation a and the state z. The decision maker has the choice between operation alternatives a_1, a_2,...a_m at a given time. The quantity $A = \{a_1, a_2, ... a_m\}$ of the possible operation alternatives forms the operational domain for a given individual stand.

From the view of forest management all paths a_i of the stand i form the operational domain A_i. Every path passes through a temporary time window which is determined by an initial and a final state as well as by forest operations.

Forest operations affect the direction of the paths directly. Possible influences are for example the change of the nutrient budget of the soil by fertilisation, the change of value features of individual trees by pruning or the promotion of natural regeneration by fencing. From the view of forest growth thinnings are the most important operations. According to Burschel (1994) it is the most decisive forest operation with regard to the quality development of individual trees and the stability of forest stands. The consequences of an individual thinning can only be evaluated as a partial element within a sequence of measures (Kramer, 1988, p. 186). In the context of this study we only consider thinnings as forest operations and for the definition of the paths.

The number of all possible treatment paths (the *operational domain*) is limited by the predominant ecological and socio- economic constraints, which can be defined at different levels and with different accuracy (Gadow and Füldner, 1995; Gadow and Puumalainen, 1998; Pretzsch, 2001). The constraints are described by constants and variables, which represent limiting values for the model. In the broadest sense the limiting values of the individual constraints of a model are given by scientific legitimacies. However, they are often specified by the model developer in response to a specific question. With regard to the model formulation for a system for automatic path generation in mixed stands this is of decisive importance, because the inclusion of as many paths as possible in the decision-making process for the medium-term control represents the objective of the underlying attempt for the optimization of forested landscapes. Concerning the choice and expression of the model-constraints, one should make sure that the resulting operational domain is on the one hand large enough to generate a sufficiently broad variation of different paths (lower limit) and on the other hand, regarding the constraints of the processing time, does not exceed the constraints of practicability (upper limit).

According to these assumptions a model for automatic path generation for mixed stands was designed which shall serve as a basis for the search for an optimal design of a forested landscape. The model components shall describe the complex growth circumstances in mixed stands and take specific changes of the tree species proportion into account. Path generation shall be done systematically within an operational domain which is defined by characteristic variables used in forest practice. Initially, the model was adapted only for mixed stands of beech and spruce. However, the transferability on other complex forest types was taken into account during the development of the model.

Definition of the operational domain

For the delimitation of the operational domain four constraining variables were selected which are effective at different levels and can be used to adjust the size of the operational domain according to certain requirements (see fig. 2).

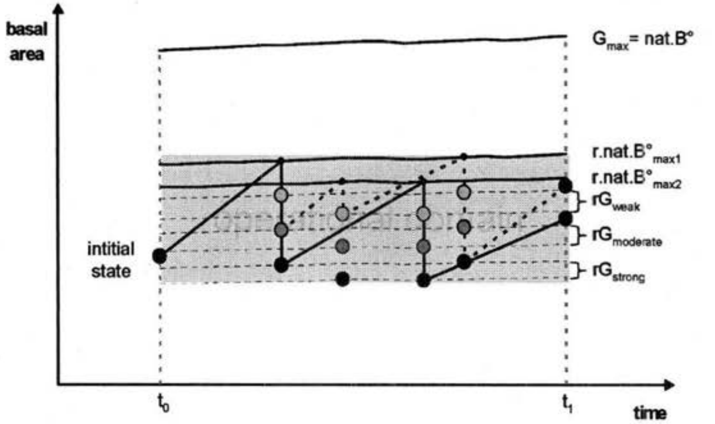


Figure 2. The valid operational domain, restricted by the maximum density (r.nat.B°$_{max}$), the thinning weight (rG) and the time window (t_0 , t_1).

As a growth limiting constraint the relative share of the maximum basal area (G_{max}), which is here described as relative natural stocking degree, is used (Reinecke, 1933; Assmann 1961; Gadow, 1987; Sterba 1987; Döbbeler and Spellmann 2002; Pretzsch and Biber, 2005). The transgression of the maximum limiting value (r.nat.B°$_{max}$) established by the user initiate a thinning. To make sure that the stand density variable at thinnings is maintained, two maximum density steps are predefined (r.nat.B°$_{max1}$, r.nat.B°$_{max2}$).

The characteristic of the thinning is limited by specification of a weak, a moderate and a heavy thinning weight (rG$_{weak}$, rG$_{moderate}$, rG$_{heavy}$). The relative share of the basal area of removed trees (rG) is used as a measure for the operational intensity.

The length of the planning period (t_0-t_1) and the maximum number of thinnings per planning period serve as further restrictions.

Model components

On the one hand, the G_{max} curve may move depending on changes of the tree species proportions caused by thinnings or natural mortality. On the other hand, every stand passed through a certain stand history until time t_0. As result every stand has a individual initial state and a different growth of the trees. It is consequently not possible to determine the actual number of possible treatment paths without a corresponding check by simulation. To include all possible paths, all theoretically possible alternatives are generated by means of a combinatorial algorithm. All these alternatives are simulated using a growth- and thinning model and are checked by a plausibility test. At the end one receives the desired information about the actually possible treatment paths with the respective characteristics of the forest operations with regard to the times and weights of the thinnings and the ecological and economic consequences in the form of characteristic quantities, such as the change of the species proportions or the net present value at the end of the simulation.

Model for the automatic generation of the possible paths

Assuming a predefined number of operations per planning period, number codes are generated for every theoretically possible path (Seo et al. 2005). Every operation is coded by two numbers in which the first digit defines the thinning weight (1 = rG_{weak}, 2 = $rG_{moderate}$, 3 = rG_{heavy}). The second digit defines the predefined density (1 = $r.nat.B°_{max1}$, 2 = $r.nat.B°_{max2}$). A path with two operations is therefore described by four digits, a path with three operations by six digits and so on. The theoretically possible number of all paths or the number of different number codes can be calculated as:

$$\sum_{i=\min DF}^{\max DF} Number(rG) \cdot Number(r.nat.B^{\circ}_{\max})^{i} \qquad (1)$$

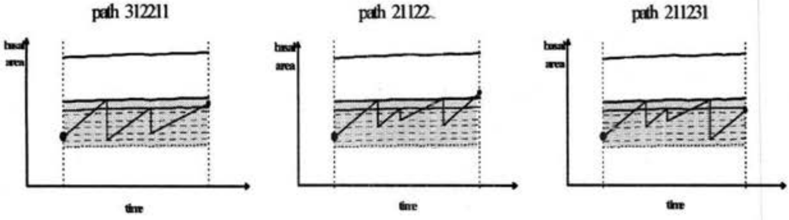
with:

minDF = minimum number of thinnings
maxDF = maximum number of thinnings
Number (rG) = number of possible thinning weights
Number (r.nat.B ° $_{max}$) = number of possible maximum density steps
For example, if the *minimum number of thinnings* is zero and the maximum *number of thinnings* is five operations within a given time period, the number of theoretically possible paths is:

$$\sum_{i=0}^{5} (3 \cdot 2)^{i} = 9331$$

After generating all theoretically possible paths they are simulated one by one in the sequence of their number codes. Afterwards a plausibility test is carried out to check whether the appropriate paths violate the restrictions of the operational domain or not. All thinnings must take place within the defined planning period and the basal area density of the stand may do not exceed the highest permitted density, which is predefined by the greatest of the two $r.nat.B°_{max}$. at the end of the planning period (see fig. 3).

The path 312211 whose simulation course is shown in the left graph in fig. 3 is invalid because the third thinning operation (11 = rG_{weak} / $r.nat.B°_{max1}$) cannot take place within the planning period because $r.nat.B°_{max1}$ is not reached. In other words the thinning weights are too heavy within the particular sequence. The path 211221 (fig. 3 middle) is also invalid because the basal area density exceeds the highest permitted $r.nat.B°_{max}$ at the end of the planning period. The thinnings are too weak. The path 211231 in the right graph is a valid one. Unlike in the previous path, the last thinning is heavy, not moderate, therefore the basal area density is below the highest permitted density at the end of the planning period. Moreover, all thinnings are carried out within the planning period.



invalid

invalid

valid

Figure 3. Possible variations of the plausibility test for identifying the valid paths. The graphs on the left and in the middle present invalid, the graph on the right a valid path.

Growth model

For estimating tree growth, the position dependent variant of the individual tree growth model BWINPro (Nagel et al. 2002) is used. The growth routines are made available in the context of the TreeGrOSS open source project of the Forest Research Station of Lower Saxony (Nagel, 2002). This system has been discussed extensively in the forestry literature and is therefore not described in the context of this study.

Thinning model

Depending on the desired forest development type (Lower Saxony, 1996) the thinning algorithm determines the relative share of the removal basal area per species using a rule-based approach. A "forest development type" (WET) is a strategic goal used in Germany, which defines a certain ideal forest with a particular species composition and silvicultural treatment. According to Spellmann et al. (1999) the removal of the individual trees is carried out depending on the top height in the intermediate felling stage and is subject to a target diameter in the final felling stage. This represents a selective thinning, followed by a target diameter felling.

A thinning is carried out when the first of all maximum relative natural stocking degrees is reached or exceeded. The observed r.nat.B° will be compared with the predefined permitted r.nat.B° at the beginning of the simulation and again after every growth period. The r.nat.B° is derived from the ratio of the observed basal area in relation to the maximum basal area. These are found out selectively and then summed up for every tree species. The maximum basal area is estimated using an equation by Sterba (1987), which was parameterized for northwest Germany by Döbbeler and Spellmann (2002; see tab. 1). The correspondingly transformed equation enables the regulation of the Gmax in subject to the top height H_{100} (see formula 2).

Table 1. Coefficients for estimating the maximum basal area for beech and spruce (according to Döbbeler and Spellmann, 2002).

Tree species	Coefficients			
	a_0	a_1	b_0	b_1
Beech	1.0829 E 07	1.5374	8.3652	-1.7365
Spruce	1.28745 E 06	0.7148	1.2842	-1.1914

In the case of an operation, at first one decides how the removed basal area (rG), defined before the beginning of the simulation, is assigned to the different tree species. In this particular case the observed species proportions do not yet represent those of the desired forest development type, and the under-represented tree species is given preference. This is done by removing more trees of the other tree species. Relative rates of the rG which are marked by rrG in the following serve as a measure for the proportionality of the operations per tree species. The weighting is carried out with regard to the observed species proportion, over the relative basal area proportion of the tree species dominating according to WET.

Table 2. Defining rrG (relative basal area removal rates) for beech and spruce WET (MA%$_{ideal}$ = mixture rate as per WET, MA%$_{real}$ = observed mixture rate, Grel.$_{Be}$ = relative basal area for beech, Grel.$_{Sp}$ = relative basal area for spruce.

WET 20 (Beech)
MA%$_{ideal}$: Be 80-100%, Sp 10-20%

MA%$_{real}$Be	rrG	
	Beech	**Spruce**
0≤MA%<20	0	1
20≤MA%<40	Grel.$_{Be}$*0,25	1-(Grel.$_{Be}$*0,25)
40≤MA%<60	Grel.$_{Be}$*0,50	1-(Grel.$_{Be}$*0,50)
60≤MA%<80	Grel.$_{Be}$*0,75	1-(Grel.$_{Be}$*0,75)
80≤MA%≤100	Grel.$_{Be}$	1-(Grel.$_{Be}$)

WET 50 (Spruce)
MA%$_{ideal}$: Sp 90-100%, Be 0-10%

MA%$_{real}$Sp	rrG	
	Spruce	**Beech**
0≤MA%<20	0	1
20≤MA%<40	Grel.$_{Sp}$*0,25	1-(Grel.$_{Sp}$*0,25)
40≤MA%<60	Grel.$_{Sp}$*0,50	1-(Grel.$_{Sp}$*0,50)
60≤MA%<80	Grel.$_{Sp}$*0,75	1-(Grel.$_{Sp}$*0,75)
80≤MA%≤100	Grel.$_{Sp}$	1-(Grel.$_{Sp}$)

WET 25 (Beech-Spruce)
MA%$_{ideal}$: Be 60-80%, Sp 20-40%

MA%$_{real}$Be	rrG	
	Beech	**Spruce**
0≤MA%<20	0	1
20≤MA%<40	Grel.$_{Be}$*0,25	1-(Grel.$_{Be}$*0,25)
40≤MA%<60	Grel.$_{Be}$*0,50	1-(Grel.$_{Be}$*0,50)
60≤MA%<80	Grel.$_{Be}$	1-(Grel.$_{Be}$)
80≤MA%≤100	1	

WET 52 (Spruce-Beech)
MA%$_{ideal}$: Sp 60-80%, Be 20-40%

MA%$_{real}$Spruce	rrG	
	Spruce	**Beech**
0≤MA%<20	0	1
20≤MA%<40	Grel.$_{Sp}$*0,25	1-(Grel.$_{Sp}$*0,25)
40≤MA%<60	Grel.$_{Sp}$*0,50	1-(Grel.$_{Sp}$*0,50)
60≤MA%<80	Grel.$_{Sp}$	1-(Grel.$_{Sp}$)
80≤MA%≤100	1	0

Tab. 2 shows the settings for the forest development types (WET) with the proportions of beech and spruce. In WET 20 (Beech) and 25 (Beech - Spruce) the beech dominates, whereas in WET 52 (Spruce Beech) and 50 (Spruce), the spruce represents the dominating tree species regarding the species proportion. The desired species proportions according to the respective WET are given in the header lines with MA%$_{Ideal}$. For example the mixture rate of beech is in the initial state between 20 and 40 per cent and in the long run the WET 25 is aimed at. The rrG which is assigned to beech, escapes 25 per cent of its relative basal area proportion and the rrG assigned to spruce equals to 1-0.25 therefore 75% of the relative basal area amount of beech. If at the same initial state the WET 52 is striven for, the rrG representing the spruce exactly equals its relative basal area proportion and the rrG for beech equals 1- relative basal area proportion of spruce.

After the removed basal areas are fixed, the withdrawal of the individual trees is carried out. They are removed in single stem manner, until the aggregated basal area sum exceeds the basal area value to be taken.The trees which reach the target diameter are taken at first. If the target diameter is not reached yet, the removed trees are selected from the collective of the 50 per cent biggest trees below a tree species-specific stand top height. After exceeding the mentioned top height limit the ten per cent biggest trees are spared as temporary crop trees. The withdrawal is therefore carried out from the collective of the 50-90 per cent biggest trees.

If sufficient trees are not in the defined collectives, the biggest remaining trees are taken as long, until the required basal area is reached.

An example

A Java based software module, known as *STAG (Silvicultural Treatment Alternatives Generator)* was developed for automatic path generation in multi-species stands. For the execution of a simulation, at first individual tree data which conform to the TreeGrOSS Exchange format from BWINPro must be imported. By use of this file format an interface to BWINPro and its additional functions, like the data completion routines or the stand designer, is given. Thus the software module STAG confines itself on generating treatment paths and further processing of the raw data set can be carried out with BWINPro or a spreadsheet program. The results of the path generation are stored in the CSV file format so that they can be processed by means of arbitrary spreadsheet programs or stored in a database.

Regarding the thinning model the desired forest development type, highest permitted relative natural stocking degree ($\text{r.nat.B°}_{\text{max1}}$, $\text{r.nat.B°}_{\text{max2}}$) and the three possible operation weights (rG_{weak}, $\text{rG}_{\text{moderate}}$, rG_{heavy}) must be predefined by the user before the simulation. Furthermore the planning period, the length of the growth period and the maximum thinning intensity has to be defined.

As an example for the applicability and the evaluation of the model, the possible paths for two test stands with beech and spruce are generated using the software STAG, based on two different predefined forest development types (Beech-Spruce and Spruce-Beech). The planning period was set to 15 years and the maximum thinning intensity is limited to four operations per planning period. The thinnings are carried out at $\text{r.nat.B°}_{\text{max}}1$ of 0.8 or $\text{r.nat.B°}_{\text{max}}2$ of 0.7, with a thinning weight of $\text{rG}_{\text{weak}} = 0.06$, $\text{rG}_{\text{moderate}} = 0.12$ or $\text{rG}_{\text{heavy}} = 0.24$. The target diameter and the top height steps, which are decisive for the identification of the crop tree collective, are set to a dbh of 60 cm for beech and 45 cm for spruce Accordingly the top height H_{100} is 22 m for beech and 20 m for spruce. The extrapolation of growth is carried out in one-year periods.

Data material

The single tree information of the test stands based from the Lower Saxony forest district Reinhausen. They were assessed in the context of the Lower Saxony forest management inventory (Böckmann et al. 1998). The individual tree data from the test plots were projected onto the double area size (0.11 hectares) to have a sufficiently large number of individual trees as a basis for the thinning algorithm. The individual tree variables required for the extrapolation of the growth were produced by BWINPro with the help of the data complement routines. Tab. 3 shows the characteristics of the initial states of the considered stands, which are referred to as Rein 001 and Rein 002 in the following.

Table 3. Basic data for two stands: Rein 001 and Rein 002 describing the initial states at time t_0.

Stand	Tree species	Age	Stem No.	Ba	Vol	dg	hg	d100	h100	Mix	r.nat.B*
		[years]	[N/ha]	[m^2/ha]	[m^3/ha]	[cm]	[m]	[cm]	[m]	[%]	
Rein 001	**Beech**	81	164	15.0	161.6	34	20	40	22	53	0.37
	Spruce	70	491	17.6	169.5	21	19	33	24	47	0.33
	total	-	655	32.6	331.1	-	-	-	-	-	0.7
Rein 002	**Beech**	88	473	17.2	182.2	22	21	32	24	62	0.42
	Spruce	88	164	15.2	189.1	34	28	37	28	38	0.26
	total	-	636	32.4	371.3						0.68

The initial states of the test stands are different with regard to the age of the tree collectives. The trees in stand Rein 001 are with 81 years (beech) and 70 years (spruce) respectively, seven years and accordingly 18 years younger than in stand Rein 002. The mean heights of the tree collectives suggest low and nearly similar site classes of the stands. Therefore the bigger dimensions of the trees in stand Rein 002 result merely from the higher age. The basal areas of the stands are with 32.6 m^2/ha (Rein 001) and 32.4 m^2/ha (Rein 002) on a similar level. The same applies to the relative natural stocking degrees and the stem number per ha which are with 0.7 and 0.68 accordingly and/or 655 and 636 trees/ha relative alike. Under the given density conditions and nearly similar site classes stand Rein 001 produces a growing stock of 331.1 m^3/ha and the older stand Rein 002 a growing stock of 371.3 m^3/ha.

Results and discussion

In consideration of the parameter settings mentioned above, 33 valid paths for WET 25 and 38 valid paths for WET 52 were generated for stand Rein 001 out of 1555 theoretically possible paths. For stand Rein 002, 54 paths for the WET 25 and 31 paths for the WET 52 passed the plausibility test in the path generation. Fig. 4 describes the characteristics of the paths using the basal area development subdivided according to the stands and the forest development types.

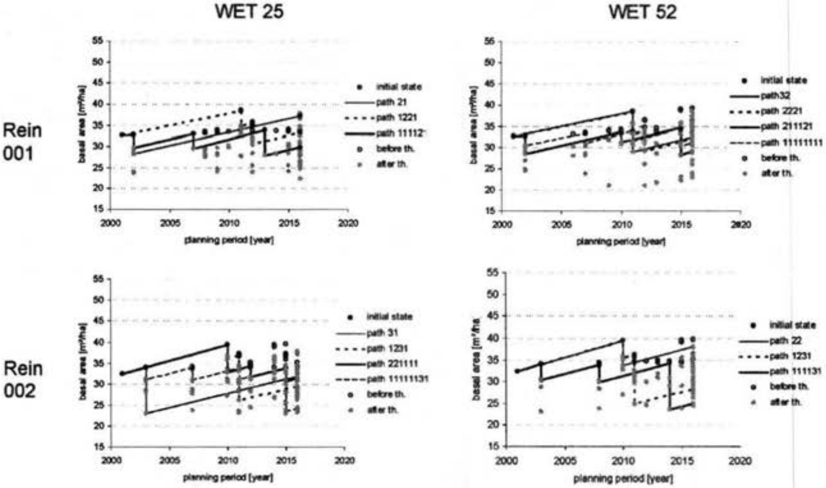


Figure 4. Basal area development of the valid paths for stand Rein 001 and Rein 002. The graphs on the left describe the developments for the long term strategy WET 25, the graphs on the right the developments for WET 52 The basal area at initial state t_0 in 2001, the basal area before (before th.) and after (after th.) thinning during the planning period (t_0-t_1) of 15 years are presented.

Starting from slightly different initial states of the stands, the paths show a similar frequency range at final states regarding their basal areas, which cover values between 23 and 38 m²/hectare almost continuously. While in stand Rein 001 at most four thinnings are possible at WET 52 and only three at WET 25, in stand Rein 002 maximal four thinnings took place at WET 25 and at most three thinnings at WET 52. On the whole over all paths in stand Rein 001 the thinnings took place at eleven points in time at WET 25 and at ten times at WET 52 accordingly. In stand Rein 002 thinnings where carried out at eight (WET 25) and nine points in time (WET 52) accordingly. Altogether, at first sight hardly different stands, have a relatively high variability regarding to there number of valid paths and the possible sequence measures. So for the development of stand Rein 002 in the direction of WET 25, 16 paths more are available than in stand Rein 001, which represents an increase of the possibilities of 42 per cent. In stand Rein 001 the treatment alternatives are rather varying in regard to the highest number of possible thinnings for the two different forest development types. In stand Rein 002 the number of treatment paths differs around 74 per cent. Although the paths of all considerations lead to similar final results, altogether, they offer a completely different range of planning options with regard to the spatial and temporal coordination of the thinnings.

For the description of the effects of the paths on the stand structure as well as for the check of the control behaviour of the thinning algorithm with regard to the species proportions, the development of the species proportions during the planning period is represented in fig. 5.

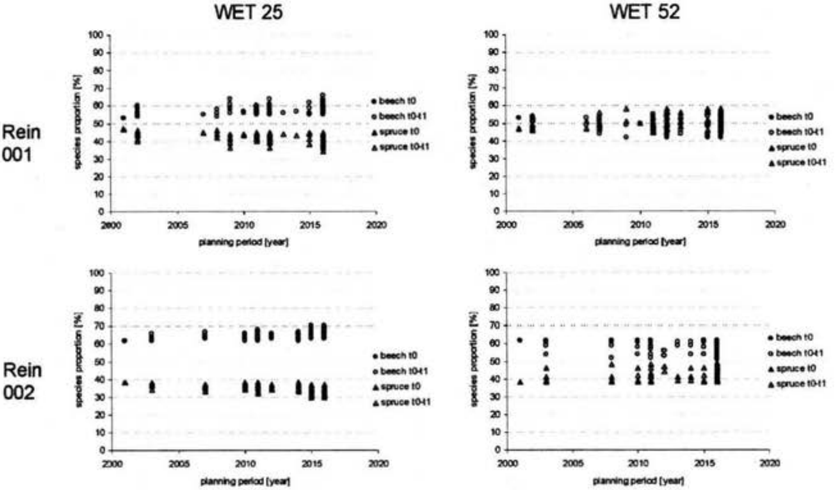


Figure 5. Development of the species proportions (in terms of basal area) for the valid paths in the stands Rein 001 and Rein 002, for WET 25 and 52. The species proportions are presented separately for the two tree species, from t_0 in 2001 until t_1 in 2016.

Stand Rein 001 has a mixture rate of 53 per cent beech and 47 per cent spruce in the initial state. The amount of beech at the WET 25 rises by seven percentage points to 60 per cent average over all paths during the planning period. According to that the amount of the spruce decreases to 40 per cent until the end of the planning period. At the WET 52 the mixture rate of beech decreases around six percentage points to 47 per cent while the mixture rate of spruce increase to 53 per cent on average. Rein 002 shows also an increase of the beech mixture rate at the WET 25 which turns out a little lower with four percentage points from 62 per cent in the initial state to 66 per cent in the final state on average over all paths. At the WET 52 the species proportion of beech also diminishes a little more moderately by five percentage points to 57 per cent.

These results suggest conformity of the objective of the thinning algorithm in regard to the specific control of the species proportions. If the actual state of the species proportions ($MA\%_{real}$) represents the debit state established in the model of the desired forest development type ($MA\%_{ideal}$) the mixture rates are kept more or less constant (Rein 002, WET 25 and Rein 001, WET 25). If $MA\%_{real}$ deviates from $MA\%_{ideal}$ an adjustment of the mixture rates has been carried out in the direction of the desired species proportions (Rein 001, WET 52 and Rein 002, WET 52).

Outlook

The objectives of the forest utilisation are primarily determined by the requirements of society. These requirements are not constant. They are changing in time periods which are often shorter than the timber rotation. The competitive status of a particular tree species is affected by the growing conditions. These conditions are also not constant. Every stand offers a variety of often equivalent silvicultural treatment paths. The choice of the optimal path for a specific stand is primarily determined by the current state of the stand variables, the weighting of the objectives and the forest-wide constraints. A long-term specification on given silvicultural programmes with rigid decision patterns does not seem plausible due to the vicissitude of the requirements of the society, the variability and disturbances of growth conditions and the frequent equivalence of several different paths.

Numerous studies in the field of forest management research especially from Scandinavia and North America demonstrate how the medium-term control can be realized under consideration of the various treatment alternatives of the stands by linking methods of forest growth and operations research (Ware and Clutter, 1971; Adams and Ek, 1974; Brodie et al.1978; Clutter et al.1983; Siitonen, 1983; Dykstra, 1984; Hoganson and Rose, 1984; Bare and Opalach, 1987; Buongiorno and Gilless, 1987; Clements et al.1990; Gadow, 1991; Lappi, 1992; Eid, 1993; Valsta, 1992; Pukkala and Kangas, 1993; Hoen, 1996; Bettinger et al., 1997; Hof and Bevers, 1998; Murray, 1999; Öhman and Eriksson, 1999). The advantage of these approaches is that they replace the previously common extensive standard silvicultural specifications by the analysis of various treatment alternatives which orientate themselves at real instead of hypothetical forests.

A general theoretical basis for a variety of approaches that attempt to combine stand level objectives and forest level constraints is the "multiple path principle" (Gadow, 2005). And one of the most famous practical application of this principle is the Finnish MELA system, introduced to a broad public by Kilkki and Siitonen (1976). MELA connects the objectives and constraints at stand and enterprise level (Siitonen et al., 1996; Nuutinen, 2000; Redsven et al. 2004). The implemented JLP optimization algorithm (Lappi 1992) in MELA is suitable for large-scale enterprises with up to 50 000 stands. MELA has become the most important base of the Finnish forest management and is used regularly in private forest enterprises, in the state-owned forests and in the small private forests.

Models for generating multiple treatment paths form the basis for practical use of the multiple path principle. The results depend on the accuracy of the growth models and the realistic application of the thinning models. These essential tools have to be permanently improved.

The model for the automatic, basal area oriented path generation in mixed stands introduced here makes it possible to generate a relatively high number of relevant paths, within a clearly defined operational domain. The number of possible paths of a stand is greatly influenced by the initial states of the stands and the restrictions imposed.

For the practical application of the multiple path concept within a decision support system for the management of larger forest complexes it is imperative that one is able to access stand or individual tree information which satisfy the precision requirements for reliable forecasts. The cost-efficient assessment of suitable data is one of the yet unsolved problems of forest management research. Nieschulze et al. (2005) presented a promising approach for regionalization of sampling data to get information on stand level, which is based on causal connections between information of aerial photographs and terrestrial samples.

With regard to the optimization on operational levels which selects the optimal path combination from the sum of the valid paths of all stands a multicriterial evaluation of the individual paths is essential (cp. Kangas, 1993; Vacik and Lexer, 2001; Albert, 2003). For this purpose various indicators have to be identified, to make sure that the objectives are measurable in an objective function (Sodtke et al., 2004).

The net present value *(NPV)* has often been used as an economic criterion in a variety of studies. The NPV represents in this particular application the sum of the discounted cash flow of the thinnings during the planning period and the discounted value of the stand at the end of the planning period (Hille et al., 1999; Öhman, 2001; Sánchez Orois and Vilcko, 2002).

In addition, there is a variety of ecological indicators, such as the species diversity which can be described in different ways (Pielou, 1975; Albert 1999; Pretzsch, 2001; Hui and Albert, 2004).

For the final search for the optimal path combination of the stands of a forested landscape heuristic search methods such as Simulated Annealing and Tabu Search are powerful tools (Chen and Gadow, 2002; Pukkala, 2004). They are able to deal with large optimization problems by approaching the optimum solution in a more or less satisfactory processing time.

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DEFINING PLANTING WINDOWS FOR SUCCESSFUL RE-ESTABLISHMENT OF *PINUS PATULA* IN SOUTHERN AFRICA

J.W. Crous and R.G. Mitchell
Sappi Forests Research, Ngodwana Nursery, South Africa
E-mail: jacob.crous@sappi.com

Abstract

The site environment and particularly climatic conditions during and after planting significantly affect the survival of young trees. Using temperature and rainfall data for all Sappi land types (map units that are relative uniform in macroclimate, terrain form and soil patterns), a model was developed to identify periods in the year when the probability of successful establishment is most likely. The critical values utilized in the model aimed to ensure sufficient soil moisture at planting and a reduction in temperature extremes. The model was validated using survival results from 56 trials. The results indicated that mean survival at 241 to 360 days after planting improved by 15% when planting occurred within the recommended period. Furthermore, an establishment risk, associated with each land type, was derived from the model output. Sites favouring re-establishment success (Low risk) were characterised by a longer re-establishment period.

Keywords: Planting periods, establishment, survival, planting risk

Introduction

Successful re-establishment does not only lead to increased short term profits through a reduction in blanking costs, but it has a significant impact on the long term increase in fibre production (Morris, 1997). The initial survival in the field after planting is affected by a number of factors such as the site environment, handling, morphology, and physiology of the seedlings. Of these factors the site environment is the most important (South, 2000). This includes soil water content at time of planting, temperature and amount of rainfall soon after planting, soil texture, soil depth, nutrient availability, competition from weeds, and amount of pests or diseases (Barnett and Brissette, 1986; Fancher, Mexal and Fisher, 1989; South, 2000; Mitchell, Zwolinski and Jones, 2005). The most important environmental factors that can cause stress in plants are extremes in climate, e.g. drought, heat, cold and frost. Furthermore, the effects of these factors are closely inter-related. For example, high temperatures may lead to excessive transpiration, which in turn could lead to severe moisture stress (Bidwell, 1979). Biotic factors that influence survival, such as insects or diseases and weed growth, are also affected by climate. Therefore, if plants are re-established during periods when environmental conditions are favourable, the stress on plants should be reduced, which should result in better survival and growth.

Previously, Guy (2001) developed a model to predict periods when the environmental conditions will be favourable for good post-planting survival of *Pinus patula* at Usutu, Swaziland. Environmental conditions favourable for seedling establishment occur when soil moisture and temperature conditions in the rooting zone are adequate for root growth (Landis, 2003), air temperature and humidity are at levels that encourage transpiration and photosynthesis, and the risk of frost damage is minimal (FRDA, 1988). By identifying these planting windows, Guy (2001) uncoupled the planting programme from between season climatic variation, which allowed for better scheduling of nursery production and planting operations. However, this model was only applicable to Usutu and it had to be adapted to identify planting windows for all the different sites suitable to planting *P. patula* on all Sappi land holdings. This paper reported how a model, which incorporated all Sappi land holdings, was developed and validated.

Developing the model from current knowledge

The model that Guy (2001) developed was based on identifying periods when planting risk associated with soil moisture and temperature would be the lowest. As discussed previously, these climatic parameters are not only the most important environmental factors that contribute to post-establishment mortality, but can also be used as a surrogate for other factors that influence mortality. As a result, the climatic criteria used in the current model were based on predicted long term monthly temperature and rainfall data. The current understanding of these climatic events and thresholds and its effect on survival will be discussed in more detail in the following sections.

Rainfall

"Available soil moisture is the most critical factor in evaluating the suitability of a site for planting. Soil texture and moisture content determine the soil water potential, which is a measure of the amount of water in the soil available for plant growth" (Barnett and Brissette, 1986). Moisture stress occurs whenever the rate of transpiration exceeds the rate of adsorption, leaving plant cells less than fully turgid. Seedling moisture stress will be the lowest when the soil can supply sufficient moisture, the seedlings are able to absorb it, and atmospheric evaporative demand is low. The evaporative demand is generated primarily by increasing air temperature and decreasing humidity, although radiation intensity and wind speed contribute indirectly (McDonald, 1984). The effects of moisture stress are particularly severe on seedlings or new transplants, because their roots occupy the uppermost layers of soil where the most rapid drying occurs. In addition, root damage may occur during the planting operation, which can exacerbate the situation. Severe moisture stress causes primarily root damage and metabolic changes, which substantially alters the physiology of drought-stressed trees. A significant secondary effect of moisture stress is that it weakens trees and predisposes them to secondary invaders and opportunistic pests (TFS, 2002; Douglas, 2005).

Critical thresholds have been established for rainfall requirements prior to planting. At Usutu, Swaziland, it was determined that at least 75 mm of rain should be recorded to ensure successful planting in spring (Usutu Silvicultural Manual, 1997). Unfortunately only predicted average monthly rainfall data were available for modelling purposes. This meant that cumulative rainfall would reflect the total amount as at the last day of the month, while the prediction should really be applicable to the middle of the particular month. Therefore the critical value for **previous month rainfall** (Table 1) was reduced to 50 mm to achieve a total of 75 mm when half of the critical amount of **current month rainfall** (25 mm) was added to it. Rainfall in the month following planting is of less importance than when actually planting, because the seedlings had time to generate roots and are therefore able to access soil moisture in a larger soil volume (Close, Beadle and Brown, 2005). The critical value of more than 20 mm for **future month rainfall**, used in a previous model developed for Usutu by Guy (2001), was incorporated in the current model.

Table 1: Criteria and critical values used to determine periods when the probability of successful planting will be the highest.

Criteria	Unit	Planting conditions	
Previous month rainfall	mm	>	50
Current month rainfall	mm	>	50
Future month rainfall	mm	>	20
Mean maximum air temperature of month	°C	<	24
Mean minimum air temperature of month	°C	>	6

Temperature

The direct effect of high temperature is to denature and coagulate proteins (Bidwell, 1979). This leads to cellular membrane injury, cell component decomposition, or both. These effects are normally immediate and obvious. This type of heat injury normally occurs on the stem, just above the soil surface. Heat energy is concentrated above the soil surface due to infrared radiation reflected from the soil surface and limited air movement in that region. Indirect heat injury due to metabolic disturbances is more subtle and varies from reversible damage to death. Older seedlings are less prone to direct heat injury, because they have developed a lignified outer stem that insulates sensitive tissue from hot soil (McDonald, 1984). However, an important side effect is the increased rate of water loss that accompanies high temperature (Bidwell, 1979; Kolb and Robberecht, 1996). At constant relative humidity, evaporative demand increases exponentially with air temperature. Consequently, under conditions of increasing temperature and low humidity, plants can suffer significant short-term moisture stress even in wet soil (McDonald, 1984). This is of specific importance if hot dry conditions occur shortly after planting, before the plants have had time to acclimatize and recover from the stress of planting (Burns, 2005).

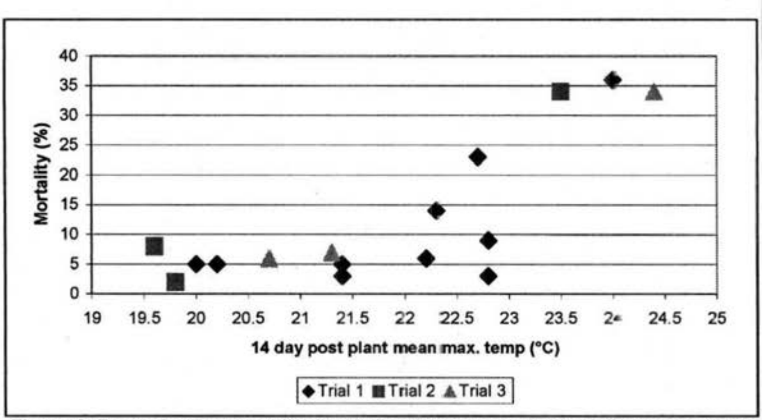

Figure 1: Post–planting mortality in relation to mean maximum daily temperatures over 14 days following planting in three different trials at Usutu. All plantings were treated with insecticide. From Morris (1990).

Morris (1990) correlated various meteorological parameters with total mortality of transplants at Usutu. He found that the strongest correlation was with the mean daily maximum temperature for the 14 days following planting (Figure 1). A quadratic equation fitted to this data accounted for 78% of the variation in mortality. One of the main conclusions from this study was that mortality increased markedly when the mean daily maximum temperatures, for the two weeks following planting, exceeded 22.5 °C. However, in three trials Morris (1990) recorded the most severe mortality when the mean maximum temperature increased to above 23.5 °C. In controlled-environment trials with Douglas-fir seedlings and other conifer species the optimum temperature for growth was found to be 24 °C, although other findings suggest that the optimum temperature for growth may drop as plants increase in size and age (Lavender, 1984). Dvorak, Hodge, Kietzka, Malan, Osorio and Stanger (2000) reported that average monthly temperatures for *P. patula* in particular should range from 5 to 23 °C. Therefore, a critical value of less than 24°C for the **mean maximum monthly air temperature** was utilised in the model.

Frost probability influences decisions relating to species choice and the planned time of establishment (Pallett, 1999a). Most temperate plants are affected by freezing temperatures when they are in an actively growing state (Glerum, 1985). The freezing damage might be two-fold. Firstly, the ice crystals that form in the cells might cause mechanical damage. Secondly, the consequence of ice-formation is the reduction in water content of the tissue, which eventually causes a drought situation (Bidwell, 1979). The frost killing temperature may vary widely, depending on the manner of temperature change, the season and the physiological state of the plant and species (McDonald, 1984). Although *P. patula* exhibits moderate resistance to frost (Dvorak *et al.*, 2000), late frosts in spring or early frost in autumn can cause serious frost injury if the seedlings have not had time to adapt to the cold (Close *et al.*, 2005; Mitchell *et al.*, 2005). Tree seedlings planted into cold environments can be very susceptible to frost damage for a number of reasons. The young, recently developed foliage often has a high water content and relative large-celled leaves with low osmotic concentration - characteristics that are associated with high susceptibility to frost. Furthermore, cleared re-establishment sites lose more energy during cloudless nights through infra-red radiation than adjacent forested areas (Close *et al.*, 2005).

Two mechanisms lead to frost namely advection and radiation. Advection frost occurs when cold air flows from a higher location to a lower one, displacing lighter, less dense warm air. This cold air will pool if it encounters an obstruction, causing a "frost pocket" (McDonald, 1984). Radiation frost occurs when excessive amounts of heat energy in the soil and plants are lost to the sky as long-wave radiation on cold cloudless nights, with little or no wind. Under these conditions the temperature of the soil surface, air near the ground and plant leaves can fall below freezing (McDonald, 1984). At a land type level (unit denoting land over which there is a marked uniformity of climate, terrain form and soil pattern at a 1:250 000 scale [Van der Watt and Van Rooyen, 1995]) radiation frost can be predicted more easily, because it is not as affected by localised topographical effects as advection frost (Pallett, 1999a).

Cold dense air sinks to the surface, causing large temperature differences between the surface and the air above the ground. Temperature sensors located at 1.2 m above a grassed surface, which is the South African Weather Service's standard for temperature observations (McBride, 2001), do not represent the temperature of the air or plants at the surface. Therefore, frost may occur on the ground when the "official" temperatures are as high as 2 °C (Vega, Robbins and Grymes, 1994). However, the critical temperatures that will cause damage to plants are slightly below the freezing point of pure water, due to freezing point depression by the solutes in the cell sap (McDonald, 1984). Determining the critical value for the model to identify periods when frost is likely to occur was further complicated by the fact that only predicted mean minimum temperature, 1.2 m above the soil surface, was available from the land type database. The absolute minimum temperature per month would have provided a much more accurate indication of possible frost occurrence during that month. Fortunately, a strong relationship (R^2 = 0.92) was found between the mean monthly minimum temperature and absolute minimum temperature within any particular month. This relationship was determined over an altitude range by using official weather data (1997 to 2002), supplied by the South African Weather Service for the Nelspruit, Piet Retief and Ermelo weather stations (Figure 2). From this relationship it was determined that if the **mean minimum temperature** for any month drops below 6°C, there is a good chance that an absolute minimum temperature less than 0 °C will be recorded in that month, which in turn could lead to frost damage in plants that have not acclimatised to frost.

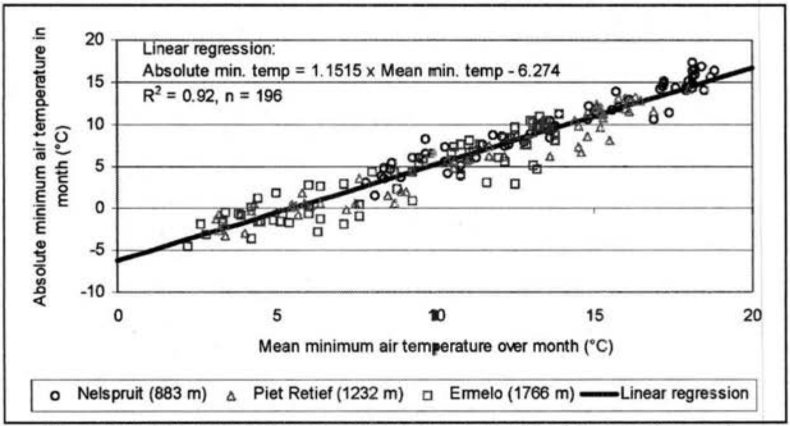

Figure 2: Relationship between mean minimum monthly air temperature and absolute minimum monthly air temperature for three weather stations over an altitude range.

Applying the model to the land type database

Previously, all sites on Sappi land holdings that are uniform or show a predictable variation in macroclimate, terrain form and soil patterns have been mapped as one of 170 land types (Pallett, 1990; Pallett, 1991; Pallett and Mitchell, 1993; Crous, 2003). The climate, terrain and soil information associated with each land type has been compiled into one single database. The various monthly predicted climatic parameters e.g. mean maximum temperature, mean minimum temperature, rainfall, etc., in the database were derived from modelled grid data for Southern Africa. The planting model criteria (Table 1) was applied to the data for the 100 land types suited to growing *P. patula* (Pallett, 1999b) on a monthly interval. Planting was only recommended for months where all conditions were complied with, i.e. when there would be a high probability of successful establishment. An example of the model output per land type is shown in Table 2.

Table 2: Example of model output per land type.

LAND TYPE	Risk*	Oct	Nov	Dec	Jan	Feb	Mar	Apr
416	**H**		Plant				Plant	
417	**L**	Plant	Plant	Plant	Plant	Plant	Plant	
418	**M**	Plant	Plant	Plant	Plant		Plant	
419	**L**	Plant	Plant	Plant	Plant	Plant	Plant	
420	**M**	Plant	Plant	Plant			Plant	Plant
421	**M**	Plant	Plant	Plant			Plant	
422	**H**		Plant				Plant	Plant
424	**L**	Plant	Plant	Plant	Plant	Plant	Plant	

* H – High, M – Moderate, L - Low

Validation of the model

In order to validate the model, survival results from 56 research trials were used. The trials were planted over 18 years (1987 to 2005) and on 21 different land types in Mpumalanga (South Africa) and Usutu (Swaziland). The dataset consisted of 415 records. Average survival percentage per treatment and plant date were recorded at various intervals after establishment. An angular transformation was applied to survival percentage in order to normalize the data and to reduce the variance. Only survival of the original plants was used and the effect of blanking was excluded from this dataset. The survival results were grouped into three assessment periods, depending on the time since planting. Early assessments were those done between 30 and 120 days after planting (dap), mid assessments those between 121 and 240 dap and late assessments those between 241 and 360 dap. Based on the month of planting and the land type associated with the compartment where the trial was planted, the model recommendation was determined for each record. Subsequently, the average survival was calculated per assessment period, depending on the model prediction. The means were compared with t-tests. The angular transformation of the survival data did not make any difference to the conclusions and as a result untransformed values were presented in the graphs to simplify interpretation.

The comparison of survival results indicated that the mean survival percentage was significantly higher during all three assessment periods in both regions when planting occurred within the recommended period (Figure 3). At the late assessment the mean difference over both regions was 15% (within a range from 7.4% to 22.5% at a 95% confidence level). The model was effective in both regions. Furthermore, the variability in survival decreased when planting occurred within the recommended planting window. This is clearly illustrated by the lower standard error values for mean survival associated with planting during recommended months (Table 3).

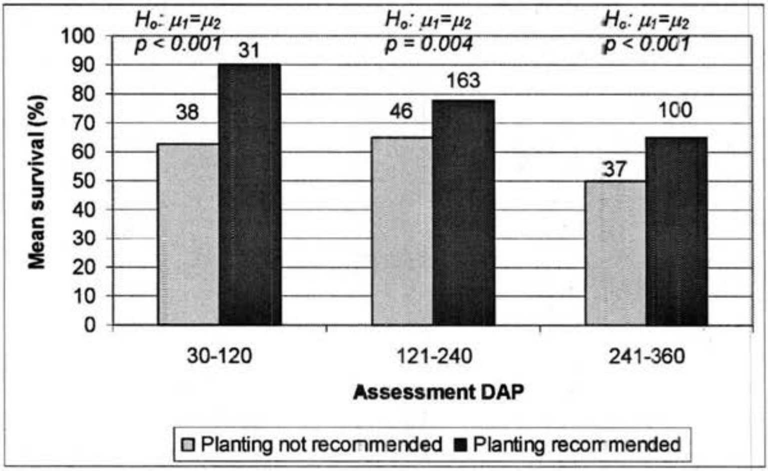

Figure 3: The survival was significantly higher during all three assessment periods in both regions when the planting model recommended planting. Numbers on top of bars indicate the number of records the mean was based on.

Table 3: Verification of the model showed that, for both regions, survival in the research trials improved and that the variability in survival was reduced when planting was done during the recommended period.

Region	Assessment DAP*	Planting model						Survival increase	T-test: $H_o: \mu_1=\mu_2$	
		Planting not recommended			Planting recommended					
		No. obs	Mean Survival	Standard Error of Mean	No. obs	Mean Survival	Standard Error of Mean		t value	Prob.
Mpumalanga	30-120	19	**74.6**	6.4	19	**88.0**	2.5	13.4	-1.95	0.063
	121-240	25	**58.4**	5.5	77	**70.8**	2.3	12.7	-2.14	0.046
	241-360	33	**50.0**	3.8	58	**62.5**	2.6	12.3	-2.73	0.007
Swaziland	30-120	19	**50.8**	7.8	12	**92.8**	1	42.0	-5.36	<0.001
	121-240	21	**72.6**	5.6	88	**83.7**	1.6	11.1	-1.88	0.072
	241-360	4	**49**	2.8	40	**68.7**	2.9	19.7	-2.12	0.040

*DAP = Days after planting

The effect of various factors, including the application of water or pesticides at planting on general survival, was tested with a Spearman's rank correlation. The survival percentage of each record was correlated with the planting model recommendation, risk category, the presence of harvest residue (slash) and different treatments applied at planting. Only late-assessment data from the Mpumalanga region were used. The late assessment data were considered indicative of final stocking. Data from the Swaziland region were excluded from the dataset, because of insufficient data per treatment category. The results (Table 4) indicated that the application of water on its own did not affect survival significantly, but that the application of water and fungicide did improve survival significantly (1%-level). This confirmed other similar findings (Crous, 2005). The presence or absence of harvest residue did not have any effect on the mean survival.

Table 4: Spearman's rank correlation for all trials assessed between 241 and 365 dap in Mpumalanga.

		Planting model	Risk category	Water	Water and Fungicide	Water, Fungicide and Insecticide	Harvest residue
Survival	Correlation	0.267	-0.393	0.198	0.289	0.180	0.099
	t Approx.	2.644	-4.071	1.836	2.878	1.749	0.946
	P-value	0.010	0.000	0.070	0.005	0.084	0.347

The interaction between mean survival, as per the model recommendation, and the influence of some at-planting treatments was also investigated. Again only the late-assessment data from the Mpumalanga region was used (91 records). The t-test results (Figure 4) indicated that the model only had a significant effect on mean survival when no additives or only water was applied. In cases where pesticides were applied, the mean survival of planting inside or outside the recommended window was not significantly different. The largest increase in survival was achieved by planting during the recommended periods, without a costly application of any chemicals.

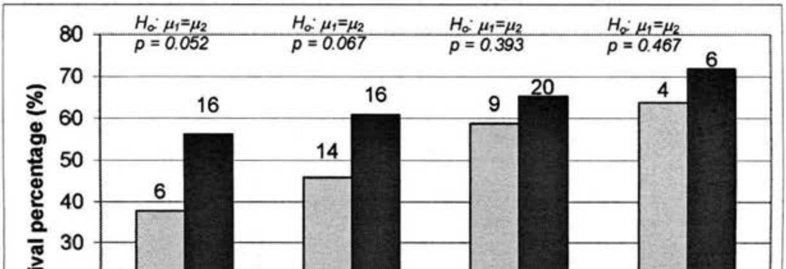

Figure 4: Results from the 241-365 dap assessments in Mpumalanga indicated that the model became less efficient when pesticides were applied. Numbers on top of bars indicate the number of records the mean was based on.

Risk identification

The model output was further used to derive an establishment risk, associated with each land type, based on the duration of the planting window. Sites favouring re-establishment success (Low risk) were characterised by a longer re-establishment period, whilst sites frequently associated with poorer survival (High risk) were characterised by a very short recommended re-establishment period (Iverson, 1984; Mitchell *et al.*, 2005). In this study, land types with a planting window of 1 to 3 months were classified as high risk sites. The criteria used to define the other two classes are shown in Table 5.

Table 5: Risk associated with establishment was derived from the duration of the modelled planting window.

Risk	Duration of planting window
Low	6 or 7 months
Moderate	4 or 5 months
High	1 to 3 months

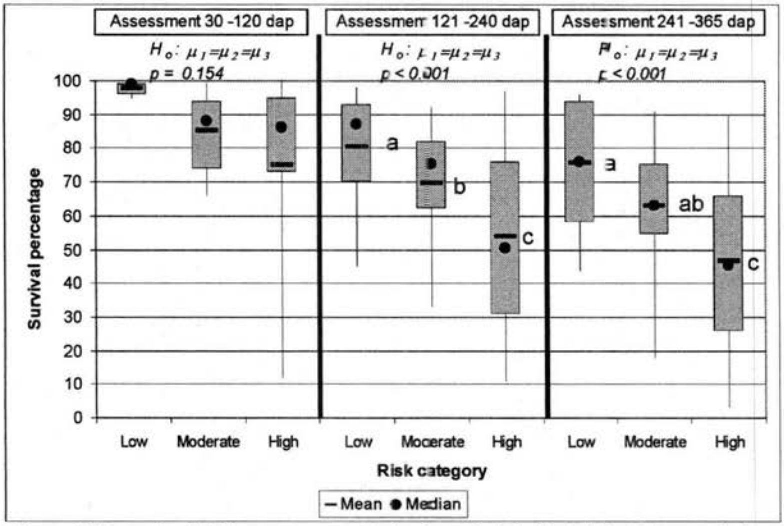

Figure 5: From the 121 day assessments the box-plots indicated that the survival percentage on High-risk sites was significantly lower than on Low-risk sites in Mpumalanga. Different letters indicate significant differences between means at the 5%-significant level within each assessment period.

The establishment risk, defined by the planting windows model, was validated with the Mpumalanga survival data from the research trial database (231 records). Residual Maximum Likelihood (REML) analysis (GenStat 8.1, 2005) was conducted separately on each of the three assessment categories to test the null hypothesis that there were no significant differences between the mean survival in the different risk categories. Both angular transformed survival and original survival percentages were used individually as a y-variate in the model, whilst risk category was included in the model as a fixed effect. Where the null hypothesis was rejected, the critical difference at the 5% level was used to inspect differences between the means. Results indicated that, from the mid-assessments, mean survival and minimum survival decreased significantly with an increase in risk. The box-plot (Figure 5) also indicated that the range increased as the risk increased. This proved that on land types classified as low-risk sites, chances of successful establishment were much higher than on the high-risk sites.

Operational application

Foresters are faced with various operational constraints, before and during planting. Pine planting stock has to be ordered 8 to 10 months in advance – long before the forester will know how the actual planting season will turn out. During favourable planting conditions the most important operational constraint foresters are faced with is that the area that can be planted is limited by the size of available planting teams. The planting windows model can assist foresters to overcome some of these operational constraints. Periods can be identified when the probability of successful establishment will be high. Thus nursery orders, site preparation and planting activities can be scheduled beforehand. Provision can also be made for periods when peak resource demand is anticipated.

The establishment risk rating can be used operationally to identify compartments that will need special effort to re-establish successfully. On these sites, very healthy plants should be planted into freshly prepared pits. Weed growth and insect activity should be intensively monitored and controlled on the high-risk sites to limit stress and mortality related to biotic factors. Furthermore, the risk rating can be used to budget for increased or additional blanking operations in high-risk compartments.

Additional considerations

Research at Usutu identified harvest residue, site preparation and insects (*Hylastes angustatus*) as important influences on the immediate post-planting survival of *P. patula* (Morris, 1990; 1993a; 1993b; 1993c). Similar research work has not been extensively conducted in other *P. patula* growing areas. Therefore, these results were not incorporated into the current planting windows model. As our knowledge of the factors that influence survival improves, these factors and their critical values will also be included in the model to improve its accuracy.

Conclusions

This planting windows model can be used as a decision support system to schedule nursery orders, site preparation and re-establishment activities for periods when the probability of successful establishment is high. Validation of this model, by using results from research trial plantings, showed that planting during the recommended periods is the cheapest and most effective single method to improve survival. The establishment risk rating, derived from the model output, can be used operationally to identify compartments that will need special effort to re-establish successfully. Future expansion of the model by including more factors and adjustments to the current critical values will improve the accuracy of predicting suitable planting windows.

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IDENTIFICATION OF TREE ROOT SYSTEM DAMAGE CAUSED BY HEAVY MACHINERY USING NEW MEASUREMENT TECHNOLOGY SUITABLE FOR PRECISION FORESTRY

Čermák, J., Neruda, J., Naděždina, N., Ulrich, R., Martinkova, M., Gebauer, R., Pokorný E., Prax A., Naděždin V., Hruška, J., Gašpárek, J., Culek I.,
Faculty of Forestry and Wood Technology, Mendel University of Agriculture and Forestry, Czech Republic
E-mail: cermak@mendelu.cz

Abstract

Damage to tree root systems caused by movement of forwarders along skidding tails in forest stands have been usually checked earlier through measurement of growth increment in neighbouring trees. We focused on measurement of soil and tree parameters using modern technology, which is being applied e.g. in tree-physiology studies. Several types of forwarders were tested in Norway spruce stands growing in soils with different moisture conditions. We measured pressures occurring in soils under heavy machinery, soil compaction and immediate and long-term changes in CO2 concentration. Tree root systems were analysed using the geo-radar technique and excavated harmlessly by the supersonic air stream. Microscopic technique served for explanation of changes, which were not visible in the field. Root functions were characterized via sap flow measurements in coarse roots and stems. Sensors based on the heat field deformation method allowed measurement radial patterns of flow, i.e., to assess where were damaged surface or deep roots. We obtained first important results and selected best combination of methods suitable for such studies.

Keywords: soil pressure, soil CO_2 concentration, supersonic air-stream, geo-radar, sap flow, microscopy,

Introduction

During tending measures in all age stages of forest stands and during their regeneration the extent of applications increases of progressive logging technologies using mobile means of mechanization (particularly harvesters and forwarders). As compared with present motor/manual technologies, these machines make possible to increase markedly labour productivity and occupational safety, to decrease health risks, to facilitate felling records etc. The majority of used machines is of considerable weight being equipped with wheeled undercarriages. During their passage, unfavourable structural changes occur in forest soils. According to the results of research, the changes can cause losses in forest production by 17 and even more per cent (Becker, 1999). Damage to root systems of neighbouring trees can be expected even under directed movement of machines along determined tracks, i.e. extraction lanes. It is possible to suppose a direct relationship between the rate of damage to soil and tree roots and the frequency of passages of machines along tracks, weight, undercarriage specific pressure, soil character, weather and other effects (McMahon, 1995). Through the interactions of a wheel working machine – energy source, adapter or aggregate and the stand soil surface during logging and transport operations pressures are induced in soil being dependent particularly on the level of tyre inflation, their stiffness and on the adhesion load of a traction system.

Through the impression of tyres into the soil surface deformations of the upper soil layers occur resulting in the origin of ruts the depth and width of which is related to the type of tyres, their load, surface conditions, type and texture of soil, soil moisture and number of passages. The level of pressures transferred into soil by the tyre of a given type, inflation and load is changed in relation to depth (decreases) where it is determined, in relation to ground cover, the occurrence of coarse and reinforcing components in soil etc. Therefore, comparisons of consequences of the effect of passages on soil compaction and damage to root systems are a subject of the study. We analysed soil physical properties and concentration of CO_2, macro- and micro-structure of root systems and sap flow dynamics and their changes using special instrumentation.

This contribution represents only a brief overview of the comprehensive study edited by Neruda et al. (2005) with some examples of obtained results.

Experimental sites, soils and species

The experimental sites were situated at the Mendel University Training Forest Enterprise in Krtiny (49°25´N, 16°45´E). The altitude is 450 m, annual average temperature is 6.8°C and an annual rainfall total is 685 mm. Soil reaction is acidic and in the surface layer strongly acidic, porosity in soil layer 7-11 cm is 56 % (Prax, Pokorný 2005). Brief description of sites, where we tested impact of forwarders on soils and tree root systems is summarized in he table (**Table 1.**). Medium-heavy pseudogley and cambisol soils occurred at all sites, which differed more significantly only in soil moisture. Norway spruce (*Picea abies* (L.) Karst.) was taken as the study species.

Table 1. Main characteristics of experimental sites.

Site	Latitude	Longitude	Forest type	Soil type	Soil texture	Parent rock	Altitude	Age	Machinery
ŠLP Křtiny Vranov 3	49 18 38	16 35 47	Querceto-Fagetum mesotrophicum	Eutric Cambisols	clay sand	granodiorite, plum-puddingstone	460	37	Power saw
									Zetor+Kronos
Kynský Žďár Dářko-Polnička	49 38 28	15 54 26	Piceto-Abietum variohumidum acidophilum	Gleyic	clay sand	loess loam	620	46	Valmet 911.3
				Stagnosols		gneiss,granite			Valmet 930.1
LSO Přibyslav Ransko	49 41 12	15 47 27	Piceto-Fagetum fraxinosum humidum	Eutric Gleysols	clayey-bamy	gabbro	550	56	harvest. HTM
									Valmet 820
LČR Telč Řásná	49 15 01	15 24 28	Piceto-Abietum variohumidum acidophilum	Gleyic	clay sand	gravelly granite	640	44	Power saw
				Stagnosols	clay				LKT 81+Kronos

Evaluating of soil pressure conditions caused by movement of forwarders

Soil compaction was measured by penetrometers (penetrometer STS Brno). Pressure conditions in soils loaded by movement of heavy forwarders was measured using a system composed of pressure sensors, digital transducer and data logger (sensor type P8AP made by HBM firm, measuring range 0-10 bar, transducer DAS CS Compex, a notebook was applied for data-logging). Sensors were inserted at the depth of 15 cm below the original soil surface. CO_2 concentration was measured using instrumentation based on absorption of IR beam of the Finish firm Vaisala, particularly the measuring device CARBOCAP GMT 221 and sensors CARBOCAP GMP 221 with the range of measurement up to 3% CO_2 and accuracy of 0,02%. We measured the actual CO_2 concentration, but also its long-term changes after the loading treatments.

Measured soil pressures reached in average about 1.0 to 3.0 bar, depending on the type of machines and magnitudes of applied loading. The specific tyre pressure at the solid bed was about 1.0 bar. Peak soil pressure values occurring during the loading reached up to 4.0 bars. This seemingly looking anomaly can be most probably explained by the dynamic impact of forwarder movements, i.e., creating the traction force and the effect of inertial forces of the machines when passing across little unevenness in relatively hard soils. We confirmed similar conclusions by Schlaghamersky (1991) this way. Increased soil pressure took place only when tires were actually above the sensors and did not remain afterwards. Our results also demonstrated a positive impact of soil cover by a 40 cm deep layer of spruce branches. Soil pressure was often up to 50% lower under such conditions. We should not overestimate this effect of coarse, because the cover cannot decrease soil pressure below the value of specific pressure in the tires.

Physical parameters of medium-heavy soils occurring at all experimental plots changed significantly during the first movement of forwarders and such changes increased during similar following treatments. Penetrometric results have shown higher values of soil resistance in ruts created by tractor movement when compared to the control (**Fig. 1**). Soil density increased down to the depth of about 20 cm, its porosity decreased by $5\%_{vol}$ (similarly but even more decreased also air capacity) and worsening of soil ventilation can be expected too.

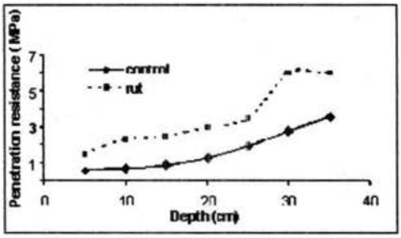

Figure 1. Penetration resistance of soils at the Telč experimental site

The above mentioned changes of physical soil properties lead to accumulation of CO_2 below compacted soil surface. Releasing of CO_2 from soil surface as a result of soil respiration is considered as the main part of the carbon budget, because it represents about ¾ fraction of total ecosystem respiration (Law et al. 2001). Soil respiration is usually studied from the biological viewpoints; however we focused on evaluation of CO_2 concentration in soils from the viewpoint of impact of heavy forwarders. Highly increased CO_2 concentration in soil air was found in compacted soils (**Table 2**). This was happening even after a single loading (Neruda et a. 2005), but did not reach the critical value of 0.6 % and more after repeated treatments, when corresponding values increased by 100 to 200 % if compared to the control. We also found a long-term increase in CO_2 concentration.

Table 2. Example of CO_2 concentration measurement in soil air, always two hours after installment in the loaded (10 times movement of forwarders) and control soils.

Site	Type of machinery	Number of treatments	Soil moisture ($\%_{mass}$)	Load on the tyre (kg)	Soil pressure (bar)	Conc. CO_2 (%)	
						in rut	control
Jedovnice	Tractor + trailer	10	23	1650	0,9	0,8	0,2
	Tractor + trailer	10	38	1650	0,8	0,9	0,5
Vranov 3	Tractor + trailer	10	25	2150	1,6	0,4	0,2
Ransko 1	Forwarder Valmet 820	10	29	3500	2,2	1,4	0,4
	Forwarder Valmet 820	1	29	3500	2,2	0,8	0,4
Dářko	Forwarder Valmet 830.1	10	24	3500	2,7	1,1	0,3
Telč - Řásná	Tractor LKT 81 + trailer	10	32	2200	2,4	1,2	0,5

Such changes in soil atmosphere could cause limitation to root growth and survival, i.e., decreasing of actively absorbing root surfaces (Güldner 2002). Concentration reaching 0,6 % CO_2 in the soil atmosphere is taken as a marginal value indicating serious changes in soil structure with fatal consequences for fine root growth (Gaertig 2001, Moncrieff a Fang 1999). We found values mostly several times higher in our experiments; therefore a serious danger for roots was confirmed. Long-term monitoring of CO_2 concentration indicated only very slow return (months) to original values (**Fig. 2**). We can recommend wider application of the CO_2 concentration measurements when studying impact of forwarders on forest soils, because it can be rather easily applied in the field and provides the actual data, but also allows log-term monitoring of the situation.

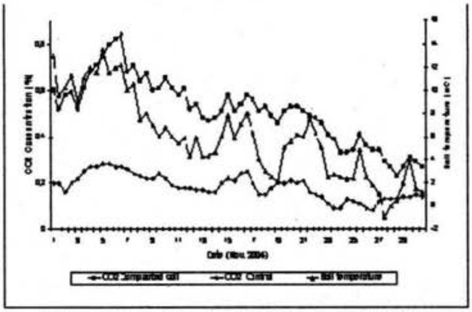

Figure 2. Long-term changes in CO_2 concentration in soil air after forwarder movement.

Spruce root systems

Geo-radar imaging of whole tree root systems in situ

The geo-radar method allows studies of whole tree root distribution in its natural position in soils in a non-invasive way (Hruška et al. 1999, 2005, Čermák et al. 2001). The geo-radar works the same way as other radars (used e.g. in association with aerial or see transportation), i.e., it is based on reflections of the radar beam from a contrasting object in its environment. The point of reflection characterizes position of the object and the time delay between releasing and reflection of the beam characterizes its distance from soil surface along which moves the antenna (its depth). Physical soil properties must be known of course. Practically spoken, root mapping is performed along a network above the object (e.g., a grid 0.25 x 0.25 m). Around 10,000 of point measurements are needed for a large tree. Positions of the antenna and time of reflections are recorded. We are getting a series of "slides" around the sampled tree this way. These data are evaluated by special software (e.g. EKKO TOOLS 4.23 by Sensors and Software), where reflections occurring repeatedly at approximately similar directions are interpreted as roots. Distinguishing of point objects (e.g. stones) from linear ones (e.g. roots) is rather a long-term (and therefore expensive) procedure, it not easy and is dependent on the experience of the particular worker.

Root systems of radared trees were opened by the supersonic air-stream and photographed by a digital camera at the end of experiments. A mosaic composed from a series of photo-images was transformed using the graphical system KOKEŠ v. 6.57 (http://www.gepro.cz/new/kokes.html) into the orthogonal projection the same way as the radar-images. Both images were than covered by each other using Adobe® Photoshop® cs v. 8.0 (http://www.adobe.com) and positions of roots were compared.

Results of similar previous experiments, which were done on more homogenous and soils with lower stone and gravel content (Šustek et al. 1999, Čermák et al. 2001, Stokes et al. 2002) were rather optimistic, the error in positioning of superficial coarse roots was up to about 20% only. Unfortunately this error increased substantially in skeletal soils with high gravel and stone content, especially when such particles were of similar diameter as roots. Most big superficial coarse roots (with diameter above 5 cm) growing close to stems (up to the distance of around 0.5 m) were detected correctly in the spruce root system study. However positioning of smaller superficial coarse roots (below 2 cm in diameter) were subjected to large errors, their depths and positions were correctly estimated only in 10 % of cases. Often some roots were supposed to occur in places, where in fact no roots existed (**Fig. 3**). Situation was still worse in deep sinker roots, growing in parallel to the radar beam. Geo-radar represents a modern technology suitable for non-invasive visualization and analysis of coarse roots. However reflections in soils with too frequent stones can simulate "false" roots. This represents a serious limit of radar application in certain forest soils at present.

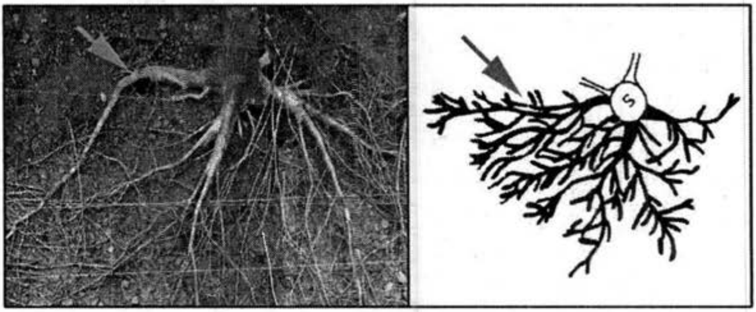

Fig 3: Example of an erroneous interpretation of geo-radar images. Most big coarse roots close to the stem (up to the distance of around 0.5 m) were detected. However the arrow shows the point where one superficial coarse root sharply turned to the side, which the usual software cannot predict and consider. More superficial roots were drawn in places (right image), where are no roots in fact (left image). Such situation is even worse when considering sinker roots (growing in parallel to the radar beam).

Root systems visualized by the supersonic air-stream

Root systems were excavated by the supersonic air stream at the areas of several tens of square meters at each site after experiments, using the air-spade technology (air-spade 150/90, made by the Concept Engineering Group, Inc., Verona, PA, USA). This system is based on airflow from the strong compressor (Ingersoll-Rand VHP 400, giving air-flow rate up to 11.4 m^3 min^{-1} at the operating pressure of 11.7 bar), which when connected to the special nozzle produces the "laser-like" thin air-stream with the velocity of Mach two. Soil was dispersed into small particles and blown away this way (**Fig. 4**). Even fine roots (around 1 mm in diameter) can be opened without significant damage. Excavated root systems were analyzed further and quantified through photo images (using the image-analyzer). We made a square network applying a raster 1x1 m in the field before taking images, which helped to keep a proper scale when composing particular pictures into a mosaic of studied area. First we compensated applied central projection (of the photographic lenses) by transforming images to orthogonal projection (otherwise we could not find correct geometrical positions of analyzed objects). Interactive graphical software KOKEŠ v. 6.57. (Gepro Praha) was used in the transformation procedure. Resulting transformed images were connected into a seamless photo-mosaic, where the mean position error was + −2cm and mean raster accuracy was 0.5 cm.

Fig. 4. Opening spruce root system with the supersonic air-stream

Spruce root systems are generally known as mostly shallow. However roots of neighbor trees create a dense intertwine network and occupy rather large areas around tree stems. Individual coarse roots are usually much longer then branches in the crown (up to about ten times), therefore also projected root area is much larger than projected crown area. Coarse roots are widely branching at some distances from stems, often as far as around neighboring trees (**Fig. 5**). Soil was sufficiently moist at some experimental plots, most thin and fine roots were developed in the upper soil horizons there, while anchoring vertical roots were rare. Having the above in mind, we must look much widely around trees, when evaluating damage to roots caused by movement of heavy forwarders. Other experimental plots were drier and roots were growing a little deeper there (in average about 35 to 45cm). More anchoring vertical roots were developed in places, reaching the depth down to about 70cm.

Fig. 5. Spruce root systems at the drier experimental plot, where impact of forwarder movement along skidding trails across neighboring tree roots was tested.

Root grafts - rapid pathway for fungi infection after root damage

The root systems are damaged by the movement of tractors namely by striping of the bark tissue or by complete root breakdown (Neruda et al., 2005; Nadeždina et al., 2005). If the bark tissue and cambium are damaged or destroyed, woody tissue is exposed to fungi infection and to deep desiccation, which is gradually destroying conductive system (Ronnberg, 2000).

From this it is obvious that the most essential disadvantage of root grafting in Norway spruce stands is the promotion of fungi infection spreading (Stenlid, 1986; Tamminen, 1985) and therefore we should avoid formation of root graft in the forest management. But also root grafting has some advantages, for example, stability of trees with joint root systems can be higher (Kühla and Lõhmus, 1999). Survival of suppressed trees can be enhanced by assimilate and nutrient support from grafted neighbour trees (Graham and Bormann, 1966).

We sampled roots at the experimental areas previously opened by the air-spade. Damage of roots by tractor movement was documented and detection of root grafts was done. The diameter of the stem, root length from the tree up to the root graft and the root cross-section horizontal a vertical axis before root entrance to the root graft were measured in the case of the biggest self-graft and two intraspecific grafts. Where intraspecific grafting occurred, the distance between the trees was measured. After that, the biggest self-graft and one of the intraspecific graft were removed. Both grafts were cut to 1 cm thin samples to find out how the root grafts were formed.

The movement of tractor severely damage roots, especially fine roots were completly breakdown and coarse root had damage on bark tissue (**Fig. 6**).In coarse root damage resulted in resin efflux (**Fig. 7**). Many studies reported that root wounds or wounds near or in contact with soil are more readily infected by decay fungi than those occurring above breast height (Wallis and Morrison 1971; Nevill 1997). Therefore harvest should not be conducted during spring and early summer when sap is flowing and bark is not tight; trees wound easily and injuries are often larger (Nevill 1997)

Fig. 6 Damage bark tissue of coarse roots due to tractor movements

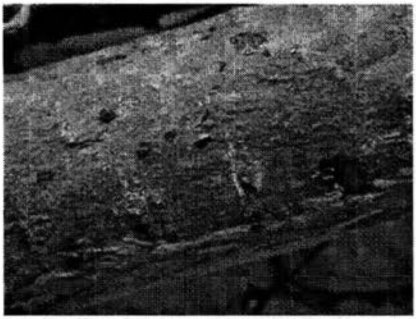

Fig. 7 The resin efflux from coarse root after tractor movements

Several self-grafts and two intraspecific root grafts were found. The stem diameter of the tree which formed the biggest self-graft was 52 cm. The root length between the base of the tree and the graft was 67 cm. The horizontal a vertical axis of the root cross-section before the graft were from 1 x 1 cm to 8 x 10 cm (**Fig. 8**).

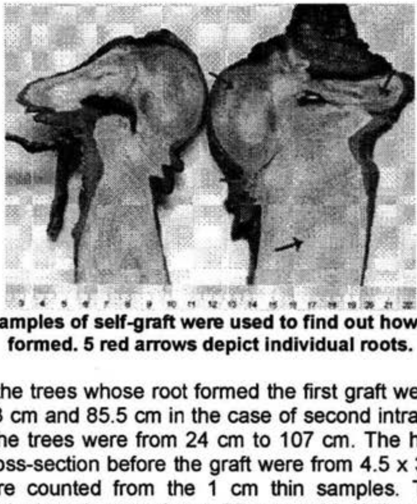

Fig. 8 1 cm thin samples of self-graft were used to find out how the root graft was formed. 5 red arrows depict individual roots.

The diameters of the trees whose root formed the first graft were 43.5 cm and 50 cm (**Fig. 9**) and 53 cm and 85.5 cm in the case of second intraspecific graft. Root lengths between the trees were from 24 cm to 107 cm. The horizontal a vertical axis of the root cross-section before the graft were from 4.5 x 3 cm to 7 x 12 cm. 14 joint rings were counted from the 1 cm thin samples. This self-graft was probably developed when the stand was 26-years-old. Külla and Lõhmus (1999) mention age of roots 10-20 years at the beginning of root graft formation in Norway spruce stand, but reconstruction of stand age at the beginning of root grafting and the results of temporal variability of grafting frequency are to be regarded with care (Külla and Lõhmus 1999). Missing rings are often apparent in roots (Fayle, 1968), but also in trunks and branches (Külla and Lõhmus 1999). After calculated intraspecific graft to 1 ha we found out 308 root grafts per 1 ha. The distance between trees with the intraspecific root grafts was from 96 cm to 120 cm. This corresponds with results of Külla and Lõhmus (1999), who found in 40-year-old Norway spruce stand root grafts, when the distances between trees were up to 1.2 m.

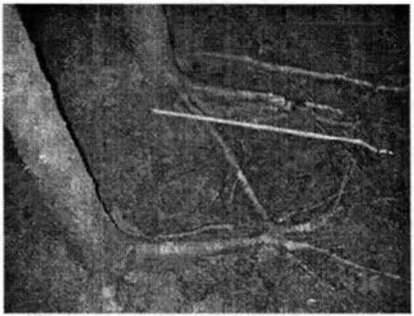

Fig. 9 Intraspecific root graft. On coarse roots you can see resin efflux.

In this study we counted 308 intraspecific root grafts per 1 ha in 40-years-old Norway spruce stand. This factor could be important when considering the disadvantage of root grafting which promotes the fungi infection spreading. Furthermore, the damage of roots by the heavy machines can start fungi infection and the connection of the trees through root grafts can therefore increase the impact of the machines on stand health status.

Tree root damage estimated via sap flow measurement

Sap flow rate in trees was measured by the heat field deformation (HFD) method (Nadezhdina et al. 1998, Nadezhdina and Čermák 1998, Cermak et al. 2004) using single-point sensors on small coarse roots and multi-point radial sensors on big coarse roots (or root buttresses) and main stems. Sensors were composed of a linear heater and two or ten pairs of thermocouples arranged at 6 to 16 mm distances and inserted in stainless steel hypodermic needles 1 2 mm in outer diameter. They were placed close to main stem basis or almost at the ground level in the case of roots. Using these sensors, also the radial pattern of flow was determined. Data were recorded by data-loggers Midi 12, EMS/UNILOG (Brno, Czech Republic) and DL2e, Delta T (Cambridge, GB).

Clear response on loading by heavy machinery was detected only in one from six treated sample trees in the experimental plot Jedovnice (Nadezhdina et al. 2005). Sap flow responded only when a significant part of surface roots occurred under the tires down to the depth of about 10 cm below the soil surface. Sap flow responded on loading very differently even in two neighboring roots of the same tree (**Figs. 10 and 11**).

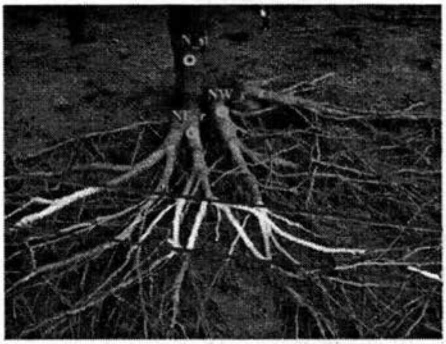

Figure 10. Detail view of treated roots of the spruce No.885. Roots painted yellow, green and white (from the left) were connected to the root NE. The multi-point sensor marked NE_r was installed on its branch, painted white color. Roots painted yellow (from the right) were connected with the neighboring coarse root NW_r. Additional multi-point sensor (marked N_st) was located in the stem base above root NE. Red lines mark trails of both wheels. Width of ruts was 30 cm, depth of marked roots was about 10 cm below original ground surface.

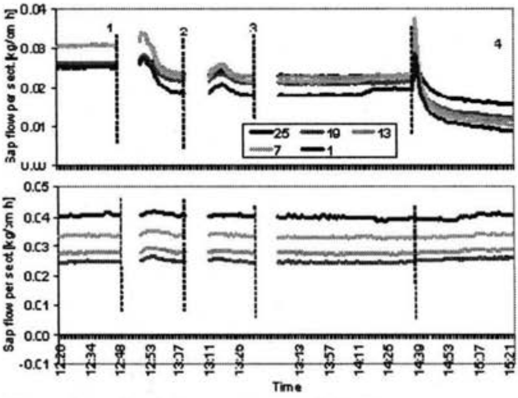

Figure 11. Sap fluxes recorded in two coarse roots (NE_r – upper panel and NW_r – lower panel) of tree 885. Numbers in legend denote depth below cambium in mm (the same for both roots). Vertical lines divided treatment on several periods: 1 – before loading, 2 and 3 – 20 minutes after trailer moving and 4 – 40 minutes after root cutting.

Fluxes in root NE_r peaked during loading and substantially decreased after the first trailer moving whereas no responses were detected in root NW_r. A small flow increase (especially in inner xylem) was recorded in root NW_r, when root NE_r was cut (compensation mechanism in roots). Flow decrease in the outer xylem was more significant after root cutting indicating connection of this part of coarse root with surface root branches.Response on loading on stem base (**Fig. 12**) was similar as in root NE_r. Fluxes significantly decreased after the first loading presumably in the outer xylem (with exception of depth close to cambium). No differences were detected after the second trailer moving. Sharp decrease of flow after root NE_cut indicates that water pathways from this root composed around one third in stem xylem (in place of measurements) – **Fig. 13**.

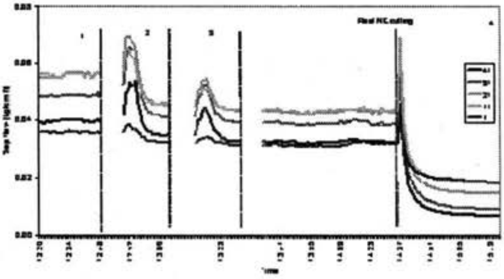

Fig. 12. Sap flow rate in the stem of treated spruce tree No.885.

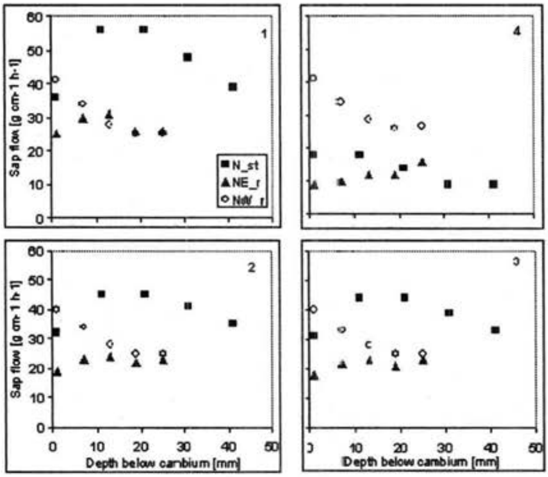

Fig. 13. Changes of sap flow radial patterns in stem (black rectangles) and roots NE_r (red triangles) and NW_R (open black circles) after both loadings (2 and 3) and cutting of root NE_r (4) when compare with sap flow before treatments (1).

The same rules was confirmed for roots of the same tree: the deeper are roots in the soil and the smaller is root area the better is root protection against loading (**Fig. 14**).

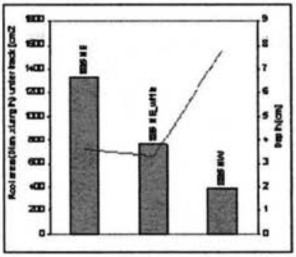

Fig. 14. Loaded area of the measured roots of tree 885 situated under wheels of heavy machinery and their depth under soil surface. 885NE_white denotes branch of coarse root NE (see Fig. 1 for detail).

Main conclusion: Soil (or artificial layers) serves as a good protector against root damage by heavy loading. Wider roads should be better then narrow for tree survival in forest subjected to periodical loading.

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GAINING PRECISION IN PLANTATION FORESTRY: BUILDING ON SOIL INFORMATION.

A. Rozanov[1], F. Ellis[1], B. Du Toit[2], W. De Clercq[1], A. Kunnike[1], S. Ackerman[1]
[1]Faculty of AgriSciences, University of Stellenbosch, South Africa
[2]Institute for Commercial Forestry Research (ICFR), South Africa
E-mail: dar@sun.ac.za

Abstract

A *Eucalyptus* plantation in complex topography with high forest productivity variations was studied in South Africa. Results of soil survey at 100 m resolution and forest inventory data per compartment were analyzed and compared to NDVI.

Detailed studies into various aspects of plantation planning, site qualities, water management and land improvement was conducted. The approaches presented here are largely related to silviculture, but can be applied to various forest operations.

The whole diversity of soil information was integrated into a single, digital site quality parameter, which can be managed through various land preparation techniques to decrease the variation of site quality throughout the tree stand. It was shown that geostatistical techniques can assist in not only quantifying the complexity, but also in managing it through understanding of short-distance and long-distance variation. A good correspondence was achieved between the soil parameters and the NDVI.

PRECISION FORESTRY AND SITE SUSTAINABILITY

Dietmar Matthies[1], Johann Kremer[1], Martin Ziesak[1], Bettina Wolf[1] & Carl Ganther[2]
[1] Chair for Forest Labour Sciences and Applied Informatics, Technical University of Munich, Germany
[2] Klinikum Rechts der Isar, Technical University of Munich, Germany
E-mail: mat@forst.tu-muenchen.de

Abstract

The constant increase of highly mechanized machine systems in forestry endanger the most important mean of timber production – the soil. The present state of knowledge about the impact of load on soil structure is quite well. Mainly three factors control the effects – ground pressure, texture and soil moisture. By means of comprehensive laboratory and field tests general deformation stages for the soil structure and especially the coarse pore system, which is of utmost importance, were identified. A prominent role do have the ATTERBERG limits, of which plastic and the liquid limits set the frame for acceptable ground pressures applied during operation. That means, machine and machine configuration have to be adjusted to the soil situation in terms of texture, soil moisture etc. in order to avoid severe soil damage. The goal of precision forestry has also to fulfil the demands of sustainability, which is not an idealistic dream but a necessary demand.

Keywords: Soil physics, soil mechanics, forest machines, forest harvesting, sustainability

Introduction

Soil is the unique mean of production in forestry and agriculture, respectively. Demands on efficiency and productivity force to introduce highly mechanized machinery and machine systems as, for example, harvesters and forwarders for timber harvest. Their steadily increasing mass as well as all year operations constantly increase the risk of heavy soil structural alterations up to the final degree of soil damage. As a matter of fact the basic ecological tasks of soil and its structure are endangered severely in future. Society tries to counterbalance this trend by laws and regulations like the German „Soil protection law" or the „Soil Charta" of the EU or certification, for example.

There is a lot of literature available describing the effects of machine traffic on different soil physical parameters as well as the consequences for root and tree growth (1, 2, 3, 4). Only rare information can be found for the relationship between mechanical load, soil mechanical and physical properties (5). This lack of profound knowledge led to the undesirable situation, that valuable management tools for soil sustainable machine action are missing almost completely (6, 7).

Modern analytical methods in soil physics bear the capability to follow load induced changes in soil structure and macropores with previously unknown precision and resolution in a non-destructive manner. This enables us to identify load, texture and moisture depended regularities in soil structural alteration. Consequently soil conserving strategies for machine actions can be derived, which preferably supported by information technology can add a substantial part to precision forestry.

Methods and Materials

The results presented mainly rely on modern computed tomographic methods as commonly known from medical services. The X-ray computed tomography (CT) in principle detects the spatial distribution X-ray absorption coefficients, which can be transferred to density values by mathematical processing (literature compilation in (8)). The result is an image of the spatial distribution of densities found within the sample. 2- as well as 3-dimensional images can be obtained in a non-destructive manner. Beside this static application methods to investigate dynamic processes like water and gas flow were developed several years ago, which serve for a close connection of structural and dynamic information (8). The latter can be obtained by sequential shots at distinct locations of the sample and time intervals convenient for the speed of processes under investigation. By means of subtraction analysis, i.e. the pixel wise subtraction of a reference image from the process image, diminishes information of unchanged density, which is mostly the solid matter, while areas with changing ones like pores become visible. So the interesting information is not blur by others not being in the focus. For our investigations we used different medical scanners of the third and fourth generation (Comp. Siemens, Somatom Scanners), which offer a physical resolution of about 0.1 * 0.1 * 1.0 - 0.5 mm^3 (thickness of slice). Somaris software allows interpolation procedures sharpening the images afterwards. As contrasting media water and Xenon gas were used. For further image processing we applied ScionImage programme.

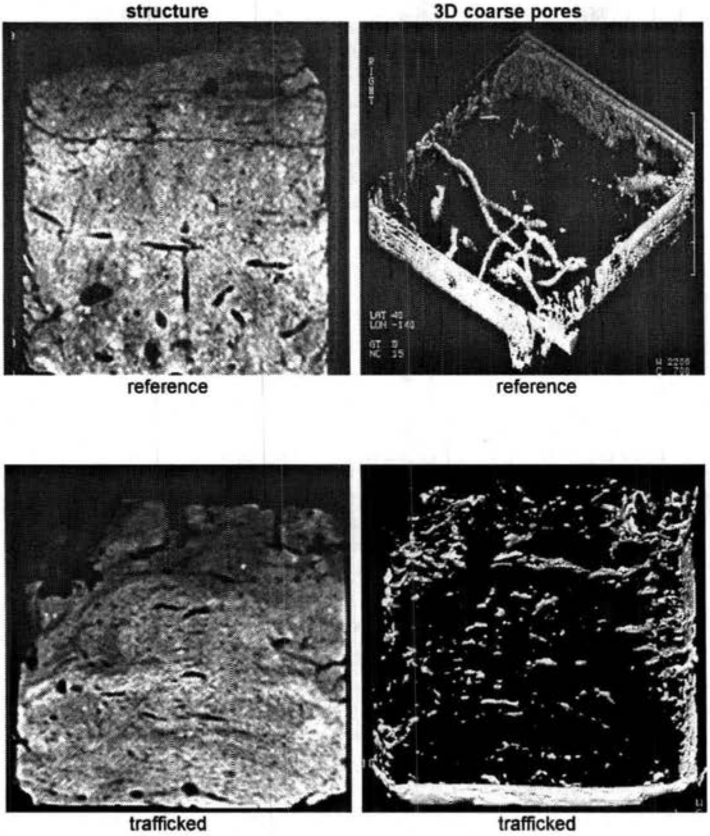
Due to the fact, that these scanners do not belong to the standard equipment of soil physical laboratories the data obtained were compared with those of ordenary k_f and k_i permeameters. In order to simulate machine traffic different loads were applied to the samples by means of an uniaxle compression device. Several load stages were chosen in accordance to the specific ground pressure of a forwarder Timberjack 810B in unloaded up to full loaded status. In addition dry bulk density, total pore volume and pore size distribution was measured.

Testing materials were soils of fine grain dominated texture, which were taken in field as undisturbed soil core samples and disturbed bucket samples. The acrylic soil cores had a size of 10 cm in diameter and about 10 cm height, which results in a volume of about 780 cm^3. The disturbed samples were sieved at 2 mm mesh air dry. Only the small fraction was used to prepare additional acrylic cylinder samples being packed to a dry bulk density of about 1,00 g/cm^3, which corresponded to the average density of untrafficked soil core samples from the field trial. For the compression tests all cylinder samples were brought to four different moisture contents, which were in accordance to the soils´ individual ATTERBERG limits, i.e. plastic limit, liquid limit and two in between. Out of these sample sets 16 different load/moisture relationships for each soil were derived (9).

Results and Discussion

Beside an increase in dry bulk density especially the coarse pores, mainly biogenic macropores like earthworm borrows, experience structural deformation while being loaded. Figure 1 proves how far this deformation can go (5). In the 3-dimensional reconstruction of an untrafficked sample (right) a well structured biogenic pore system with a high degree of connectivity can be seen. The conductivities of such are extremely high. Water drainage and soil aeration are no limiting factors. Below, the contrasting situation is shown. The same soil was trafficked at a moisture content close to liquid limit. Although the total pore volume remained almost at reference level (pores were filled with water) the 3-dimensional reconstruction exhibits a completely different picture: isolated voids of macropores are scattered all over the image. In addition their reorientation perpendicular to the direction of stress can be seen clearly. Looking at a single structural image (left) the intense puddling of organic and mineral matter (dark grey, upper part left) becomes obvious. The missing soil in the upper left corner represents the imprint of the lug. Though the total pore volume is still sufficient, the pore system lost its ecological function, i.e. the capability for water drainage and gas exchange.

Figure 2 demonstrates this matter of fact for the drainage capacity under comparable conditions (10). The image to the left shows a typical well developed structure of aggregates (bright areas) surrounded by matrix material (grey) and numerous biogenic macropores in all orientations (black). The sample to the right, which was taken directly from a rut 2 m apart, reveals the impact of mechanical load at a moisture content around liquid limit. Macropores are almost extinguished completely. The aggregated structure is gone. Missing connectivity's lead to dramatically reduced water conductivity and the soil will suffer anaerobic conditions on a midterm run. The increase in bulk density is expressed by a general brighter appearance of the sample.



structure

3D coarse pores

reference

reference

trafficked

trafficked

Figure 1: Examples from CT images of untrafficked and trafficked soil samples. Lefthand images are single slices of 1 mm thickness, right-hand images are 3-dimensional reconstructions of 15 mm thickness. Trafficked images show clear evidence of viscous flow and reoriented coarse pores. Image size is 10 * 10 cm^2.

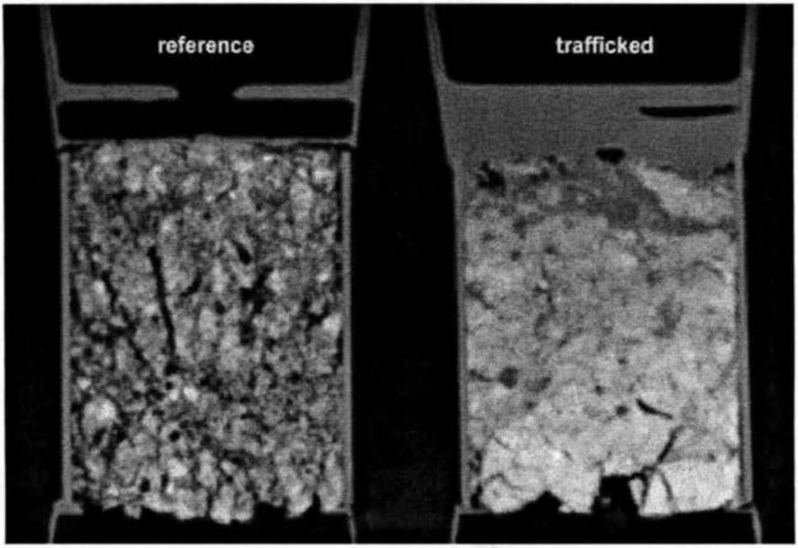
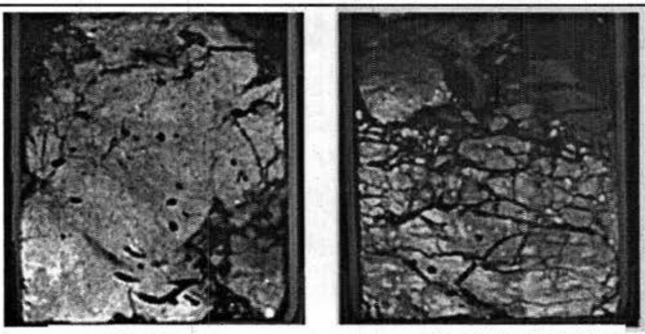


Figure 2: The drainage capacity demonstrated for a reference and the same soil trafficked at liquid limit. While the reference sample drains within a few minutes time span, the trafficked one is more or less sealed as can be seen by standing water on the soil's surface.

While increasing the moisture content soil structure passes distinct deformation stages, which can easily be identified in the CT (fig. 3) (11). Starting at liquid limit (top, right) the loaded sample exhibits a typical framework of fractures heading in all directions, which are artefacts of soil core sampling. Anyhow, the coarse pore system is almost not affected. This can be attributed to the deformation stage „stable". A water content in between plastic and liquid limit leads to planar fissures (middle, left) due to beginning reorientation of clay like particles. A further increase in soil moisture introduces compaction going hand in hand with the beginning loss of structure elements and the considerable decrease in pore volume (middle, right). This stage is called „structural deformation" and characterized by the closer allocation of aggregates, which are still intact. The „total deformation" stage describes a status, where all structural elements are destroyed, i.e. also the aggregates themselves. Due to the viscous reaction an intensive mixing of humic and mineral matter occurs, which can be seen by the greyish haze in the last image (bottom, right).

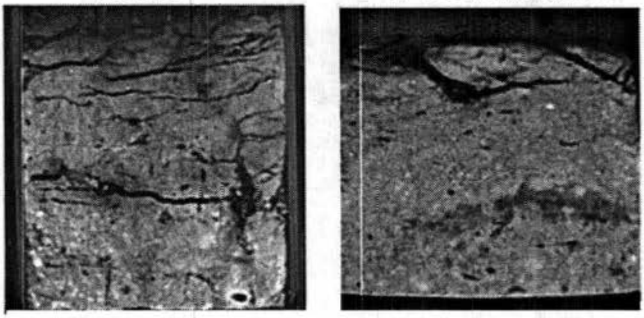
These examples from simple CT scanning outline some general rules of structural deformation mainly in dependence from the soil moisture content. Two major thresholds can be derived from these experiments: the plastic limit, which marks a soil moisture status dry enough to bear mechanical loads typical for forest machinery, so far, without risk of considerable deformation. Machine traffic does not endanger the sustainability of soil ecological functions. The contrary threshold is the liquid limit.

Soil moisture is that high and, consecutively, bearing capacity so low, that severe soil damage is inevitable.



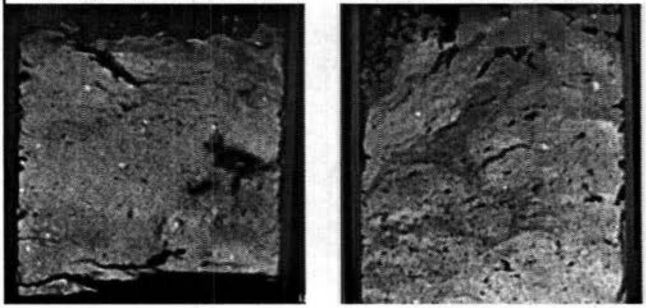
reference

w = 20 vol.-%, plastic limit



w = 26 vol.-%, planar structures

w = 32 vol.-%, compaction

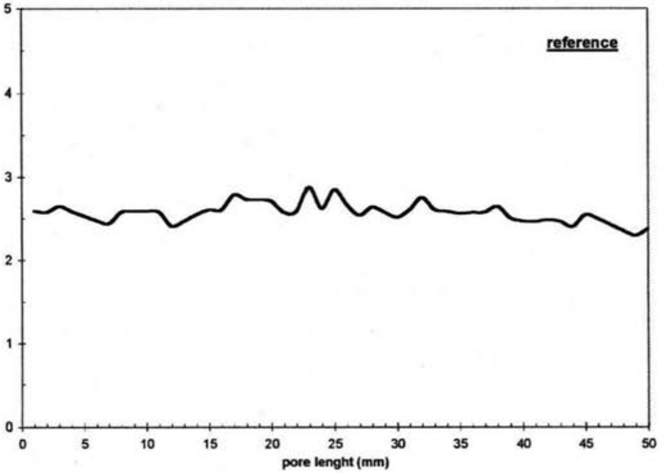


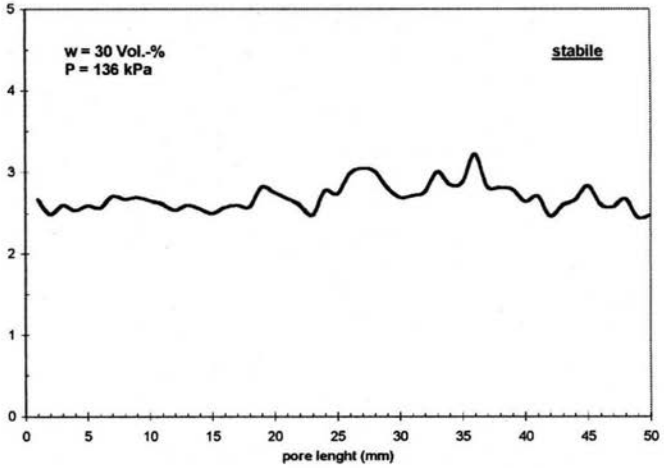
w = 40 vol.-%, liquid limit

w = 43 vol.-%, intense puddling

Fig. 3: CT images depicting typical moisture related soil structural alterations after traffic. Up to moisture contents of 26 vol.-% total pore volume and coarse pores show little effects only, while moisture contents around liquid limit lead to a complete loss of soil structural diversity (= soil damage). Image size is 10 by 10 cm^2.

Somewhat delicate is the range of plasticity between both limits. Unfortunately this is the dominant moisture situation all over the year. In order to evaluate the risk of unacceptable soil deformation one has to take the specific ground pressure into account. Therefore, field trials as well as laboratory tests were carried out under varying loads and machine masses (12, 13). In the following examples from the latter will outline general results.





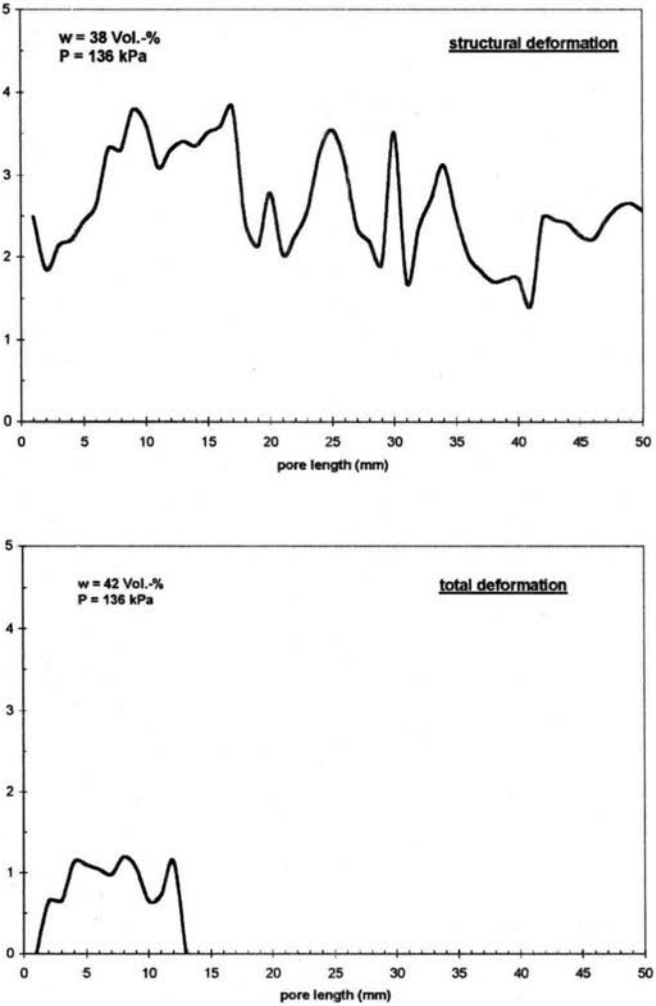


Figure 4: Measurements of the pore radius visualize the different stages of deformation. Under a constant load of 136 kPa the pore is stable at plastic limit (w = 30 vol.-%), while it experiences a total deformation at liquid limit if compared to the reference.

By means of continuous scanning laboratory samples from compression tests were reconstructed and the pore deformation analyzed. Results in figure 4 refer to artificial macropores of 5 mm in diameter sticked with a needle in vertical direction and compacted with a pressure equivalent to 136 kPa ground pressure. The inner pore surface was very smooth in case of the uncompacted reference (dd 1,0 g/cm^3) and the compacted sample at 30 vol.% soil moisture equal plastic limit (refer to scale !). The same load applied at 38 vol.-% leads to a considerably undulating surface creating several bottle necks. Although the mean radius hardly decreased many water menisci bound to the bottle necks will hinder gas exchange considerably under natural conditions, e.g. after rainfall and drainage. In addition the water permeability will strongly decrease as the flow through a reduced cross sectional area, such as a bottle neck, is controlled by the radius to power 4 (Hagen-Poiseuill law). Therefore, a slight reduction in pore radius has extreme consequences for the kf-value (saturated water permeability). The typical shape of the inner surface is caused by aggregates moved into the pore space. Coming close to the liquid limit - in our example 42 vol.-% - a significant reduction in pore diameter and length takes place. In general the inner surface of the pore becomes smoother again, which now expresses the destruction of the aggregates as well. At this stage the extension of the void is correlated to the saturation rate as water resembles in the pore space conserving it while compacting the soil. Anyhow, during this process pores become reoriented loosing the connection to the borderline soil/atmosphere as sown above.

Table 1: Semi quantitative evaluation of the cross sectional pore areas and structure deformation stages in dependence from load, moisture content and pore orientation. Open fields represent samples, which lack of measurable pores.

		vertical pores					pores of 45 degree angle				
load (kPa)		ref.	80	108	136	164	ref.	80	108	136	164
water content (Vol -%)	30	21 mm^2	≈	≈	≈	≈	21 mm^2	░ ↘	▒ ↓	▓ ⬇	▓ ⬇
	38		≈	≈	░ ↘	▒ ↓		▓ ⬇	░ ↘	░ ↘	▒ ↓
	42		▓ ⬇	█	▓ ⬇	▓ ⬇		▓ ⬇	▓ ⬇	▓ ⬇	█
	46		▓ ⬇	▓ ⬇	▓ ⬇	▓ ⬇		█	█	█	▒ ⬇

≈ area not significantly reduced; ↘ area reduced by < 25 %; ↓ area reduced by 25-50 %;
⬇ area reduced by > 50 %

stages of structure deformation	
□	stable
░	minor deformation
▒	structure deformation
▓	totale deformation
█	extinction

The transition in terms of moisture content from one deformation stage to another is, therefore, depending from specific ground pressure and soil moisture content. The thresholds plastic and liquid limit are dominantly ruled by texture, especially the fine grain fraction, as factors like humic content, clay mineral composition etc. are of minor importance. Table 1 demonstrates the dependence of the deformation stage from both factors mentioned above for a silty loam (5, 9). As a matter of fact pore deformation is also depended from pore orientation. The stability of vertical pores is considerably higher than that of inclined ones. Although not investigated systematically one can assume a positive correlation between angle and stability. A quite similar result adduced investigations on samples from field trials, although there exists a systematic shift in the corresponding ground pressure values. This can be attributed to the effect of the possibility for the cylinder samples to react in one direction only during compression.

If „precision forestry" is in the scope of modern forestry one has also to take soil issues into account. At least soil is the first part in the entire chain of timber growth and production, respectively. Therefore, site sustainability or sustainability of site management systems have to focus on the soil, too, of course beside other important aspects. The present state of knowledge offers to meet these economical and ecological demands in this aspect. Taking the site characteristics we have enough knowledge about the effect of machine operation on the soil and its structure. Information regarding texture is in almost all cases available, out of this the important ATTERBERG limits can be achieved. Soil moisture is easy and fast to determine by modern equipment whether by hand or onboard the machine. As soil and moisture content are hardly to control from the planning point of view (may be the soil moisture by postponing the operation), the main screw is the machine and its configuration in order to adjust the system machine-soil properly (14). A main part is already developed – the information system ProFor. So far it combines soil and machine information calculating the maximal tolerable water content suitable for a given situation (15). Some useful extensions could be included like a load control by means of a balance in the loading crane of a forwarder, for example (16). It might stop loading activity as soon as the ground pressure exceeds the maximum tolerable ground pressure for a given situation. Or might initiate deflation of the tyres in order to increase the loading capacity. Such inflation pressure regulation systems do exist, although they can hardly be found in forest machinery. Another interesting option is a link between an information system such as ProFor and geographic information like digital site or soil maps. There is a number of decent options to include soil and site protection without interference with the main goal – to produce timber. One has only to take the chance !

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PLANNING LOGGING SYSTEMS THROUGH SITE ANALYSIS

Raffaele Cavalli, Stefano Grigolato, Daniele Lubello
Dept. Land Use and Agricultural and Forestry Systems, University of Padua, Italy
E-mail: daniele.lubello@unipd.it

Abstract

Strategic planning for defining forest operations and for supporting decision on the most appropriate forest equipments requires deep spatial analyses, especially in mountains condition where the terrain and the forest stand characteristics change in space and in time.

In order to evaluate the feasibility of forest logging systems and consequently the estimation of their costs, a rough quantitative analysis was carried out by GIS models. Since these GIS models, previously developed, have evidenced different drawbacks associated to the low quality of digital data representing forest stand volume, forest road network and terrain characteristics, topographic surveys were used in order to reduce the gap of the quality of the digital data. In fact, it was evidenced that spatial methods for enhancing the resolution and accuracy of the model must require the support of global positioning analysis, in order to reduce so inappropriate rough results and consequently to improve the quality of the spatial investigation. Topographic surveys with global positioning equipments were tested as primary investigations to link field site data to the digital spatial model. With the aim to define a Decision Support System apt to be an useful tool for planning forest operations, a methodology based on the integration between a GIS model and field surveys was developed in a northern Italian alpine district.

Keywords: GIS models, GPS, forest operations

Introduction

In Italy all wood-related economic sectors operate in a highly disconnected forestry-wood system. According to Pettenella *et al.* (2005), the existing situation can be referred to the fragmented and limited internal wood supply that mainly depends on economic and environmental constraints and to a lack of integration between forest activities and the wood working industry. Consequently, Italy presents a low self-sufficiency rate for wood supply and the national wood demand requires import of wood from Austria, Slovenia, France and Swiss markets.

The most productive high forests (mainly coniferous) lie in the North-eastern regions while coppices predominate in the centre of the country. The only relevant examples of forest plantations are the poplar stands in the northern plain areas of the river Po valley.

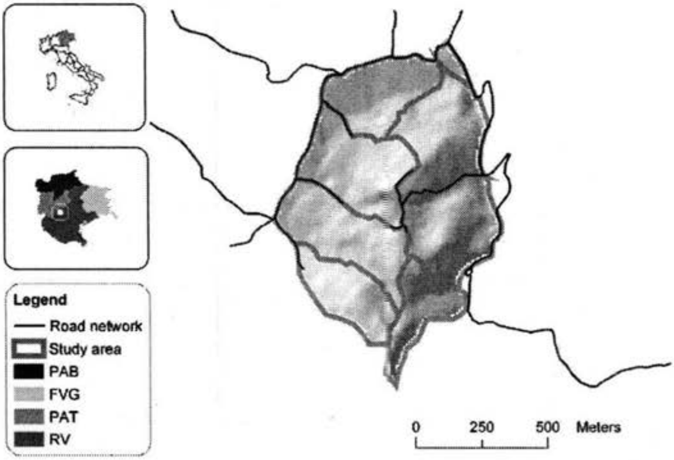

Figure 1: North-eastern Italy and its Regions and Province with location of study area

By an overview on the North-eastern (NE) area of Italy that includes Bolzano Autonomous Province (PAB), Trento Autonomous Province (PAT), Veneto Region (RV) and Friuli-Venezia Giulia Region (FVG) (Figure 1), it is evidenced that the most of the coniferous productive high forests are located in mountainous areas (Table 1). Therefore in this area the forest work is mainly performed on slope terrain, which affects the operational methods, the machinery use, the road network requirement, and the length of the working periods and the availability of manpower (Cavalli, 2004). With the only exception of the Veneto Region, high forests are prevalent on coppice forests. In Veneto Region the contribution of the hilly areas, in which the coppice forests are dominant, even if subjected to extensive interventions of conversion toward high forest, compensates for the contribute of the mountainous areas in which high forest dominates. A specific consideration should be done by comparing the spruce and fir area (Table 2) to the Italian forest area in which the above species are spread. The North-east of

Italy contributes with more than 70% to such forest area and consequently to the spruce and fir wood production. Spruce and fir are the prevailing species, representing around 80-85% of the utilized wood; larch and different pine species follow in relation to the area where the forest enterprise mainly operates.

Table 1: Total forest area and elevation distribution in North-eastern Italy (Cavalli, 2004)

Feature		PAB	PAT	RV	FGV	NE Italy
Forest area provincial or regional distribution						
A Forest area	ha	308 844	323 005	271 885	184 156	1 087 890
B Provincial or regional area	ha	740 043	620 687	1 836 400	784 600	3 981 730
A/B	%	41.7	52.0	14.8	23.5	27.3
Forest area elevation distribution						
C Mountain	ha	308 844	323 005	211 603	135 285	978 737
D Hill	ha	0	0	45 752	35 348	81 100
E Plain	ha	0	0	14 530	13 523	28 053
C/A	%	100	100	77.8	73.5	90.0
D/A	%	0	0	16.8	19.2	7.5
E/A	%	0	0	5.3	7.3	2.6

Table 2: Forest area per silvicultural system and forest utilization per silvicultural system and per year (Cavalli, 2004)

Feature		PAB	PAT	RV	FGV	NE Italy
Forest area provincial or regional distribution						
Coppice forest area	ha	17 633	68 968	125 084	62 923	274 608
High forest area	ha	291 211	254 037	146 757	121 193	813 198
Spruce and fir high forest area	ha	55 798	31 195	20 809	10 405	118 207
Forest utilization per year						
Coppice forest	m^3/year	26 488	17 980	134 705	58 836	238 009
High forest	m^3/year	597 947	204 410	123 902	135 293	1 061 552

Operating systems

In Italy, tree cutting consists in felling and delimbing and cross-cutting at stump by chainsaw (cut-to-length system) and in terrestrial yarding (80%) or aerial yarding (20%). Yarding is carried out through different ways in relation to the slope of the field and the road network density. Terrestrial yarding is mainly performed with tractor and winch; tractors are mostly 4WD (80-85%) and crawler (15-20%) agricultural tractors, the winches being mounted (60%) and fixed (40%). Only in these last years forwarders have made their appearance. Aerial yarding is carried out by means of cable cranes based on sledge winch yarder and mobile tower yarder. The use of the helicopter yarding is not so common.

Processor has been introduced, mounted or self-propelled, able to delimb and cross-cut the stem, ground or cable yarded in relation to the size of the tree and to the slope of the logging area. At the moment in Provinces and Regions of North-eastern Italy a number of 12 processors is estimated. The velocity these machines are spreading with and opinions of forest entrepreneurs let suppose that their number is going to increase in the alpine area (Cavalli, 2004).

Logging practice in Italy

In Italy felling methods of high forest are largely based on selective (individual tree or groups) cuttings because clear cuttings are forbidden since 1923 to ensure soil

protection and water conservation. The prescribed yield is usually about 10% of the total stand volume, but it could be also 5% or even 15% of the volume. Actually, a minimum of standing trees volume, not depending on the total cutting area, has to be ensured for economic harvesting. In the most cases a maximum of 30% of the stand trees is harvested at every diametric class.
Public forest areas have to conform to forest management plan with a duration of ten years, while private forest rarely have a plan since they are usually very scattered. A forest management plan involves different forest stands: every stand must be cut following the guidelines defined in the plan and concerning cutting year, treatment methods and other useful information in order to ensure a growing stock to achieve the goals of the forest manager.

Often the prescribed yield, defined in the forest management plan, is not completely harvested. Main causes are: lack of infrastructures, difficulties of access, strict regime of protection, insufficient economic value of wood and a tree selection that does not consider the harvesting operation. Concerning the stumpage sale, often the harvesting site condition does not ensure an economic purchasing by the forest enterprises and the prescribed yield remains unsold. Harvesting volume (according to the selection method) has to be planned according to the most suitable harvesting operation as in this way the purchasers would feel sure about the convenience on the harvesting operation.

Some problems related to the management plans must be pointed out:

- the forest manager who plans the cutting amount usually does not consider the system or the local level of mechanization (it should be needed to achieve an economic intervention);
- data are calculated from several surveys but at the end they are generalized per hectare and they are not geo-referenced (so information is lost);
- according to law (clear cutting is forbidden), felled trees are usually distributed on the entire surface so that some systems can not work properly (e.g. cable cranes).

Objectives

During the assessment process of Italian forests, planning logging systems is necessary to develop efficient forestry-wood systems. The introduction of GIS-based models simulating forestry operations allows good silvicultural management of forests. Moreover, adding information with GPS data, outputs should achieve more satisfactory precision.

Methods

Study area is located in North-western part of Veneto Region (Figure 1), near Trento Autonomous Province, more or less in the centre of North-eastern Italian Alps, lying under the Asiago town forest management plan. In table 3, stand data are illustrated. Altitude of the area rises from 1175 to 1400 m a.s.l. and GPS coordinates are: Lat (N): +455158.82; Long (E): +0113131.46. A good access to the area and a certain ground variability are the reasons for selecting this area. To verify how the use of GPS field data can influence a GIS analysis on logging systems, two different GIS model were developed: a basic model and a precise model (Figure 2).

Table 3: stand data as reported on the forest management plan

		Tree parameter					Stock parameters			Terrain parameter
		Height	Age	Density	Diameter		Basal area	Mass	Yield	roughness
Stand	Area				Max	Average				
n.	ha	m	y	trees/ha	cm	cm	m^2/ha	m^3/ha	m^3/ha	-
46	8.9	20	70	564	60	25.2	28	258	26	localised
47	11.3	29	160	422	80	32.4	35	358	36	localised
48	11.0	29	156	407	70	33.2	35	362	37	localised
49	7.3	27	163	331	85	35.6	33	322	49	localised
60	5.9	29	149	223	65	36.0	23	239	17	absent
62	10.6	29	165	286	65	34.9	27	285	49	partial
63	11.0	29	100	408	85	34.0	37	383	37	localised
67	0.9	20	80	462	65	31.2	35	332	33	absent

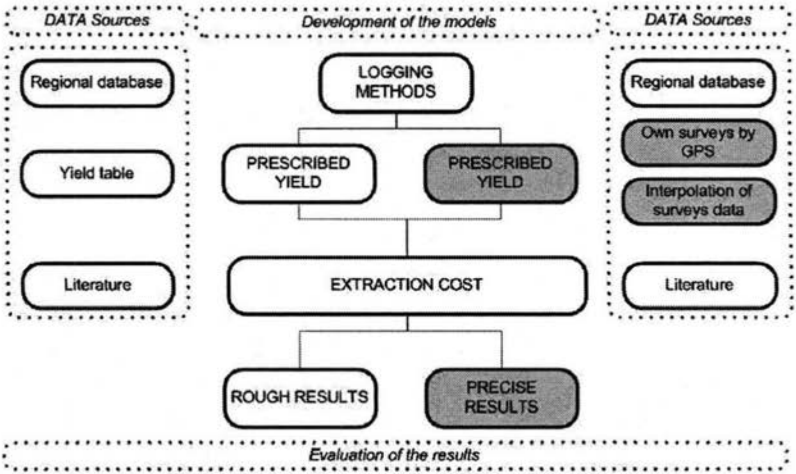

Figure 2: logic diagram of the GIS-based model

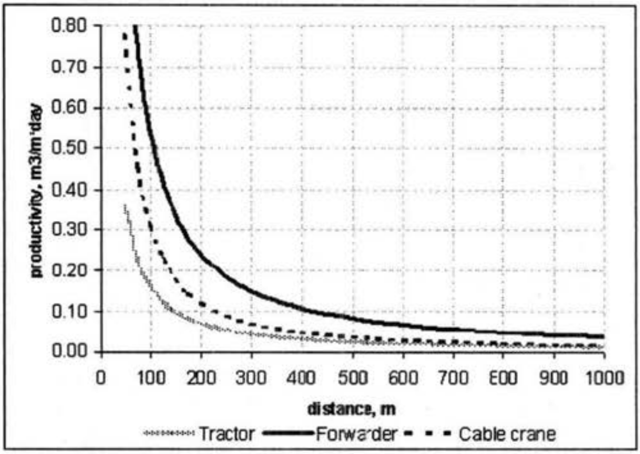

Figure 3: productivity of tractor, forwarder and cable crane in relation to yarding distance

The basic model

Firstly the basic model consisted on developing a GIS-based model to map the study area according to the most suitable logging system. Tractor with winch, forwarder and cable crane have been selected considering latest research and literature data for logging systems as commonly used in Italy. The model was based on geographic features and on technical limits of applicability of logging systems as the three systems have different technical limits: table 4 shows data on which model runs.

At a first level, the methodology consisted on acquiring on rearranging fundamental elements, as elevation and forest road network data, to develop the basic model. Therefore, Digital Elevation Model (DEM) has derived the precision from an elaboration of orthophoto contours. In this way It was possible to reduce the pixel size of the available regional data from 30 m to the more precise 10 m pixel size which was considered more suitable and adapted to model. The forest road network has been converted to *shapefile* deriving them from regional technical map (CTR) and corrected with GPS surveying.

By elaborating DEM, forest road network and forest management plan, the following GRID data were carried out: slope steepness, extraction distance, ground roughness and stand yield. Consequently the logging systems map was created by reclassifying GRID data using relative value, on the same scale, and thus combining them to create an overall surface with unique values identifying the most suitable logging system for each GRID cell (Grigolato et al, 2005).

In order to compare different systems in the model, productivity data were needed. Therefore, elaborating data from literature (Emer, 2005; Dellagiacoma *et al.*, 2002; Fanari *et al.*, 1999; Piegai, 1990) and adding Authors' research data, graph in figure 3 was obtained. Starting from this, logging costs per grid cell were evaluated.

Adding precision: the precise model

The basic model was based on the yield reported on the forest management plan. Thus this yield was referred to the entire stand such as an equal value of wood mass for each stand was reported. By GIS mapping, the yield results evenly distributed over the stand area evidenced an unreal situation. As an alternative to the basic model, the *precise model* aims to know how yield is really distributed and what is the distance from forest road.

By using GIS extensions, random survey points have been created (Figure 4). Referring to a real application which supposes the forest manager using relascopy to evaluate wood mass, every point has been reached using GPS and a surveying with Bitterlich relascope was carried out. To obtain a yield field value, inverse distance weighted tool was used. This tool estimates cell values by averaging the values of sample data points in the vicinity of each cell. The closer a point is to the centre of the cell being estimated, the more influence, or weight, it has in the averaging process. This method assumes that the variable being mapped decreases in influence with distance from its sampled location. Two different methods exist: the Spline method was chosen because constant mean per stand is known. Inside Spline method, tension method was selected because it tunes the stiffness of the surface according to the character of the modelled phenomenon and it creates a less-smooth surface with values more closely constrained by the sample data range (Burrough and McDonnell, 1998; Mitchell A. 1999). Ten points were used in the calculation of each interpolated cell. With precise yield distribution new yarding costs were calculated and compared with previous results.

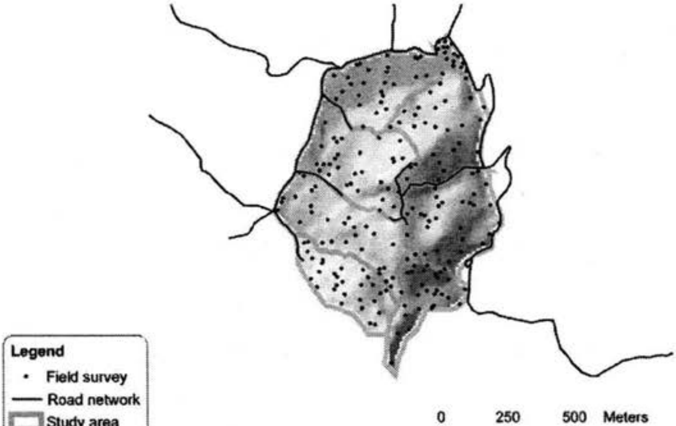

Figure 4: random generated points for GPS surveying

Results and discussion

Results of the basic model
Referring to technical limitation in yarding operation (Table 4), the combination of extraction distance, ground roughness and slope steepness values was used to identify the logging system (Figure 5). Results show that forwarder can work more than tractor with winch and explores a larger area (even if forwarder is not yet widespread in Italy). Cable crane is the only useful concept if wood is far from roads and on steep slopes (more than 40%).

Table 4: technical limits of three systems

	Extraction distance		Slope steepness		Terrain roughness
	downhill	uphill	downhill	uphill	
Logging system	m	m	%	%	class
Tractor	350	150	30	15	Low
Forwarder	500	500	30	35	Medium
Cable crane	100-500	100-500	100	100	high

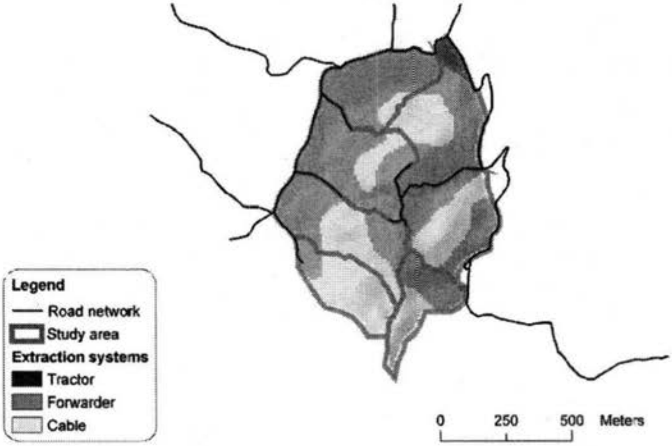

Figure 5: the optimal use of concepts under the study area

In figure 6 yield per stand is represented. The value is the same for the single stand and this is the actual situation for forest management plans data in Italy.

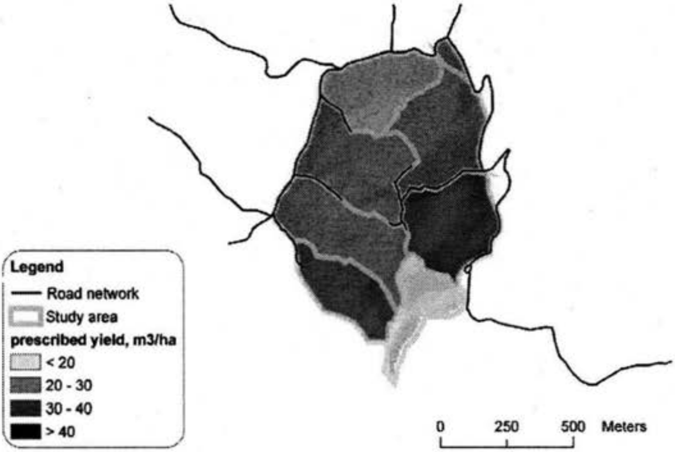

Figure 6: yield distribution on study stands

Different extraction costs for every concept have been considered in the model: 9.5 €/m^3 for tractor with winch, 14 €/m^3 for forwarder and 29 €/m^3 for mobile cable crane. Knowing also hourly productivity and the distance from roads, figure 7 was obtained by performing map operations. The sum of every cell's cost of each stand divided by the total cutting amount (table 3) gives the cost per cubic metre (Figure 10)

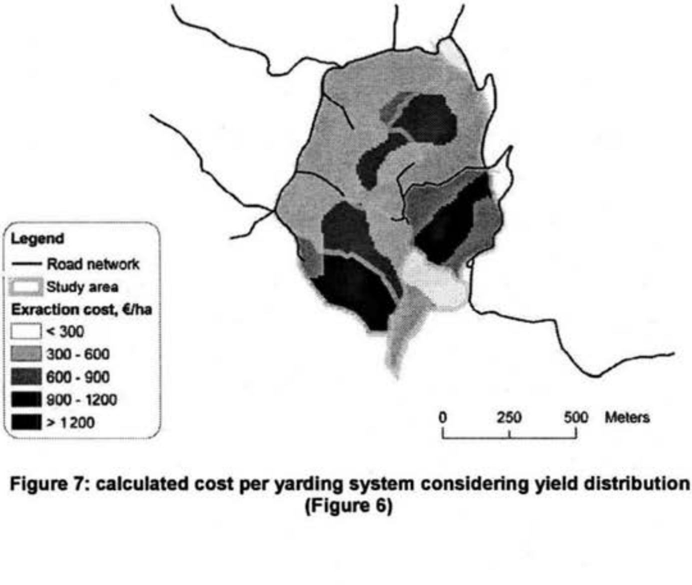

Figure 7: calculated cost per yarding system considering yield distribution (Figure 6)

Results of the precise model

After GPS data interpolation with GIS tools, a sort of wood mass field (something like air pressure field) was obtained to represent the real distribution of wood in the forest (Figure 8). Comparing figure 8 with figure 6 is possible to see that in some stands and near forest roads there are some gaps where nobody will cut trees and where machines will not work. In the first approach the yield was higher (because it is an average value) and this determines an evaluation error bigger than in precise model. This error affects cost calculation.

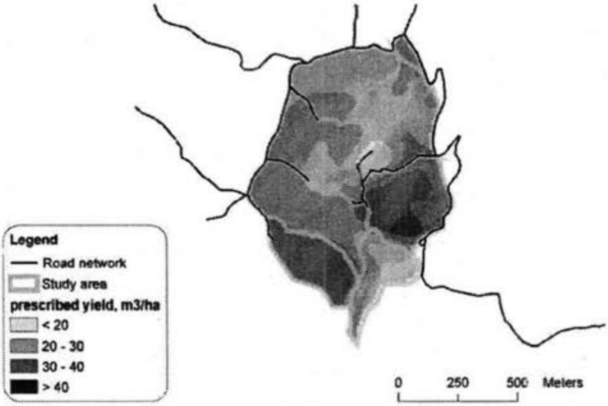

Figure 8: real yield distribution on study stands

Figure 9 shows different degrees of extraction costs also for the same concept. With these results the forester can decide in which area is more economic to cut trees and cuttings should be carried out in that area.

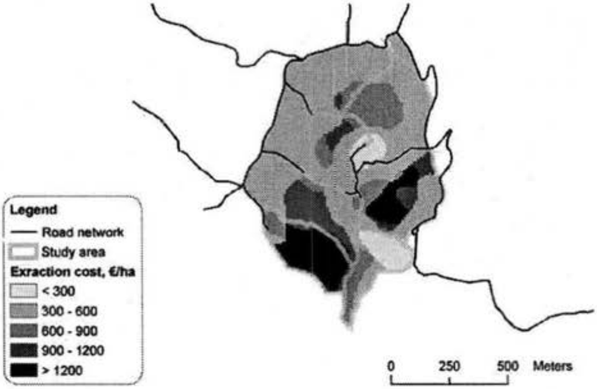

Figure 9: calculated costs per yarding system considering yield distribution

Figure 10 compares extraction costs per wood cubic metre of the two models. In stands 46 and 67, where steepness and age are lower, simulated costs are lower in the precision model. In the others stands, after GPS surveying it became clear that wood mass is not equally distributed: there is more wood mass far than near forest roads because in the past it was easier to skid wood near roads with tractors or horses. This means that in the future, especially when using cable crane extraction, if the cutting area is not economically and technically evaluated, costs will increase while wood net price will decrease.

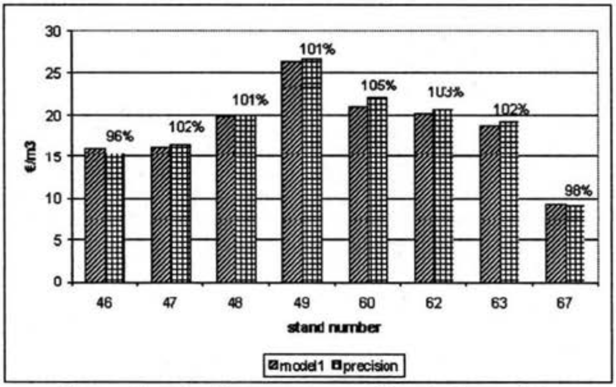

Figure 10: extraction costs comparison in the models

Conclusion

The present work can be considered a first approach of precision forestry method in Italy. Comparing the two developed model, results show that in forest assessment a higher precision is required. In fact, the Italian standard method in forest management plans editing foresees the use of relascope with the exclusion of the use of GPS and saving of digital geo-referenced data. As showed in the precise model, If surveying work is based on additional use of the GPS tool, masses and yields calculation will be better represented on forest map and consequently modelling on GIS environment can represent a more useful tool on supporting logging decision.

We wish that the use of the proposed methodology could be increased and applied to all the Asiago forest properties. The accuracy in wood mass information, revised several time at the expiry of the plan (every 10 years), could be used by other researchers like ecologists who study dynamisms in forests. They will be also able to study the effects of the harvesting on these processes.

From the obtained results it is clear that the current areas are not homogeneous. It would be possible to propose and reconsider stand boundaries in function of harvesting machinery systems and of extraction costs.

As a result, forwarder is to be preferred to the tractor. Actually the model will be used at regional level to define and quantify the areas where forwarder can work in view of put into effect a regional regulation which gives regional contributions for the technological development of forest enterprises.

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MANAGEMENT OF WOOD HAULAGE THROUGH GIS/GPS TOOLS IN MARITIME PINE FOREST (FRANCE)

Richard Emeyriat, Maryse Bigot
AFOCEL Station Sud-Ouest, France
E-mail: emeyriat@afocel.fr

Abstract

At the end of the nineties in Aquitaine, two wood supply companies (from Smurfit and Gascogne groups) developed a common project with AFOCEL to improve their control over the wood flows between forests and mills (sawmills and pulp mills) through an efficient GIS. In practice, four components were studied and evaluated in pilot operations: the numeric GIS maps, the accuracy of GPS under maritime pine canopy, the efficiency of radio data transmission and the GPS navigators in forest conditions. Finally the two companies and their main haulage contractors decided to invest in an operational GIS. All the participants of the logistic chain have been trained; forwarder and truck operators as well as logging operations managers. The systems are now well implemented (trucks are equipped with GPS navigators and logging operation managers use GIS every day) and produce their first results. Efficiency of the wood procurement has been improved, but there are also some limits to the systems, especially for small sized companies (important cost / potential benefit). That is why wood supply stakeholders must, in a further step, integrate internet tools and develop data standards to facilitate exchange of information between companies and its optimization.

Keywords: Logistical chain, GIS, GPS tracking, on-board computer, navigation, data transmission.

Introduction

Enhanced productivity in forest harvesting and specialization of sawmills have increased the complexity of transport flows. Wood piles at road side are quickly mobilised, required qualities are more precise, and delivery periods must be short. In these conditions, it is necessary to improve control of supply logistics of sawmills and pulpmills, according to local conditions, in order to reduce transport cost, to improve safety and to provide high quality services. For all these reasons, several important actors of the Aquitanian forestry and logging sector decided to start a common project to optimize maritime pine transport for the partners of the project. More precisely, the aim of this project was to define and evaluate the components of a Geographic Information System (GIS) for supplying the regional pulp industries and sawmills logistics. In 1997, at the beginning of this project, full solutions for wood supply chains did not existed yet. In this paper, we present the results of the different steps of the project: first, the preliminary tests of different tools (evaluation phase), second the two pilot operations that have been developed in two different wood-supplying companies, and third the implementation phase (operational logistics systems used in the two companies).

Identification and evaluation of tools

Digital maps

Various digital maps (type and scales) were tested to estimate their effectiveness for locating landing areas, navigation and calculation of routes. The same cartography is used with a GIS program at the office and in trucks (on-board computer), and covers the whole Aquitanian forest area (40 000 km^2). Two kinds of digital maps were selected: a raster map (Figure 1) and a vector map (Figure 2). The raster map with 1/100 000 scale gives a good representation of the roads and area names. The tests carried out showed that it is possible to reach the wood piles 95% of the time. The price and size of this kind of digital map is a good trade-off between precision and easiness of use. However, with this kind of map, they were no calculation possibilities. The vector digital map has been added to allow calculation and to make possible the addition of important elements just as new roads, parcels or wood piles.

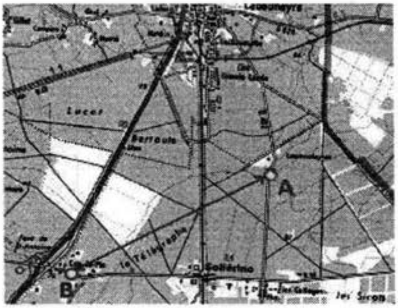

Figure 1: Raster digital map: IGN (French National Geographic Institute) Scan 100

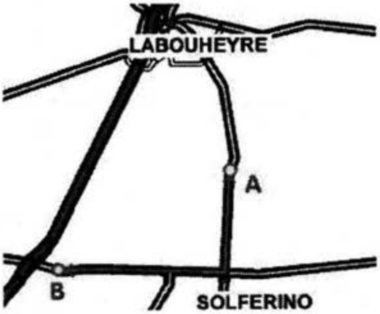

Figure 2: Vector Digital map IGN (French National Geographic Institute) Route 500

On-board equipments
GPS receivers provide the users with geographical coordinates integrated into the GIS. Different kinds of receivers have been tested in order to evaluate their efficiency in locating landing areas and to check if they could correctly work in a forest environment. Tests were carried out with and without correction signals from a reference station (DGPS). The results show that it is possible to use GPS in forest to locate landing areas, even under forest canopy. Differences between measured and real position (evaluated with ProXR DGPS) vary from 20 to 50 m : this is a satisfying level of accuracy for locating landing areas, thus differential correction is not necessary. GPS receivers must however be of good quality and have at least more than 6 channels. As GPS receivers used during the tests were not easily handled by forest operators, it has been decided in a further step of the project to automate GPS measurements by inserting a GPS card in on-board computers. Then, the operator has just to enter quantity and quality of wood piled at road side.

Data transmission
Within a logistic chain, data transmission between the field and the company office is essential. In the Aquitanian forest the main problem encountered was the lack of coverage of the communication networks. Three systems were tested: transmission by 3RP radio, GSM and satellite (Inmarsat C). For each system, their coverage rate of the Aquitanian forest, their capacity to transmit data and their speed of transmission were evaluated. There were no significant differences between the success rate of these three transmission modes (Table 1).

Table 1: Data transmission in Aquitaine

System	Inmarsat C	3RP (Radio)	GSM
Success rate	88 %	91 %	90 %
Average distance to walk or drive to find good transmission conditions	300 m	2 000 m	1 150 m

However, causes of transmission failures were not identical for satellite and for terrestrial transmissions (3RP radio or GSM). Immediate environment has a very strong influence on satellite transmissions. The presence of high trees in the south makes satellite transmissions difficult or even not possible. In case of failure, we measured that it was necessary to move about 300 m to find good transmission conditions. Quality and success of terrestrial transmissions depends on the distance between the point of measure and the terrestrial relay. In case of failure, the distance to move to find good transmission conditions in our tests was about 1 to 2 km. Speed of transmission by satellites was longer than terrestrial transmissions. For economic reasons, terrestrial transmissions were selected.

Navigation

Several tests of navigation systems were carried out. Equipments used were on-board computers like PC (Figure 3), loaded with a GIS programme and digital raster and vector maps. The positions of the vehicles were calculated by an internal GPS card with 8 channels. A communication box was also used for exchanging information (receiving coordinates of reference points and description of assortments of logs to collect, sending data concerning transportation in progress...). This equipment also informed truck drivers about their itinerary by using waypoints and giving them real-time position thanks to GPS.

Figure 3: On-board computer with radio equipment

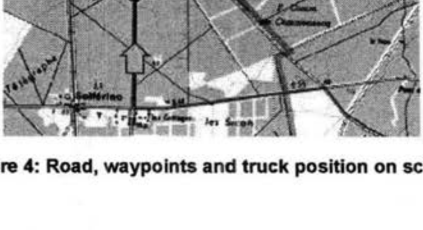

Figure 4: Road, waypoints and truck position on screen

During the tests, the main difficulty was the reading of the maps on the screens. It appeared that the use of raster maps was more easy than the one of vector digital maps (Figure 4). The best scale for truck drivers was 1/100.000.; it contains enough details to locate roads. After a training period, drivers could easily use the navigation system with 1/100.000 raster map. They had to check the map only during direction changes and final approach. Drivers could reach landing areas quicker, avoiding useless routes, errors and U-turns in difficult places. They always knew their position and could anticipate changes of direction. Navigation system allowed a very precise location and avoided long explanations between operators, being also more efficient and safer, particularly under difficult conditions (during the night, in rainy weather or with fog).

Pilot systems

Two pilot systems were set up in two different Aquitanian wood-supplying companies (Figure 5). Those systems were built on the same principles but presented some differences according to the internal organization of each of the two companies. The general outline is presented here (figure 5) :

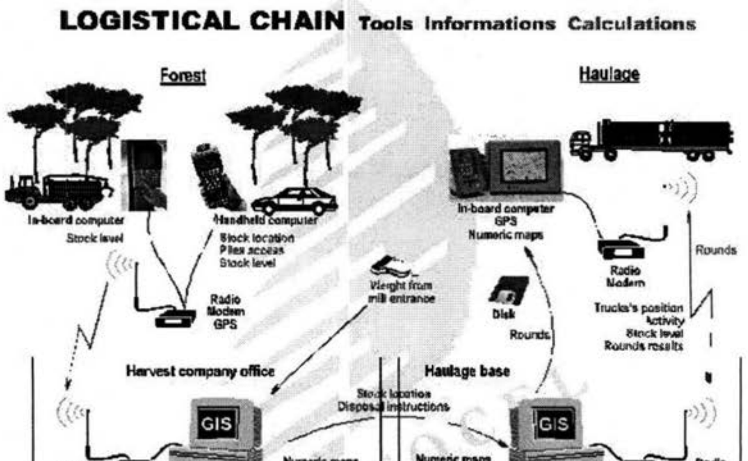

Figure 5: Pilot systems organization

Information related to wood stocks on landing areas (parcel number, quality and estimated quantity of wood) is captured by the forwarder operator, the truck driver or the logging operation supervisor with an on-board or handheld computer, and sent by radio or GSM to the company office. For every new location recorded by the supervisor, a GPS position is automatically transmitted. At the mill entrance, during the unloading of wood, truck drivers record parcel number and quality by bar code, and this information is transmitted by modem to the harvest company office. At the company office, data are recorded on a database and the calculation of wood stocks can be executed. When all the logs from a parcel are removed, this parcel is referenced in the database as a "closed parcel". Collecting instructions are sent once a day to a haulage base for truck monitoring and scheduling according to mills requirements. Planning is made each day for the day after but plans can be easily changed if necessary.

The pilot operations confirmed that data recorded into a GIS can be used both at a strategic and at a tactical level to take medium or long term decisions. These decisions are very well related to the internal organization of the company and can engage its durability. This aspect of logistical GIS, set back from operational level, should not be neglected. A main condition for a GIS project success is the integration of the system in the inner functioning of the organization. If supplying data to the GIS represents too much extra work for the operators, the project will be unsuccessful. This is why it is essential to plan acquisition of recording, communication and restitution GIS data tools adapted to concerned operators.

At the end of the research program, the two wood-supplying companies involved in this project decided to invest into operational logistic systems. Their choice of organization was different. The first aimed at an optimization of haulage, the second needed improvement of its structure because of a big project of sawmill.

Integration of tools into operational logistic systems

First company

This company is in charge of wood procurement to one pulp mill and several sawmills (about 1,500,000 m³/year). The area of wood procurement is divided into ten "districts" of about 3,000 km^2 each. Each district manager has the responsability of wood purchase from the forest owners of the district, logging operations and organization of the haulage to the mills within and out of the district. Schedules of haulage are established once a week and adjusted during the week if necessary. Because he plays the role of coordinator, the district manager has many different tasks. He knows his area very well and works with a permanent team. As truck drivers have been working within the same district for a long time, they know very well where to go and where not to go, and what to do in case of problems. A simple oral description is generally sufficient for them to understand where to pick up the logs and where to deliver them. This kind of organization is well adapted to forest conditions but has major disadvantages:

- haulage is organized in journeys there and back and the charge rate is about 50%, rarely more ;
- truck drivers are not able to find landing areas in forests outside their regular district.

To improve this organization, the company created a logistic team dedicated to haulage management. A GIS network has been implemented to support transfer of information from district managers to the logistic team and from the logistic team to truck drivers. District managers locate landing areas and access routes by single clicks on a large scale raster map (1/25.000). GPS is not used at this stage of the process for two reasons. First, sectors managers know their sector very well so they can locate landing areas on the map without difficulties. Second, this work is cheap because it can be done at the office (Figure 6).

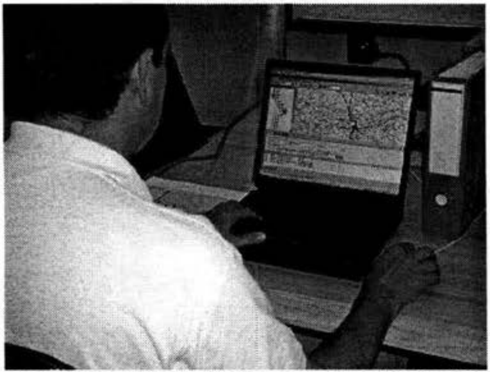

Figure 6: Sector managers locate landing areas by a single click on the map

Forwarder operators are equipped with robust mobile computers (Figure 7) which can transfer data from forest to office by the GSM network. Their task is to inventory quantities of wood available for haulage each day. They do not transfer the daily forwarded quantities but the whole stock available at roadside at the end of each day. Daily, this organization is able to establish a global map of wood stocks available for haulage. This information is very useful for haulage optimization at a global scale, without the constraints of district limits. The logistic team can organize the work of each truck across several sectors. Trucks have been equipped with a navigation system connected to GIS via the GSM network. They receive their planning by GSM and can locate their landing areas on a numeric raster map (1/100.000). Navigation system helps them a lot to locate piles of wood in unknown areas. After each loading and unloading, truck driver informs the logistic team that the work is done.

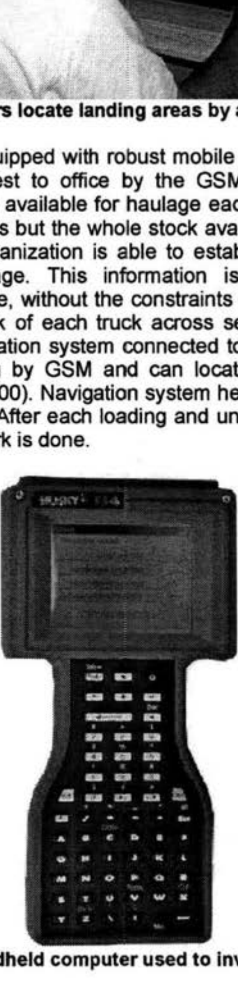

Figure 7: Handheld computer used to inventory stocks

Second company
The second company supplies several large sawmills and one pulp mill (about 1,300,000 m³/year) but contracts the haulage to a big transport company. The two companies implemented their own GIS. One locates stocks in order to manage them and the other one locates landing areas and trucks in order to organize haulage. As before the implementation of the GIS, district managers are not in charge of haulage organization. They transfer information regarding wood stocks to the haulage company, but on a daily basis instead of a weekly basis. The aim of the implementation of the GIS was not to change the organization but to increase efficiency of the information system in order to be able to provide wood to a new sawmill.

Each district manager is equipped with a GPS. He records coordinates of each landing area and transfer data to the central GIS at the wood-supplying company headquarters. As in the first case, forwarder operators are equipped with robust mobile computers and they transfer data from the forest to the office by the GSM network. Each day, the wood-supplying company transfers to the GIS of the haulage company the data regarding wood piles that are to be transported. Planning is done each day and transferred to trucks by GSM. Truck drivers use the navigation system to locate landing areas (Figure 8). Hence, they are able to work in any area, even if unfamiliar.

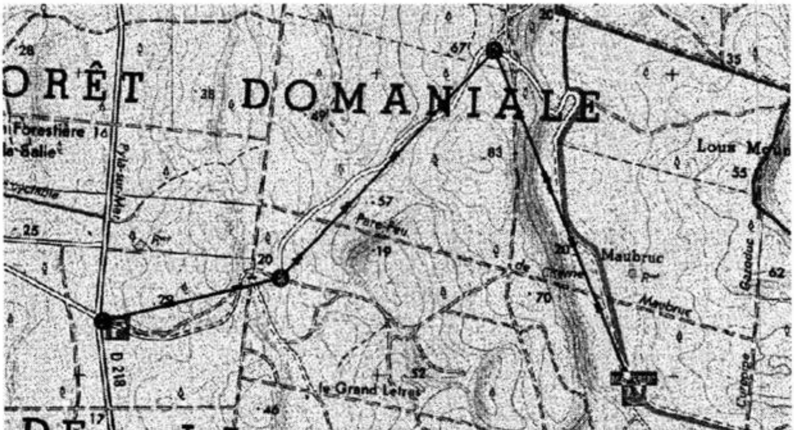

Figure 8: Map used by the navigation system

Advantages and limits of logistics GIS implemented in South-West of France

Advantages:

- Administrative tasks regarding wood logistics are more efficient: operational data regarding haulage are transferred to administrative systems easily and efficiently, reducing the frequency of errors.
- Tracking of wood is easier: GIS allows wood supplying companies to analyse wood flows in order to make tactical decisions.
- Navigation has become an essential tool for truck drivers. They can travel everywhere without any problem when they have the location of the landing areas on their navigation system.
- The approach stage to landing areas is more secure and efficient: truck drivers do not hesitate any longer when they have to quit the public road network for a forest road. They anticipate actions and take the direct route to landing sites.
- The work rate of trucks has increased while the charge-out rate has been reduced. GIS gives valid and up-to-date data about quantities of wood available, which allows to better plan the work of trucks, at a regional level and not only district by district. The productivity of trucks has increased and the use of optimization software has become feasible. The reactivity of the logistic team has improved.

Limits:

- Such logistic GIS systems are interesting for big companies which have large volumes of wood and so a greater potential for haulage optimization. It is profitable for them to invest into a GIS system.
- GIS needs a specific investment in technology but also in training; all operators concerned need to be trained.
- Most of the wood supply companies rely on many other wood suppliers and contractors. Nowadays, these small and medium companies do not use logistic systems but cannot progress alone. A further step of the logistic project is to integrate these small suppliers and contractors into the existing GIS network.

Conclusion

Management of maritime pine haulage through GIS/GPS tools has become a reality for the big supply companies in the South-West of France. However, logistics systems implemented are specific. They are based on the respective objectives and organization of the companies, and cannot dialog with external applications without extra developments. This diversity of the network systems used is problematic for small suppliers or contractors working for several large supplying companies. They cannot invest in the solution of one single client without marginalizing the others. One solution would be the definition of a common language by choosing a data standard and developing generic tools adapted to small companies. This project is about to start in 2006 in South-West of France. The aim is to define common standards for data by probably using existing standards such as StanForD or ELDAT, and to develop an internet application dedicated to the medium and small companies. GIS and GPS tools have helped big companies to smooth the borders between their internal districts. Standard internet tools should help the wood supply network to go beyond borders between companies.

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INTEGRATING HARVESTING AND SAWMILL OPERATIONS USING AN OPTIMIZED SAWMILL PRODUCTION PLANNING SYSTEM

C. Brand Wessels[1], C. Sue Price[2], Philip Turner[3], Murray P. Dell[4]
[1]University of Stellenbosch, South Africa
[2]Forestry and Forest Products Research Centre UKZN / CSIR, South Africa
[3]Napier University, UK,
[4]Formerly *i*comtek CSIR, South Africa
E-mail: sprice@csir.co.za

Abstract

The opportunity exists for sawmills sourcing their logs from intensively managed softwood plantations to include quality information as well as log and product volume in their production planning process. A destructive sampling procedure and three integrated software systems were developed and can be used to optimize profit of the timber manufacturing production chain. Using inputs from pre-harvest quality assessment procedures and software, and sawmill simulation software, a linear and mixed integer programming production planning system is used to find the optimum sawmill production plan subject to market and forest supply constraints. The outputs can also be used for harvest scheduling purposes.

Keywords: Sawmill production planning, pre-harvest quality assessment, simulation, linear programming, mixed integer programming.

Background

In South Africa, sawmills source their timber from intensively managed softwood and hardwood plantations. Each compartment of trees is subjected to a single silvicultural regime, and the trees planted there all come from the same genetic material. Pine plantations earmarked for solid wood processing are usually pruned up to three times before being clearfelled and processed. Although relatively uniform timber quality is expected within a single compartment, differences in factors such as pruning age, quality of pruning, site quality and species can cause considerable differences between compartments. Timber is harvested either by the plantation owner or independent contractors and merchandising is done either in the field or at a central merchandising yard. Sawmills (which are usually separate cost-centres from the forests, or separate companies) pay for merchandised logs and very rarely do any merchandising themselves although they provide length requirements to the log supplier. Logs are delivered to the sawmill where they are pre-sorted into log classes according to diameter and sometimes length. Depending on the log size and quality, high-value knot-free products are recovered from the outside portions of the log and lower value structural and industrial products from the core regions in the wetmill. The boards are then edged, stacked according to thickness and dried in kilns. After kilning, the boards are sent to the drymill for grading; further processing (e.g. planing, finger-jointing, ripping) may occur prior to the boards being bundled and dispatched to customers.

In this article, we concentrate on softwood sawmilling operations, although similar principles would apply to hardwood processes.

Introduction

Traditionally, softwood timber growers and processors have tended to concentrate on volume production, ignoring quality issues until sawn timber has been produced. This situation leads to a poor ability to predict the volumes and grades that a sawmill can produce from a particular log resource – an approach resulting in the timber production chain being volume driven rather than one aligned to the market. This paper describes a decision support model which includes dimensional and quality criteria from standing trees in the sawmill production planning process.

The manufacture of timber consists of a sequence of interrelated operations resulting in an end product of specific dimension and grade. The objective of the processor is to produce a set of saleable products that maximizes net revenue. Each operation usually optimizes its functionality in isolation from the preceding and following operations. It is a well documented fact that the optimization of decisions through the whole chain of operations is considerably more profitable than the optimization of individual operations (Faaland and Briggs, 1984; Maness and Adams, 1991; Mendoza and Bare, 1986). Numerous decision support models in timber manufacturing have been developed using mainly the linear programming technique to optimize either the sawing or merchandising (bucking) strategies or both, based on tree and end-product geometry (Eng *et al.*, 1986; Faaland and Briggs, 1984; Jackson and Smith, 1961; Maness and Adams, 1991). Todoroki and Rönnqvist (2002) developed a dynamic control system which includes quality information of processed boards in the model. The importance of quality related information about standing softwood trees and unprocessed logs to the processor is mentioned by several authors (Park, 1989; Turner and Price, 1996; Uusitalo, 1997). The system described here includes some of these quality considerations in a formal production planning system which aims to maximize the net revenue of the timber production chain (forest-sawmill-market) subject to certain constraints. It is assumed that integrated decision-making between grower and processor can take place although it is not a pre-requisite for using modules of the system. The system is being developed and tested in South Africa.

The system consists of three integrated software modules i.e. pre-harvest quality assessment software (PHQA), a sawmill simulation package (Simsaw 6) and a sawmill production planning system (SPPS).

Integrated decision support system for the timber production chain

Because trees come from an intensively managed softwood plantation, timber quality can to a large extent be predicted. For the processor this creates the opportunity to include quality information in his production planning system. Decisions about the harvesting and merchandising of trees, together with the sawmilling production decisions, can be dictated by market demand. This decision support system aims to optimize the timber producer's profit globally, subject to the forest supply, market demand and production constraints.

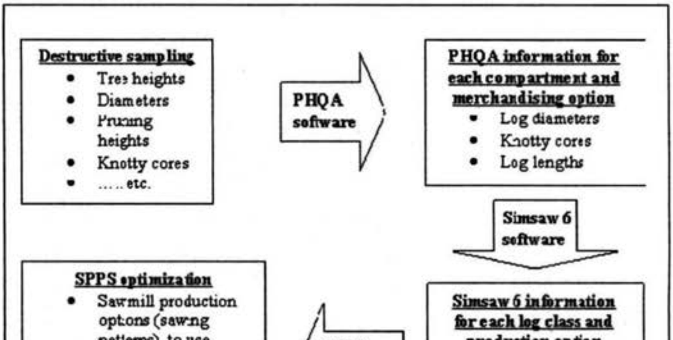

Figure 1. Schematic of information flow in an integrated decision support system for the timber production chain.

The optimization system consists of three integrated software packages i.e. pre-harvest quality assessment software (PHQA), sawmill simulation software (Simsaw 6) and sawmill production planning software (SPPS). The PHQA software is dependent on information from destructive sampling procedures and describes the logs which results from a compartment of trees with a specific set of merchandising rules. The Simsaw 6 simulation package gives the boards which will be produced with each user defined production option. The SPPS software uses the Simsaw 6 outputs to generate an optimum production plan for a given log supply, production and market scenario (see Figure 1).

Pre-harvest quality assessment procedure and software

Pre-harvest quality assessment is a method of determining the quality of a compartment of trees before it is felled. This is done by destructively evaluating a sub-sample of trees in each compartment and measuring key variables influencing the quality and volume of logs. In South Africa where the largest price differential exists between clear (knot-free) board products and knotty products, the size of the knotty core in the pruned section of the tree and the height of pruning are the most important quality indicators. Where accurate historic pruning information is available, these indicators can be predicted without destructive sampling. Other information of interest e.g. occurrence of resin cracks and abnormal wood, is also recorded. A software package has been developed which uses data from the destructive sampling procedure to predict the volume and quality of different log products that can be expected with user-defined merchandising rules (Price *et al.*, 2002). The user can allocate logs of different size and quality to different end-users; for example, a single tree may end up as veneer logs, saw logs and pulp logs.

For a single compartment and set of merchandising conditions, the software predicts the number of logs of each dimension as well as the sweep, ovality and the knotty core diameter of each log (see Figure 2).

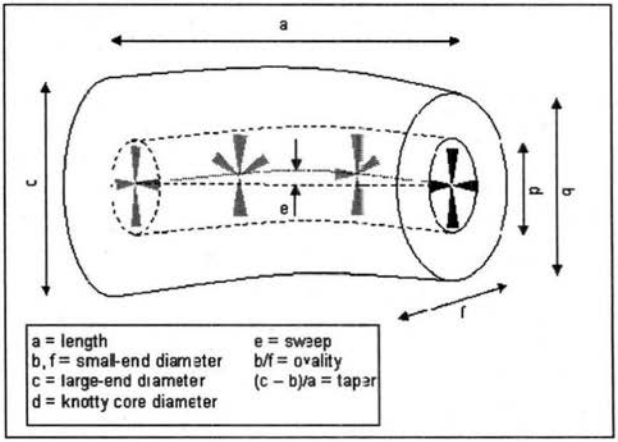

Figure 2. Characteristics of logs measured in the Pre-Harvest Quality Assessment procedure.

Apart from being used in sawmill production planning, the Pre-harvest Quality Assessment software can also be used for testing log market scenarios, log grading and log pricing scenarios.

Sawmill simulation

Simsaw 6 is a sawing simulation tool which predicts the end-product (board) recovery from logs given certain user inputs (Wessels *et al.*, 2001). It uses inputs such as board dimension and grade definitions, log dimensions and knotty core diameters, to predict the expected board recovery for each sawmill production option (sawing pattern, production line, machine settings) in terms of volume, dimensions and grades.

In order to link the inputs of log quality and dimensions and sawmill production options with board grades, Simsaw 6 uses the relative proportion of knotty core present in a board together with user-defined probabilities to assign a grade to a specific board. An example of the stochastic method of assigning board grades can be seen in Figure 3.

Board A: 0% knotty core
95% probability of being Grade 1
5% probability of being Grade 2
0% probability of being Grade 3

Board B: 70% knotty core
5% probability of being Grade 1
60% probability of being Grade 2
35% probability of being Grade 3

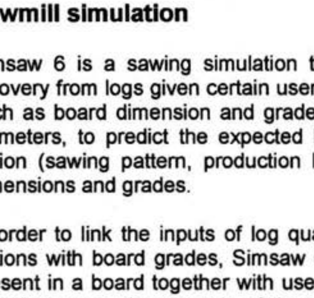

Table with user defined probabilities to assign a grade to boards with different knotty core portions present

Knotty core portion present in a board	Board grade probabilities		
	Gr 1	Gr 2	Gr 3
0%	95%	5%	0%
1 – 50%	20%	70%	10%
51 – 99%	5%	60%	35%
100%	0%	30%	70%

Board C: 100% knotty core
0% probability of being Grade 1
30% probability of being Grade 2
70% probability of being Grade 3

Figure 3. The stochastic method used in the sawing simulation program Simsaw 6 links log quality (in terms of knotty core diameter) with board grades.

The user is allowed to generate numerous sawing patterns for each log class, where a log class is user-defined in terms of the log diameter, length, sweep, taper, ovality and knotty core. For the purpose of production planning, it is not the objective to design a single optimum pattern for a scenario, but rather to generate the maximum number of (practical) sawing patterns possible for each log class.

For each log class and each sawing pattern, Simsaw 6 generates the predicted board output in terms of volume and grades.

Sawmill production planning system (SPPS)

The sawmill production planning system (SPPS) is the decision-making module of the integrated planning system. The objective of the model used in this system is to maximize the total profit subject to constraints set by the user. Simulation data from Simsaw 6 is exported to SPPS which uses linear programming and mixed integer programming techniques to generate a solution.

The objective of the SPPS model is to maximize profit, i.e. the sum of product value less log costs, fixed costs and the cost of buying in timber. There are several types of constraints:

- Log volume constraint – the volume of logs available per log sorting class in the sawmill is constrained. Information for this constraint comes from the PHQA software and is different for each harvesting and merchandising option.
- Timber demand constraint - the minimum and maximum volumes of each board category (dimension and grade) that are required to satisfy the market demand needs to be input. This comes from the sawmill's order book, less what is already in stock.
- Available processing time constraint - Every production option has a throughput (m^3/hr) associated with it. Each production line has limited processing time available and the sum of the time needed to complete the optimum production options must be less than or equal to the total processing time available.
- Integer shift volume constraint – this constraint forces the volume of logs to be sawn to be a multiple of the log input volume that can be processed during a single production shift with a specific production option. This is necessary for some machine types that have very long set-up times and therefore production options (i.e. sawing patterns) can only be altered between shift changes.
- Drying constraint - The drying constraint ensures that the products manufactured stay within the limits of the drying capacity of the sawmill.

Applications

SPPS can also be used independently from the PHQA software and would typically assist in the following decisions:

1. Determine the optimum production options (production line & sawing patterns) to use in the sawmill (operational planning).
2. Determine the best forestry compartments to harvest to meet the current market demand (operational planning).
3. Determine which set of merchandising rules to use (operational planning).
4. Determine the best markets for the available log resource (tactical planning).

5. Determine the best capital investment with the available log resource (strategic planning).

If the plantations are not owned by the same company as the sawmill, or if they are run as two separate cost centres, integrated planning is not always possible. It is therefore necessary to design a set of pre-harvest quality assessment procedures and the three software packages so that they can be used either as an integrated system or as stand-alone packages.

Acknowledgements
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A NEW APPROACH FOR WOODY RESOURCE MONITORING IN NAMIBIA: FIELD INVENTORIES AND REMOTE SENSING

V. U. Kazapua and P. N. Haindongo
Ministry of Agriculture, Water and Forestry, Directorate of Forestry, Namibia
E-mail: lusepani@iafrica.com.na

Abstract

In 1995 a forest inventory covering Northern Namibia was initiated based on stratified systematic field sampling of plots with a radius of up to 30 m. In these plots detailed tree parameters were measured. Due to security problems the most important wooded parts of the area could not be covered completely, while the inventory method used was also very costly. The study investigates if Land sat TM imagery can be used to estimate the necessary woody vegetation parameters in areas where only limited fieldwork is possible, based on similar data collected in other areas. Statistical tests between pixel values of different bands of the imagery with the tree parameters obtained by the existing field sampling method did not result in significant relationships useful for modelling woody vegetation parameters in three test areas. Two methods of different design were tested in one pilot area. Both resulted in statistically significant correlations (up to R= -0.74 for trees and R= +0.70 for shrubs) between % woody vegetation layer cover and pixel values of band 4 of Land sat TM. The increased size of the sample plots in both methods was likely to be the main reason of the improved correlations as the results of both the new methods tested were not significantly different from each other. Relationships between cover and other woody plant parameters like basal area and models for estimating woody resources in parts of Northern Namibia are discussed.

USING eCOGNITION FOR IMPROVED FOREST MANAGEMENT AND MONITORING SYSTEMS IN PRECISION FORESTRY

Masami Shiba, Akemi Itaya
Field Science Education and Research Center, Kyoto University, Japan
Graduate School of Bioagricultural Sciences, Nagoya University, Japan
E-mail: mshiba@kais.kyoto-u.ac.jp

Abstract

By using new high-resolution satellite imagery (IKONOS, Quick Bird) it is possible to detect forestland use structure and to assess environmental change more easily than with conventional lower resolution satellite data. However, due to the high spatial resolution, automatic classification of such imagery based only upon the spectral characteristics (tone, color) of the features can become difficult, especially, in spectrally homogeneous areas. Object-based imagery processing techniques overcome this problem by incorporating both spectral and spatial characteristics of objectives. In this research, an object-oriented eCognition's classification scheme (eCognition is designed to segment the image into units of similar spectral and spatial patterns and to classify those segments according to a pre-defined rule base) was developed which used a DTM with IKONOS imagery (one-meter panchromatic sharpened multispectral data) for the initial segmentation and subsequent object classification. In the multi-resolution segmentation process, the influence of the DTM and multi-spectral bands on object generation was controlled by layer weight, scale parameters, the amount of color and shape factors. The accuracy of the results using this approach is promising compared to pixel-based classification. Results indicate that object-oriented approaches have great potential for improved forest management information and monitoring system in decision-making processes for precision forestry purposes.

Keywords: precision forestry, monitoring system, IKONOS, eCognition, object-based image analysis

INTRODUCTION

Forest operational planning is normally based on stands, owners or regional level as the primary unit of treatment. A forest landscape is a spatial mosaic of arbitrary boundaries containing distinct areas that functionally interact (Turner, 1989). Spatial or landscape structure refers to the relative spatial arrangement of patches and interconnections among them (Baskent & Keles, 2005). In recent years, therefore, interest has been directed towards the use of smaller area units such that the formation of treatment units becomes part of the operational planning (Lu & Eriksson, 2000; Martin-Fernandez & Garcia-Abril, 2005).

The very important function of GIS is the ability to answer geographical questions based on the information in digital maps with associated attribute database (Baskent & Keles, 2005). Forests were distributed on precipitous mountain area in Japan. Therefore, the analysis that combined the topography with other various forest attributes is indispensable for forest operational planning. The introduction of GIS through the Japan forest industry has made possible the optimization of current working methods to the extent that GIS has become one of the most essential tools for forest management. There is a business need for a continuous up-to-date inventory of forest resources and monitoring environmental change of land use structure, as well as a requirement for gathering information about the location, condition and sustainable management of these resources (Suarez *et al.*, 2005).

Remote sensing is more cost-effective technique than field survey to conduct long-term and broad area census. Internationally, there have been important scientific advances in remote sensing over the last 30 years that have produced mature techniques ready for implementation in the management of forest resources (Suarez *et al.*, 2005). Recently, high spatial resolution satellite data become commercially available, making possible fine-scale studies over large areas. The commercial IKONOS satellite (Space Imaging, USA), one of several new satellites collecting high spatial resolution data, was launched in September 1999 and provides, on request, effectively global coverage of 1 m panchromatic data and four bands of 4 m multi-spectral data in the blue, green, red and near infra-red portions of the spectrum, respectively (Read *et al.*, 2003; Turner *et al.*, 2003).

High spatial resolution data with fewer spectral bands in aerial photography and new high spatial satellite images (IKONOS, Quick Bird) can create classification problems due to greater spectral variation within a class and a greater degree of shadow (Laliberte *et al.*, 2004). On the other hand, it contains much information in the relationship between adjacent pixels, including texture and shape information, which allows for identification of individual objects as opposed to single pixels. Image segments are a way of summarizing information from a contiguous cluster of homogeneous pixels. Each image segment then becomes a unit of analysis for which a number of attributes can be measured. These attributes can include dozens of measures of spectral response, texture, shape, and location (Benz *et al.*, 2004; Thomas *et al.*, 2003). Ecologically speaking, it is more appropriate to analyze objects as opposed to pixels because landscapes consist of patches that can be detected in the imagery with object-based analysis (Laliberte *et al.*, 2004).

The aim of this study is to explore the viability of the object-oriented image analysis for the formation of treatment units in order to appropriate forest operation using the high spatial resolution satellite image (IKONOS) and the digital elevation model (DEM). For this paper, we used eCognition software (Definiens, 2000) to produce the image segments.

MATERIALS AND METHODS

Study site

The study area consists mostly of artificial forests in Miyagawa of Mie prefecture, is located in Central Japan (Fig 1, 34°19'N, 136°15'E) and covers about 1600 ha. Elevations range is between 200 and 1000 m, and topography is precipitous (slope gradient about 10-70°). The forest is an artificial forest characterized by coniferous tree species (cedar and cypress).

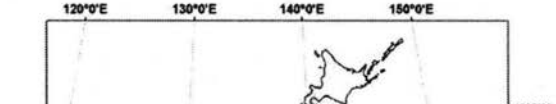

Fig 1. Location of the study site: Miyagawa of Mie prefecture

Data source

We used IKONOS satellite (Fig 2, Space Imaging™ processing level: standard geometrically projected) multi-spectral (4 m / pixel) data for about 1600 ha study area. The data were acquired on 23 November 2004. In this study the red, blue and green bands were used for a false-color composite image, which was an available image format (Erdas Imagine image) in the eCognition. Near infra-red and red bands were used to calculate a normalized difference vegetation index (NDVI). NDVI is expressed as

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}}$$

where NIR is the reflectance measured in the near infra-red band and red is the reflectance in the red band (Ustin, 2004). Calculated NDVI was also image format (Erdas Imagine image).

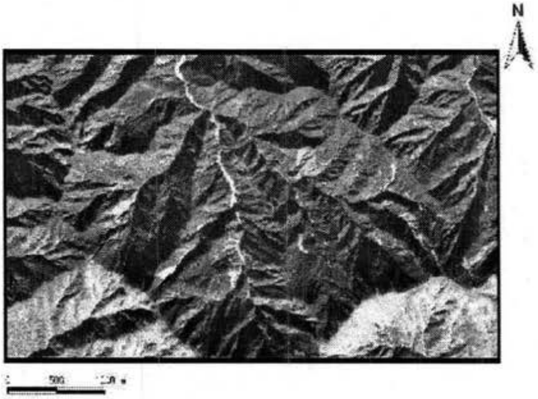

Fig 2. IKONOS data of the study area

DEM was delivered from Geographical Survey Institute in Japan. Spatial resolution was 50 m / grid. DEM was interpolated by the bilinear interpolation method to 4 m / grid in order to coordinate with the IKONOS data. The slope and the aspect were calculated by using GIS (Arc View 3.2a / ESRI, USA). Calculated topography data was 4 m / grid, which was an available grid format (ESRI ASCII GRID) in the eCognition. The output unit of the slope was a degree. The aspect assigned eight aspects to 1-8 after having output a unit with a degree, which was clockwise from the north. The flat assigned 0.

Analysis procedure

In order to form treatment units for appropriate forest operation, a false-color composite image, a calculated NDVI image, grid data of slope and aspect were used. A false-color composite image and NDVI image were used to obtain land cover information. Grid data of slope and aspect were used to obtain estimation of topographically adequacy for forest operation. Based on these data, the forest treatment units were segmented by eCognition.

The eCognition segmentation algorithm creates image or grid data segments based on three criteria: scale, color and shape (smoothness and compactness), where color and shape parameters can be weighted from 0 to 1. Within the shape setting, smoothness and compactness can also be weighted from 0 to 1. In the case of grid data, each value of grid was treated like color. These criteria can be combined in numerous ways to obtain varying output results. Scale is the most important parameter and affects the relative size of output polygons, although there is not a direct relation between the input scale and the number of pixels per polygon.

Scale is heterogeneity tolerance within a segment. Color, smoothness, and compactness are all variables that optimize the segment's spectral homogeneity and spatial complexity. The balance at which these criteria are applied depends on the desired output. Assigning a high weight value to color (spectral information) with no weight on shape information resulted in highly jagged polygons with narrow spectral range. In contrast with that, when shape information was strongly emphasized rather than color, the resulting polygons were amorphous and did not closely follow feature boundaries. A high weight for compactness also outputs amorphously shaped feature polygons that do not adhere to major features. Emphasizing smoothness rather than compactness allows for polygons that follow natural features more naturally (Benz *et al.*, 2004; Definiens, 2000; Laliberte *et al.*, 2004; Thomas *et al.*, 2003).

Table 1 Segmentation parameters used for the analysis

Segmentation Level	Scale	Color	Shape	Shape setting	
				Smoothness	Compactness
Level 1	10	0.8	0.2	0.5	0.5
Level 2	50	0.8	0.2	0.5	0.5

Table 1 shows segmentation parameters used in this study. The segmentation used in eCognition is a bottom-up region merging technique. In subsequent steps, smaller image objects are merged into larger ones based on the set scale, color, and shape parameters, which define the growth in heterogeneity between adjacent image objects. This process stops when the smallest growth exceeds the threshold defined by the scale parameter. A larger-scale parameter results in larger image objects (Benz *et al.*, 2004).

RESULTS

The study area was segmented by using a false-color composite and NDVI images at a lower level (Fig 3) and at a higher level (Fig 4) based on the image object hierarchy. The number of the objects that was obtained was 11898 (the mean area was 1289.73 m^2) in the lower level. In the higher level, it was merged to 732 (the mean area was 20963.45 m^2, Table 2). According to my observation, the segmentation which used the parameter of level 2 was more suitable for land cover than level1.

Table 2 Unit area by using each levels and attributes

Segmentation Level		Attribute used for segmentation		
		R, G, B, NDVI	Slope, Aspect	All
Level 1	No. of Segmentation	11898	6120	-
	Mean Area (m2) ± S.D.	1289.73 ± 1501.47	2537.98 ±1599.68	-
Level 2	No. of Segmentation	732	383	585
	Mean Area (m2) ± S.D.	20963.45 ± 20833.32	40554.61 ± 25896.17	26030.41 ± 23442.12

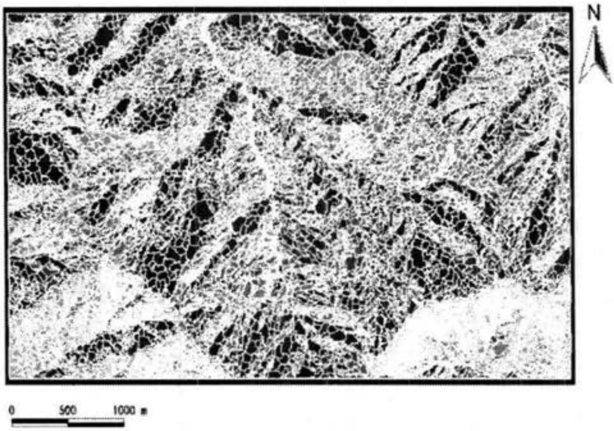

Fig 3. Segmentation of study area by level 1 using a false-color composite image, a NDVI image

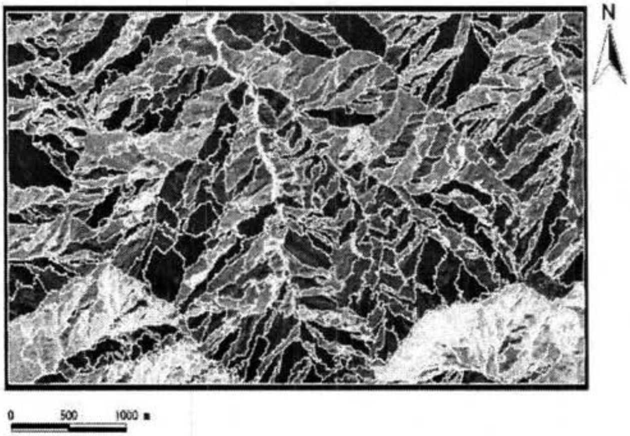

Fig 4. Segmentation of study area by level 2 using a false-color composite image, a NDVI image

Considering topography is important to estimate of appropriateness of forest operation, since forest area in Japan is the steep and complicated landform. The study area was segmented by using topography data at a lower level (Fig 5) and at a higher level (Fig 6) as well as above IKONOS image data. The number of the objects that was obtained was 6120 (the mean area was 2537.98 m^2) in the lower level. In the higher level, it was merged to 383 (the mean area was 40554.61 m^2, Table2). The segmentation which used the parameter of level 2 was more suitable for forest operations than level1 as a result of my observation.

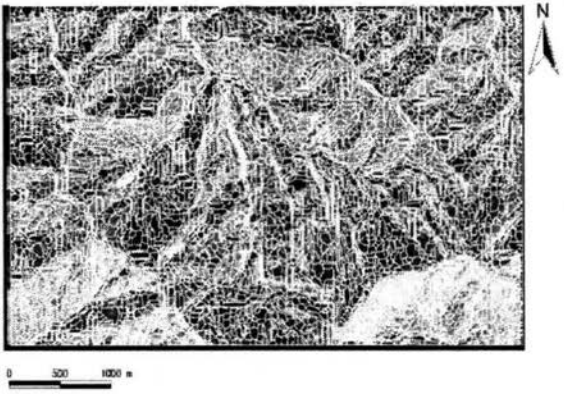

Fig 5. Segmentation of study area by level 1 using geography data

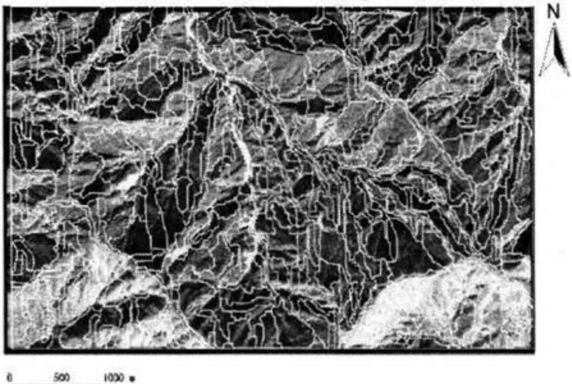

Fig 6. Segmentation of study area by level 2 using geography data

For the formation of treatment units in order to appropriate forest operation, the study area was segmented by using a false-color composite image, NDVI image and topography data (slope and aspect). It was recognized that level 2 suited the segmenting of this area by above-mentioned analysis. Therefore, after the study area was segmented at a lower level, it was segmented at a higher level (Fig 7) based on the object hierarchy. The number of the objects that was obtained was 585 (the mean area was 26030.41 m^2) in the higher level.

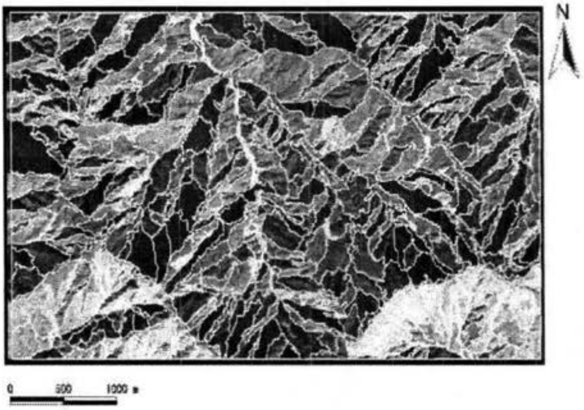

Fig 7. Segmentation of study area by level 2 using a false-color composite image, a NDVI image and geography data

DISCUSSION

The importance of concepts in sustainable and nature-oriented forest management has become increasingly recognized in recent years. In addition to governmental institutions, non-governmental organizations such as the Forest Stewardship Council (Forest Stewardship Council, 1994) have developed new, nature-oriented forest management and certification standards (Mrosek, 2001). Therefore, we should depart from the traditional management method by units of stands, owners or regional level.

The use of object-oriented image analysis was proved to be advantageous in this study. Treatment units to appropriate forest operation were generated smaller area compared to that of the stand base planning. The segmented result was the aggregation of pixels sharing similar characteristics in terms of land cover and topography (Fig 7). Forest management planning strives after a desirable course of action for the management of a forest estate (Holmgren *et al.*, 1997). Forest management practices imposed at one spatial scale may affect the patterns and processes of ecosystems at other scales (Tang & Gustafson, 1997). By using the method of this study, operation units which reflect the current condition of the forest was segmented and the management which is based on these units can be practiced. The accuracy of the results using this approach is promising compared to pixel-based classification. Results indicate that object-oriented approaches have great potential for improved forest management information and monitoring system in decision-making processes for precision forestry purposes.

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HOW MUCH ENERGY-WOOD CAN OUR FORESTS SUPPLY?

Development of a GIS-based decision support system for the assessment of the potential of energy-wood from sustainable managed forests

T. Cremer[1], H. Lechner[1], G. Becker[1], F. Hepperle[1], U. Sauter[2], M. Hehn[1]
[1]Institute of Forest Utilization and Work Science, University of Freiburg, Germany
[2]Forest Research Institute Baden-Wuerttemberg, Germany
E-mail: fobawi@fobawi.uni-freiburg.de

Abstract

Faced with an increasing interest in wood from the forest as a regenerative source of energy, this study pursues the aim to derive practicable and updatable methods with a sufficient spatial resolution to identify forest areas with a high potential for energy-wood. Two methods have been studied. One uses a top-down approach, by estimating the potential volume of energy-wood for different types of forest development and different types of treatments, based on the inventory data of forest estates and the harvesting proposal in accordance with the forest inventory. In the forest areas that were studied (6 641 ha), 1.5 m^3/ha/year of logging residue can additionally be used for energetic purposes when taking a conventional sorting scenario as a basis that optimises the log-processing for non-energetic use. In contrast, 3.9 m^3/ha/year can be harvested when applying the so called energy-wood scenario, which tries to optimise the ratio of stem-wood and wood for energetic usage. The second model uses a bottom-up approach, using the harvesting results from 36 stands representing different tree species and age classes as a basis for the estimation of the potential of energy-wood. Additionally, different sorting and harvesting variants are applied and analysed. Proposals for a further development of the models are given.

Keywords: bioenergy, potential of energy-wood, forest inventory

Introduction

Due to the public concern about climate change and due to sharply rising oil prices, the interest in wood-fuelled energy plants has increased substantially in Central Europe during the last years. Today, the existing management regimes are aimed at producing logs for the wood industry. Therefore, the vast majority of wood from thinning operations and selective and final cuttings is used by the various branches of the wood industry in Germany. Presently, only about 6 % of the total annual cut is used for energetic purposes, leaving a lot of wood remaining unused in the forest as harvest residues.

The question therefore is, how much volume can potentially be harvested for energy purposes in a sustainable way, and under which circumstances can a shift from low grade industry logs to energy-wood be technically and economically feasible. Due to the fact that the existing multifunctional forests in Central Europe are not uniform but vary substantially in terms of species, age, volume, structure and terrain, the answer can only be given on a stand level, taking into account detailed local information about the status of the forest and the terrain.

Several studies in the past were conducted to estimate the potential of energy-wood in Germany (e.g. DIETER & ENGLERT, 2001, FRITSCHE, et al., 2004, HECK, et al., 2004). These studies follow a rather general approach on a national or regional level. This makes it difficult for forest owners, to calculate the specific potential of energy-wood in their forests and stands, as factors like terrain characteristics, road networks and transport distances influence the availability and the costs for the harvest of energy-wood as well as tree species composition, age of the stands and types of silvicultural treatment. Therefore, it is not possible to predict the potential of energy-wood on a stand level, using the existing models. On the other hand, it is necessary in order to sustainably manage forests and sustainably harvest wood for energetic purposes to have specific data about the energy-wood that can be harvested on stand level. Furthermore, a differentiation of the theoretical volume of energy-wood in terms of time and place has to be done. In the past, a method that fulfils these requirements was developed by HEISIG & KÜHNLE (2004). As this method contains several problems, two approaches for a more precise estimation of the volume of energy-wood and its localisation were developed.

Aims of the study

The guidelines for these approaches were, to develop a model which allows a precise localisation, where the wood can be harvested and an exact prediction of the volume of energy-wood that can be harvested in a forest area. Furthermore, these data should be transferable and applicable to other regions and conditions. As a forest is a dynamic system, another factor that should be fulfilled, is the possibility to update the model and therewith to react to changing conditions and to adapt and integrate new factors into the model that may influence the potential of energy-wood.

Method based on stand forest inventory and planning data ("Inventory method")

Confronted with these demands, the so called „Inventory method" was developed (HEPPERLE, 2005), with financial support of the Deutsche Bundesstiftung Umwelt (DBU). This model is based on data from the inventories of forest estates, in which a sampling inventory is conducted. Every sampling point is assigned a certain type of forest and a certain type of treatment, both related to the actual status of development and conditions of this stand (figure 1).

Inventory of forest estates (Betriebsinventur):
Method, to gain information about the whole forest area of a forest estate, using permanent and systematically distributed samples. Goal: provision of data about the status of the forest for estates or large units

Type of forest development (Waldentwicklungstyp):
Forest stands with comparable stand attribute data and a comparable objective target

Type of treatment (Behandlungstyp):
Stands within a type of forest, that are treated in the same silvicultural way, as they belong to the same stage of development (e.g. pruning, thinning, care of growing stock, girth limit felling)

Figure 1: Glossary

In detail, the method works using the following data-bases:

- Inventory data of forest estates. These data result from a sampling grid of 100 x 200 m over the total forest estate. Characteristics that are recorded at every intersection are single-tree parameters (tree species, DBH, height, age), as well as characteristics concerning quality or characteristics of the stand (structure, age, stand volume, species composition, ...).
- Types of forest development. These types are defined according to a standard which has been developed by the forestry administration of the federal state of Baden-Württemberg, Germany (LFV Baden-Württemberg, 1999). Types of forest development are defined as forest stands with a comparable status quo and a comparable silvicultural target. Methods and management techniques to reach these targets are described. Types of treatment are separated within these types of developments, depending on the stage of development and silvicultural treatment (e.g. pruning, thinning, ...). Within the framework of the inventory, every sampling point is linked to a type of forest development and a type of treatment.
- Planning data of the forest inventory. These data specify a certain standard cutting volume per hectare for every type of forest development and forest treatment.

An overview of the structure of this method can be seen in figure 2. First, the types of forest development that represent at least 80 % of the forest estate are selected. This procedure is sufficient to characterise a forest estate (LFV Baden-Württemberg, 1999). Thereafter, the volume, as well as the number of trees per hectare, basal area and average height is derived from the inventory data of the forest estates, always differentiated with regard to tree species and diameter class for each type of forest treatment in each type of forest development. On basis the of these data, the characteristics of the trees that are cut are derived, using the guidelines of the forest development types and the supposed total cutting volume, taking in consideration the growth during the planning period and the number of future crop trees.

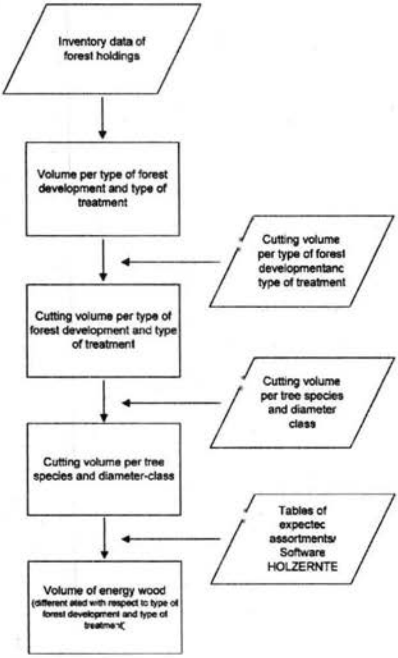

Figure 2: Structure of the „Inventory method", to predict the volume of energy wood

The data of volume and structure that were calculated are imported into the Software HOLZERNTE (FVA, 2005), separated according to tree species and types of treatment. This software calculates single-tree volumes of the extracted trees on the basis of taper curves. In a second step, the volume of energy-wood that can be harvested is derived, using the assortment tables by SCHOBER (1992). The round wood assortments to be produced as primary products can be specified freely. Concerning energy-wood (i.e. all wood that is not assigned to other assortments), reduction factors can be applied with respect to the fact that not the whole tree volume can be used efficiently as there are always some parts remaining in the forest.

These data are projected on the whole area of the forest estate, following the area distribution of the types of development and treatment of the forest. As a result, the potential volume of energy-wood on the level of types of treatment within the types of forest development can be obtained, expressed as total volume and volume/a/ha.

Applying this method, two different scenarios concerning the sorting of the trees were analysed:

- Conventional sorting scenario, with procurement of saw-logs and pulpwood to a minimum diameter as usual. Only the remaining tree crowns and other slash is used as energy-wood.
- Energy-wood scenario, where only saw-logs of better quality classes with clear positive net revenue are produced. The total remaining biomass, i.e. including pulpwood is used as energy-wood.

It becomes evident that the main intention of the conventional sorting scenario is to supply the sawmill and the pulp and paper industry. However, the energy-wood scenario intends to optimise the ratio between an industrial and an energetic utilisation of the biomass. Since the production of pulpwood is often cost intensive and the sale revenues are low and hence the product profitability may be marginal or negative, it is expected that the restriction on the production of only saw logs and the chipping of all the remaining biomass for the use as energy-wood will positively affect the net revenue. Additionally, the productivity of the energy-wood production will increase because of the higher volume per piece and per hectare. The quality of the chips produced will also be enhanced due to a higher proportion of wood instead of bark and needles.

Results of the test run

In the course of this study the presented method was analysed and applied in three different forest estates: the communal forest of the city of Freiburg (separated in a mountainous area and in lowlands), the state forest estate ‚Bad Säckingen' and the state forest estate 'Staufen'. The study area is 6 641 ha. Table 1 and figure 3 show the results.

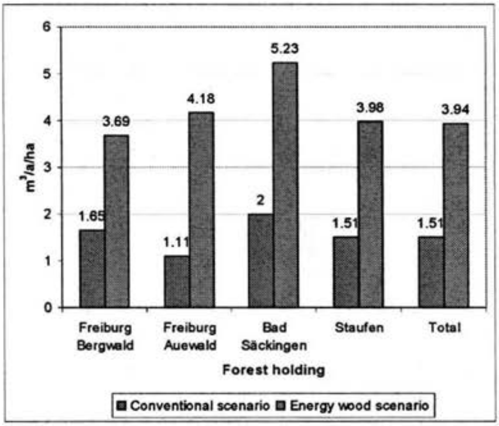

Figure 3: Energy-wood potential in the researched forest estates

Table 1: Total cutting volume of saw logs and pulpwood in the study area

Forest estate	Total area (ha)	Total cutting volume (m^3/year)	Cutting volume (m3/ha/year)
Freiburg (mountainous area)	2412	30 357	12.70
Freiburg (lowland)	1638	12 241	7.61
Bad Säckingen	681	10 269	15.30
Staufen	1910	20 370	10.79
Total area	**6641**	**73 236**	**11.03**

The total cutting volume in the study area is about 11 m^3/ha/year. When applying the conventional sorting scenario, this results in an average energy-wood volume of 1.5 m^3/ha/year and 10 000 m^3/year in the total study area. This equals approximately 20 000 MWh/year. For the conventional sorting scenario the proportion of energy-wood in the potential total cutting volume is about 14 %, whereas saw-logs and pulpwood have a share in the potential total cutting volume of 76 %. Out of the potential total cutting volume 10 % remains unused in the forests. When applying the energy-wood scenario, the average volume of energy-wood increases up to 3.9 m^3/ha/year (ca. 26 000 m^3/year respectively 55 500 MWh/year for the total area). This results in an average share for the energy-wood out of the potential total cutting volume of 36 % (saw logs 51 %, logging residues 13 %).

The comparison of the 4 different types of forest development per forest estate shows that the types of forest development that are shown in table 2 offer the highest volume of energy-wood per year and hectare compared to the average volume of the total investigation area.

Table 2: Volume of energy-wood, split into forest estate, type of forest development and type of treatment (all numbers in m^3/ha/year)

Forest estate	Forest type with the highest yield	Scenario	Tending of young stands	Thinning	Care of growing stock	Girth limit felling
Freiburg (mountainous area)	Douglas fir mixed forest	Conventional	0.11	1.89	1.64	1.58
		Energy-wood	0.47	4.62	3.58	3.38
Freiburg (lowland)	Red oak mixed forest	Conventional	1.23	2.09	1.38	
		Energy-wood	2.86	10.83	4.76	
Bad Säckingen	Norway spruce mixed forest	Conventional	0.00	2.32	2.00	3.47
		Energy-wood	0.00	7.08	2.90	5.04
Staufen	Douglas fir mixed forest	Conventional	0.67	2.20	1.72	1.69
		Energy-wood	2.68	8.34	3.48	2.20

Considering the potential volume of energy-wood with respect to the different types of treatment, it can be seen that the treatment type "thinning" offers the highest yield of energy-wood in all forest estates. This also applies to the conventional sorting scenario as the energy-wood scenario.

Model based on stand surveys and field studies

Another approach currently developed at the Institute of Forest Utilization and Work Science uses an empirical bottom-up approach for the assessment of the energy-wood potential (see figure 4). In this study 36 stands with different tree species compositions and diameter classes are actually harvested and the resulting mass output of the different assortments is recorded as well as productivity and economy of the operations. The investigated stand types cover the most important stand types occurring in Central Europe. In all the stands the conventional sorting scenario is applied as well as the energy-wood scenario. By actually harvesting the stands, the real energy-wood outcome can be derived taking into account harvesting losses and technical restrictions. Before starting the harvesting operations, all relevant stand parameters, i.e. DBH, basal area, tree height, tree species composition and crown length are measured. The harvesting operations are accompanied by productivity studies in order to gather further information about the costs for the production of energy-wood.

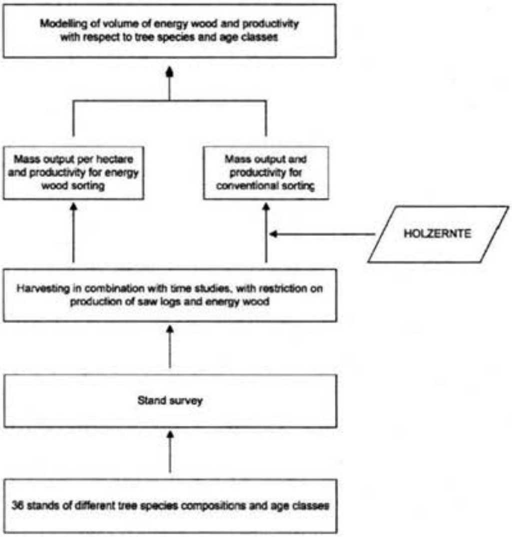

Figure 4: Structure of the „Survey method", to predict the volume of energy-wood

The collected data will be integrated into a model to identify the relevant factors influencing the volume output of saw logs and energy-wood. The model will allow the exact prediction of the energy-wood outcome to be expected, taking into account stand parameters which can be derived from the forest inventory data. When combining the model with information from the forest inventory it will be possible to localise the existing energy-wood potential on a stand level. Furthermore this approach makes it possible to revise and adjust the results found by using the presented method for the calculation of the theoretical energy-wood potential using data of the forest inventory of forest estates.

Prospect and further need for research

The presented „Inventory method" enables the forest owner to calculate the theoretical volume of energy-wood per year and per hectare for his forest estate. If the model is applied in practice, a number of restrictions for the harvest of energy-wood have to be considered. Forest reserves were excluded from the management plan. Additionally, a certain percentage for the use of tree tops was defined since parts of the crown material will remain in the forest due to technical reasons (crown breakage). Furthermore, the overall planning of the forest inventory considers certain economic aspects. Hence, the presented potential is not a mere theoretical potential.

Nevertheless it is necessary to calculate the technical and commercial energy-wood potential if it comes to harvest planning. Thereby, technical potential means the potential of energy-wood that can be harvested in consideration of the present technical restrictions (e.g. steep slopes, swampy areas). This potential can vary depending on the techniques that are applied (KALTSCHMITT, 1995). In the present concept, this will be done by integrating further components into the calculation model such as harvesting systems, accessibility, slope angle and trafficability. It is planned to transfer the results of the energy-wood assortment into GIS-based forest maps and databases. In this way stands that have to be excluded from the management scheme or that impose certain restrictions for the harvesting system to be used in consideration of terrain conditions can be identified and localised. The resulting technical potential will be combined with productivity and cost models for the harvesting and transport of energy-wood and different levels of sales revenues. This will result in the determination of the commercial energy-wood potential that is defined as the proportion of the technical potential of energy-wood that can be used with acceptable economic results (KALTSCHMITT, 1995). Furthermore, these potentials will be verified by ground checks and field studies.

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DYNAMIC MANAGEMENT OF BIOMASS INVENTORIES USING GPS

Bruce Talbot[1], **Willie Brink**[2]
[1]Danish Centre for Forest, Landscape and Planning, Denmark
[2]MTO Forestry, George, South Africa
E-mail: beta@kvl.dk

Abstract

In this paper we present a simple yet robust method for managing biomass inventories throughout the supply chain. Stage-state and locality data are captured, maintained and updated in a database application. Rudimentary transport cost curves provide a visual and economic control which can be used in procurement decision making. The method provides the procurement manager with a simultaneous overview of upstream and downstream progress in the supply chain, as well as the means of monitoring the status against predetermined target figures. Furthermore, it gives the manager the flexibility of deriving operational plans from a selection of in-process inventories while simultaneously suggesting the maximum price threshold.

Based on a feasibility study for a proposed biomass fed 4MWe combined heat and power (CHP) plant, the paper attempts to illustrate the usefulness of the method for applied inventory management.

Keywords: Biomass, Inventory management, GPS, Marginal costs

Background

Combined heat and power (CHP) plants offer long term energy security to primary wood processing industries. They can generate a supplementary source of income through the sale of excess thermal and electrical energy to a local or national grid using waste material. However, an energy sales contract brings with it obligations of supply consistency. Consistent energy production requires sufficient biomass inventories to guarantee continued production levels irrespective of disturbances upstream in the supply chain. This requirement can be met simply by ensuring that large terminal inventories are maintained at any cost, or more efficiently, by managing intermediate in-process inventories.

Biomass is a low energy carrier, and is typically well dispersed on a landscape level. This dispersion is due both to the fact that forests are often scattered over large geographic areas, but also that biomass yields a smaller portion of the normal timber harvest, as it is primarily made up of tops and branches. Having a low energy density implies that transport economics are likely to be the singularly most decisive aspect in considering the feasibility of incorporating a biomass resource. Thus the spatial aspects of biomass inventories are critical in assessing the feasibility of establishing and running a biomass fired CHP plant.

Biomass inventories can also be categorised along a temporal gradient, ranging from the operational (daily-weekly) to the strategic (annual –periodic). In considering an investment in a CHP plant, it is essential that the long term (20-30 year) supply potential for the plant is also known. This supply 'blue-print' provides an underlying structure or baseline from which annual plans should not deviate excessively if larger fluctuations in fleet sizes and year on year operating costs are to be avoided. This indication is largely static in nature, and is defined by the topology of the sources, i.e. their magnitude and spatial relationship to the plant and each other. The baseline will typically be supplemented from *ad hoc* sources, which are largely unknown prior to the planning period, but need to be included at an operational level.

Planning structures for bioenergy are often rather complex as bioenergy activities cross several traditional professional borderlines, production of biofuels takes place in integration with other production, and it happens in a supply chain with many links (Hektor, 2000).The use of Global Positioning Systems (GPS) and Geographic Information Systems (GIS) in timber procurement is generally widespread. Biomass procurement systems are often an integral component of at least part of the timber supply chain, and naturally inherit the core planning methodologies being employed there. A number of examples of such applications are available in the literature. GIS is commonly used in estimating the supply potential on a regional or national level (Graham *et al.*, 2000; Nord-Larsen & Talbot, 2004; Ranta, 2005). At a more operational level, advanced systems able to make use of the cellular network in transmitting data to a central server, which in turn schedules transport operations, have been described (Sikanen *et al.*, 2005). However, it is anticipated that mechanisms under the Kyoto protocol will promote the construction of a number of biomass fuelled CHP or liquid fuel plants in developing countries. It is important therefore that methods are developed that utilise relatively high-tech solutions within a robust and easy to use management systems.

Objective

The objective of this work is to illustrate the usefulness of basic geo-referenced data in managing a complex biomass supply chain. This is demonstrated in a case study which considers the feasibility of establishing a 4MWe CHP plant near the town of Stellenbosch, South Africa.

Materials and Methods

Biomass Supply

The biomass resource consists of 3 main supply categories:

- Plantations
- Alien vegetation eradication programme (WfW)
- Garden refuse dumps

Plantations:
The South African timber industry is heavily reliant on locally grown exotic pine species. These trees are typically grown in plantation blocks located in areas of high rainfall, often along the foot slopes of mountain ranges. In the Western Cape province, which enjoys a Mediterranean climate with long dry summers, suitable ecosystems are scattered and very localised. The predominant species in the region of interest are Monterey pine (*Pinus radiata*), and Maritime pine (*P. pinaster*). Both exhibit good growth and density characteristics in the region. Biomass from plantations arises both from thinnings and in the form of harvesting slash after clearfelling.

In illustrating the methodology, only broad assumptions are used in terms assessing the amount of energy available. Plantations were assumed to be normalised on a 30 year rotation, which included two thinnings. Clearfellings were estimated to produce 25t / ha in the form of branches and tops, while the weighted available (non-merchantable) volume from first (8 year) and second (14 year) thinnings was 30 tonnes per ha. Five supplying plantations were considered within a feasible transport range. Each plantation is divided into a number of blocks (primary sources), which are contiguous management units including a number of compartments, typically 2-300 ha in size. Some summary statistics are given in the table below.

Table 1. Summary data for the plantation resource

Plantation	No of blocks	Base Distance (km)	Annual Resource (MWh)
A	9	38	49 243
B	13	49	36 440
C	4	63	5 083
D	1	21	6 188
E	6	96	27 354
Total	33		124 299

The Working for Water Programme (WfW):

The alien vegetation eradication programme entitled 'Working-for-Water' (WfW) is a government sponsored project initiated in 1995 with the dual objective of eradicating invasive alien species (in this area, predominantly *Acacia cyclops* and *A. saligna*) from sensitive water catchment areas, while creating employment and skills development opportunities for people in rural areas (DWAF, 2006). A considerable amount of work has been done in assessing the volumes, species, dimensions and locality of this woody biomass resource in the western and eastern Cape provinces. For example, multispectral analysis carried out on earth observation data with a spatial resolution of 30 m showed that there were over 100 000 ha infested with a density over 50% (Theron et al, 2004). Tree and stand level models for estimating the biomass volumes have also been developed (Van Laar & Theron 2004). The distribution extends from remote and inaccessible mountain catchment areas into sandy coastal localities, so the data has to be filtered somewhat before arriving at utilisable volumes. Road transport distances to the resource range from under 20 km to over 200 km. While the aim of the WfW programme is to eventually eradicate this biomass resource, projections show that unless an industrial scale market is found, growth and re-infestation is likely to ensure that the resource is sustainable from a volume supply perspective for at least as long as the anticipated project lifetime.

Municipal Garden Refuse Dumps:

Five garden refuse dumps are located within an economically feasible distance from the plant. The quality of biomass varies within depots but preliminary estimates on the utilisable volumes were made using available records of daily tonnages and categories of material. The procurement area includes the entire metropolis of greater Cape Town, which is experiencing rapid development, and volumes are not expected to diminish in the future. Costs of procuring the biomass are competitive with other sources despite the need to sort the material as it is a concentrated source with good infrastructure.

Transport Cost Model

The transport cost model was derived from actual rates quoted from local hauliers and based on rigs with a total capacity of around 110m^3 loose volume, or approximately 28 tonnes (Fig. 1). The ratio of energy content-to-mass is slightly different for each biomass resource and rates per unit energy have to be adjusted accordingly. In all cases, the biomass was assumed to be comminuted to chips before road transport took place. Rates represent only the distance based direct costs associated with transport. All distance calculations were carried out on a digitial road database using Network AnalystTM on an ESRI ArcView GIS. The GIS outputs a distance table to a .dbf file which can be used directly in the computations.

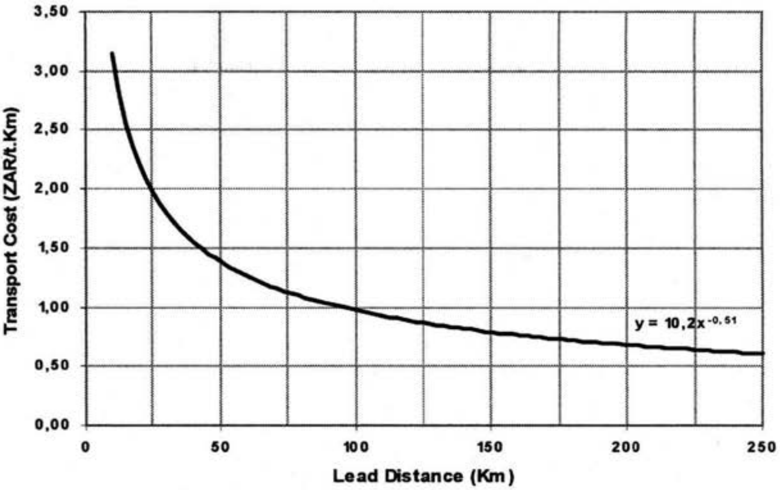


Figure 1 Transport cost model for road haulage, based on a 35-tonne rig.

Transport distances were calculated differently for each of the 3 biomass resource types. For plantations, there were a total of 33 primary sources (Table 1). For each of these, a representative node was identified in the road database and the 'base distance' to the plant was calculated and recorded. In developing the steady state supply structure (Fig. 2) the distance from this node to each of the management blocks was added to the base distance in arriving at the total transport requirement. In the dynamic management phase, a GPS generated position is used to determine the actual transport distance from the stock to the plant in each case. This could also be done by associating a compartment number with the stock, as the compartment is georeferenced, however the GPS position allows the use of a standardised methodology across all resources, and the position given by the GPS was easier to associate with the road network as the compartment centroids often were located a considerable distances from the road.

A similar method was used for calculating transport distances for the WfW data. A major part of the WfW areas aren't serviced by provincial or municipal roads, and the access routes in these areas were not digitised. To overcome this problem a 10x10 km grid was draped over the WfW resources and the centroid of each grid cell was linked via a straight arc to the nearest road node. Any volumes harvested within the grid cell were then accrued to the cell mid-point, from where the transport distance was calculated. For the steady state analysis, 93 accumulated grid cells were included. Each of these was 'normalised' over a 20 year period, i.e. one twentieth of their total volumes were included per year (Fig.2). For the dynamic management phase, biomass stocks were simulated to pop up randomly amongst and within these polygons at varying levels of production.

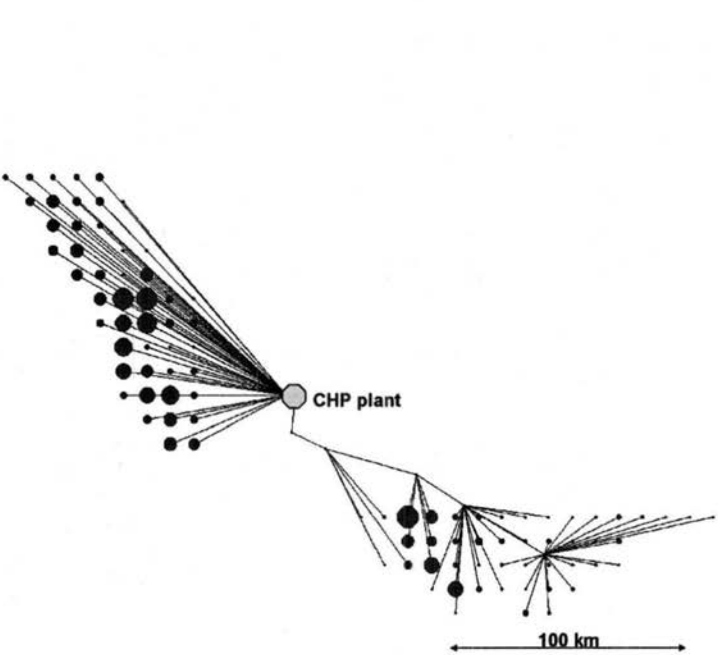


Figure 2. A schematic representation of the relative size and haulage distances for the WfW resource. The sources are centroids of 10 km x 10 km grid cells.

For the 5 garden refuse dumps, a 'one-off' distance was calculated as these would remain constant throughout the period. It was also assumed that the supply from this source would be consistent from year to year.

The energy density of the individual sources plays an important role in transport economics. For biomass arising from the plantation, a density of 2.89 MWh / tonne was used, 3.4 MWh / tonne for the WfW feedstock, and 2.5 MWh per tonne for the garden refuse. This implies that biomass from WfW can be transported marginally further than biomass from the garden refuse sources, on a unit energy basis.

Data Capture:

The biomass supply chain was simplified to include 5 discrete delivery stages:

- Planned (negotiated with owner/manager but not operationalised)
- Scheduled (included in the near to medium term planning horizon)
- On landing (felled, extracted to landing / roadside)
- At intermediary terminal (e.g. central depot)
- Delivered (into final holding bunker)

Positional data can be captured at any one of these stages; at an early planning inspection, in conjunction with a harvesting operation, or once it has arrived at an intermediary terminal. The data is captured in conjunction with the tallying of other forest products at the harvesting site, where the data logger script is extended to include parameters giving the state and stage of the biomass. There are no strict demands on the accuracy of the GPS data, as the location of the feedstock is only required for guidance. The state of the biomass, i.e. 'standing', 'felled', and 'chipped', as well as the species categorisation is logged at the same time. All the biomass supply chain data is stored in a Microsoft Access database application, which manages the relevant tables behind an easy to use interface (DFE, 2005). The relational database associates the distance table output in the transport modelling phase with the state/stage information mentioned here.

Construction of transport cost curves

The envisaged 4 MWe plant has an electrical conversion efficiency of 25%. At an optimistic 8 000 operating hours per year, 32 000 MWhe will be produced, requiring an energy input of four times that, some 128 000 MWh per year. Transport planning is maintained at a number of levels, from the operational (bi-weekly) through to the strategic (annual). As such, it is necessary to construct curves for short, medium and longer term planning. These are superimposed over the supply 'blueprint', which is an indication of the mean annual supply over a longer period of time. As there is only one point of consumption, no allocation algorithm is required. For each planning period, the available volumes of energy are simply ranked and plotted in order of ascending delivery cost. As each new source is entered into the system, all the feedstock in the chain is ranked again, and the curve is re-plotted for each iteration.

Results

Steady State Model

The results of the steady state calculations show that the supply curves for each of the three biomass resources are rather inelastic (Fig.3). The garden refuse resource appears to provide the initial 50 000 MWh at a lower price, but it then increases more rapidly and becomes the single most expensive source over and above 60 000 MWh. However, the figure shows marginal costs only, and the shape of the garden refuse curve confirms that the mean transport cost will be substantially lower than that from other resources, as the area under the curve represents the total cost of supply. The WfW cost curve and the plantation residue cost curve cross just below the 60 000 MWh mark. After this, the cost of procuring WfW material increases slightly faster than the plantation residues. Finally, the combined sources curve shows that, in terms of transport costs, there are considerable savings to be made in utilising biomass from all three sources. The entire resource can be procured at a marginal rate which never exceeds 25 ZAR / MWh. However, in terms of both assessing the feasibility of the plant and managing procurement over a shorter or longer planning horizon, the mean transport cost is the critical value. For the combined sources curve, the mean transport cost over the entire 128 000 MWh wasfound to be 19.80 ZAR / MWh, which equates to approximately 0.08 ZAR / KWhelectric (0.01€/KWhe). This is considered to be rather high, given that the relatively low price of electricity in the country doesn't allow much economic leeway.

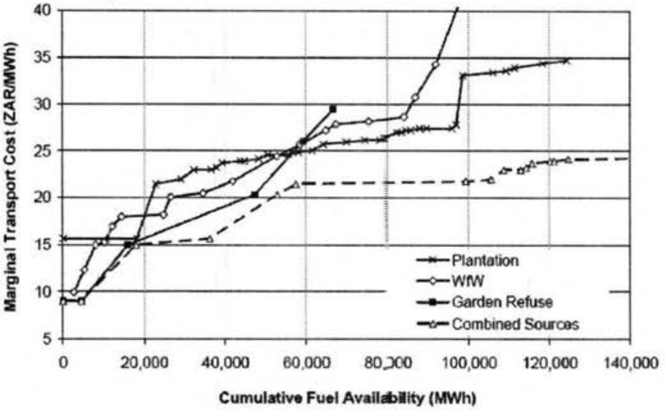


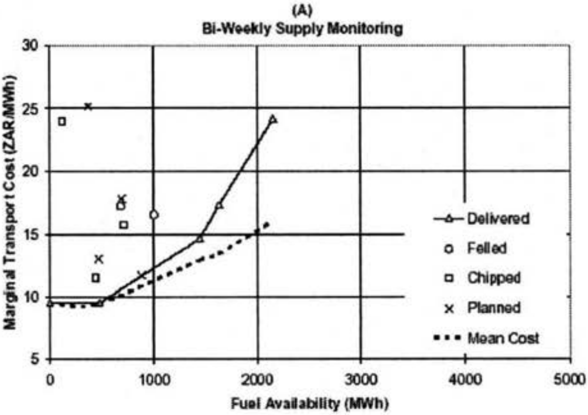
Figure 3. The supply 'blue print' which is largely rigid for the entire lifetime of the plant,unless other major sources are established nearer by. The 'combined sources' curve provides an indication of expected 'steady state' supply costs over a longer period.

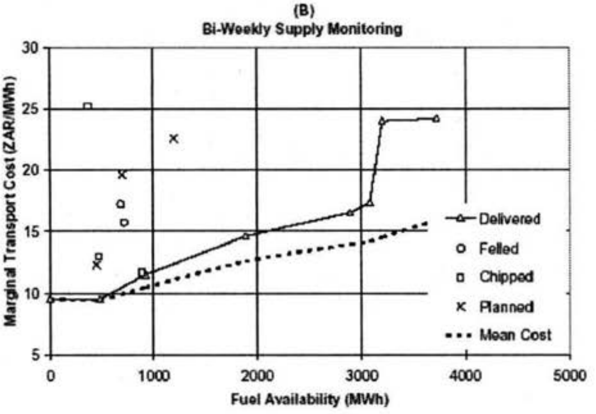
Dynamic Models

The short term (operational) dynamic models provide the procurement manager with full information on recent progress as well as what can be expected in the pipeline. In the early part of the bi-weekly period (Fig. 4 A) the mean supply cost appears to be rising steeply, but the procurement manager is able to assess the volumes and costs of pipeline inventories, and can choose to react accordingly. By the latter part of the bi-weekly period (Fig. 4 B) some of the 'planned' activities have been converted to 'felled, some of the 'felled' have been chipped, and some of the 'chipped' inventories have now been delivered. The mean cost has tapered off somewhat, and begins to approach the 'steady state' level.

As more and more stands are included over a longer planning period (Fig. 4 C), both the marginal and mean transport cost have tapered off considerably, and begin to align more with the 'steady state' values. Three stands represent substantially higher marginal costs than the others, but depending on the volumes coming from each stand, this effect is somewhat negated by the moving weighted mean. It can be seen by the point values that there is a fair spread of inventories in the pipeline, both regarding cost and size, and the procurement manager is given a good impression of what is to come.

Finally, the 'steady state' supply structure is superimposed on the annual supply monitoring chart (Fig. 4 D), in which approximately 6 months have transpired. The many data points on the 'delivered' curve indicate the large number of relatively small sources that are accessed. The procurement manager has chosen to accept biomass from sources which exceed a marginal cost of ZAR 25 / MWh, and a sharp increase in the mean cost of transport provides a caution for future selections. The procurement manager is able to assess whether the 'planned', 'felled' or 'chipped' volumes provide a sufficient buffer within the planning period, and can rectify the situation in good time.





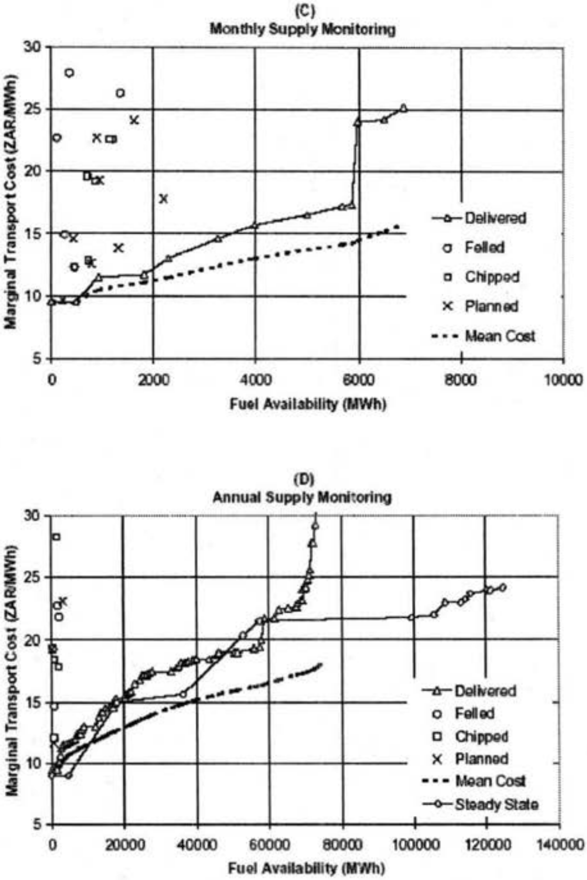


Figure 4. Results of the dynamic models for various planning horizons (note scale on x-axis): Bi-Weekly (A&B), Monthly (C) and Annual (D). The 'steady state' marginal cost is included in (D) for comparison

Discussion:

The methodology described operates at the stand level equivalent. The aggregation level used in the analysis does influence the shape of the supply curve and hence the level of detail that is passed on to the planning function. There is a considerable trade-off as smaller aggregation levels require substantially more modelling effort (Hektor, 2000). Daily updating of stock levels and positions could enhance transport management but would burden field management disproportionately. However, if the system was automated and able to handle data transmissions directly, e.g. using GPRS, it could provide comprehensive decision support for the procurement manager.

The procurement manager can use the supply cost curves to monitor progress against a planning period. Deviations from this could act as an early warning system which enables inventories to be put back on track before distortions become unmanageable. For example, forthcoming periods of low supply can be assessed visually and corrected for by changing the planned harvesting sequence, or hiring in outside capacity, accordingly. Possessing such 'forward' information is the key to managing supply chains effectively (Haartveit & Fjeld, 2003).

As a minimum, the system provides management with a tool for budgetary and accounting purposes. The area under the supply cost curve gives the total delivery cost, making it simple to calculate mean supply costs over any given planning period. Because the curve is not continuous but rather built upon a series of discrete 'entries' it's not necessary to resort to calculus to arrive at this figure, a simple volume weighted calculation of the mean is sufficient. The mean supply cost is a more critical parameter than the marginal supply cost, as it determines net profits or losses over the planning period. However, the marginal supply cost is the parameter used by the manager in making the decision to purchase from a source or not. At any stage in the monitoring period the mean supply cost, and the volume already purchased, can be used in defining the maximum marginal cost the manager can afford to pay for the remainder of the period without exceeding a given threshold mean price. This useful parameter allows for flexible procurement management, including potential sources which might never be considered using 'conventional' procurement methods. These traditionally include rigid 'concentric ring' or 'maximum distance' catchment assessment.

The capture and processing of geo-referenced data is not considered to impose any additional costs on the supply chain. Field staff commonly use data loggers in the tallying process, and the scripts are easily extended for logging the necessary biomass parameters. The most rudimentary GPS device is sufficient in capturing the position of the feedstock. An initial logging of the position already when the 'planned' stock is being negotiated with the land holder can reduce expenses simply by aiding subsequent harvesting and transport crews in locating the resource.

Finally, this paper only considers the costs associated with the transport of loose chips. A full supply cost analysis requires that each source incurs a specific harvesting, handling, transport and storage cost, which is dependant on many factors including species, operation, terrain, harvesting system etc. Transport alone could be specified to short-haul, depot costs, trans-shipping and long-haulage. Bjornstad (2005) provides a good example of this kind of model.

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THE POTENTIAL OF SITE SPECIFIC MEASUREMENTS (SSM) AND MODELLING IN AGROFORESTRY RESEARCH & DEVELOPMENT

The Case of the WaNuLCAS Model Simulation in a Gliricidia + Maize Mixed Cropping System in Southern Malawi

Paxie W Chirwa[1], Colin R Black[2], Chin K Ong[3]
[1]Department of Forest and Wood Science, Stellenbosch University, South Africa
[2]Plant Sciences Division, University of Nottingham, UK
[3]World Agroforestry Centre, Kenya
E-mail: pwchirwa@sun.ac.za

Abstract

Site specific management in Agroforestry technologies can initially be considered in the light of the interactions between the physical environment and biological processes involved between the different components. However, the complexity of AF systems is associated with problems encountered in trying to quantify the responses to different management practices. The WaNuLCAS model was used to compare field measurements of biomass production in the sole maize and tree-based treatments with output from the model and also to provide possible trends for the extent of leaching, soil surface evaporation, drainage and water uptake in the sole maize and tree-based systems.

The results showed that output from WaNuLCAS either underestimated or overestimated crop production compared to field observations. Model outputs were unaffected by applications of green leaf manure and assumed continuous availability of soil nutrients over several seasons, even when no fertiliser or green manure was applied. This suggests that adjustment of the initial model settings, especially the C:N-ratio of the litter pool and the initial C:N-ratio of the soil organic matter (SOM) litter pool, may be necessary as variation in these parameters had no significant effect on simulated crop production. In future, there will be a need to collect more site-specific data especially for phenological and physiological parameters. The model was able to provide general trends for the nutrient and water balance where it was not possible to measure specific processes involved in resource capture. Thus, the model has the potential to be used as a decision making tool where knowledge of some of the phenological and physiological parameters of trees and crop varieties can provide preliminary recommendation domains for different Agroforestry technologies.

Keywords: Agroforestry, Wanulcas Model, precision forestry, site specific management, simulations

Introduction

Site-specific management (SSM) is the idea of doing the right thing, at the right place and the right time (Bongiovanni & Lowenberg-Deboer, 2004). Lowenberg-DeBoer and Swinton (1997) defined SSM as the "electronic monitoring and control applied to data collection, information processing and decision support for the temporal and spatial allocation of inputs for crop production." While earlier highlights focused on agronomic crops, the arguments can also apply to horticultural crops which by extension could include trees in forests hence 'precision forestry'. Temporal SSM requires management of inputs based on information about the Developmental Stage (DS) of the agricultural crops or the rotational cycle in the case of forestry tree crops (Swinton, 1997 in Bongiovanni & Lowenberg-Deboer, 2004). Precision forestry or agriculture potentially provides producers better tools to manage farm inputs such as fertilizer or pesticides by facilitating targeted applications at uniform rates over large areas instead of indiscriminate application.

The entry point for Agroforestry is the consideration of it as part of the farming system, in which case, eco-physiological factors and how they are manipulated will affect its productivity. In this case productivity will be influenced by such variables as soil, water and nutrients and in the case of mixed cropping systems light. The complexity of the interactions between the physical environment and the biological response creates a situation in which it is difficult to quantify the response to different practices. However, spatial regression analysis of yield monitor data as related to soil characteristics shows promising results. The nearest to simulations in AF has been the use of some models for soil fertility management and management of the different components in different AF systems. This is similar to the developments in precision agriculture where the main methodologies for the generation of data, for example on studies on the impact of site-specific N management on the environment, was from simulation models and measured values in the field trials (Bongiovanni & Lowenberg-Deboer, 2004; Wang *et al.* 2003; Roberts *et al.* 2001; Kholsa *et al.* 2001; Thrikawala *et al.* 1999; English *et al.* 1999; Larson *et al.* 1997; Griepentrog and Kyhn 2000; and Leiva *et al.* 1997).

While process-oriented research is both expensive and time-consuming, extrapolation of experimental results using modelling approaches can help to establish boundary conditions for agroforestry technologies based on established principles and soil processes. Several models initially developed for monocrop systems have been adapted to describe agroforestry systems by combining tree- and crop-based models. Models developed to describe agroforestry systems include HyPAR, HyCAS and WaNuLCAS (Mobbs *et al.*, 1997; Matthews and Lawson, 1997; van Noordwijk and Lusiana, 2000), all of which have harnessed physiological and phenological processes as major factors influencing the capture of resources such as light, water and nutrients. HyPAR resulted from a fusion of the Hybrid and PARCH models (Mobbs *et al.*, 1997). HyCAS also resulted from the combination of two models, Hybrid and the GUMCAS cassava model (Matthews and Lawson, 1997).

Van Noordwijk and Lusiana (1999) highlighted the difficulties associated with using models produced by linking independent models and developed a generic plant-plant interaction model based on the capture of above- and below-ground resources.

Specific parameters for each species involved were derived from specialised component models which took account of phenological development. WaNuLCAS was developed to meet several objectives (van Noordwijk and Lusiana, 2000). The most relevant for the present study was for the model to describe plant-plant interactions as the outcome of resource capture efforts by the component species, as determined by their above- and below-ground architecture (spatial arrangement) and physiology.

The case study presented here was done in order to compare field measurements of biomass production in the sole maize and tree-based treatments with output from WaNuLCAS and to use the model to help assess the extent of leaching, soil surface evaporation, drainage and water uptake in the sole maize and tree-based systems in the absence of expensive high tech equipment.

Features of the The WaNuLCAS Model

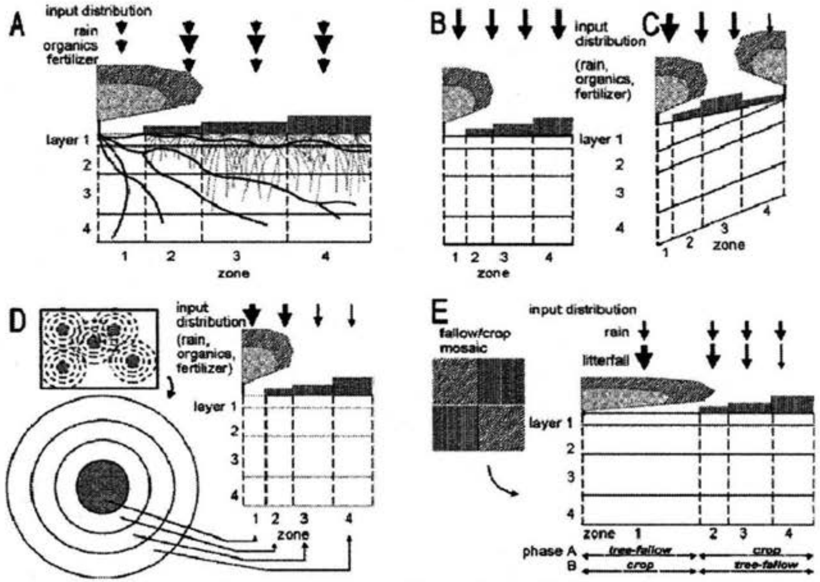

Figure 1 General layout of zones and layers in the WaNuLCAS model (A) and applications to four types of agroforestry systems; (B) alley cropping; (C) contour hedgerows on slopes with various top soil depth; (D) parkland systems, with circular geometry around individual trees; (E) fallow-crop mosaic with border effects (van Noordwijk and Lusiana, 2000)

A key feature of WaNuLCAS is the description of the uptake of water and nutrients (N and P) based on the root length densities of the tree and crop components, plant demand factors and effective supply by diffusion at specific water contents (van

Noordwijk and Lusiana, 2000). The model is suitable for a range of agroforestry systems, including hedgerow intercrops grown on flat or sloping land, taungya-type transitions into tree crops and improved fallows, and isolated trees in parklands (Fig. 1). The model represents a four-layer vertical soil profile with four horizontally distributed spatial zones, in which water, nitrogen and phosphorus balances and uptake by a crop and/or weed species and up to three types of trees may be examined. WaNuLCAS can be used for simultaneous or sequential agroforestry systems and incorporates standard management regimes, such as choice of tree/crop species, spacing, tree-pruning and fertiliser rates. The model assumes that zone 1 is occupied by trees and zones 2 to 4 are planted with a single crop at any given time or within a defined sequence (Fig 1). Analysis of sequential cropping systems is possible by specifying the crop type, planting year and day of year for each successive crop.

Model inputs

The climatic data required by WaNuLCAS mostly take the form of rainfall data, which can be input as daily rainfall or generated based on the daily probability of rainfall and the expected monthly total. Other above-ground inputs include litter, tree prunings, crop residues and fertilisers; all inputs may be distributed proportionately to the relative surface areas occupied by each system component or heterogeneously (Fig. 1). The dates of events such as tree planting pruning and/or felling, crop planting, harvesting and fertiliser application may also be specified.

The soil is represented as four horizons, the depth of which can be chosen, together with specified soil physical properties and initial water and nitrogen contents for each of the sixteen compartments. Pedotransfers are widely used in WaNuLCAS to establish relationships between water potential and water content, as these are not generally measured for all soils to which the model may be applied.

Model outputs

Outputs are basically summarised in the form of water and nutrient balances.

Water balance

Components of the water balance in WaNuLCAS include rainfall, water interception, run-on and run-off, lateral flow, surface evaporation, uptake by the tree and crop components and leaching/drainage.

Nutrient balance

Inputs include fertiliser application, fixation of atmospheric N, mineralisation of soil organic matter and fresh residues, and specific P mobilisation processes. Uptake by trees and crops is assessed in terms of the yield for both components and the biomass returned to the system as recycled residues. Leaching is driven by the water balance, N concentrations and apparent adsorption constant for each soil horizon.

Experimental inputs

WaNuLCAS was used to model two treatments examined; the gliricidia+maize (GM) and sole maize (SM) cropping systems. The agroforestry zone within the GM treatment was assumed to resemble the tree rows in an alley cropping system (Figs. 1 A and B), while sole maize system was simulated by switching off the tree component in the model. As WaNuLCAS cannot simulate simultaneous agroforestry systems containing three components, it was not possible to run simulations involving trees, maize and pigeonpea (*Cajanus cajan*).

Agroforestry treatments and soil layers

The agroforestry treatments were regarded as an alley cropping system grown on flat land, as the site (Makoka) where this study was done is on flat terrain. The distance occupied by each horizontal zone within the model was based on the spacing between the maize and tree rows. The 0.75 m spacing between maize rows in the sole maize treatment provided a combined width for zones 2, 3 and 4 of 2.25 m (Table 1). By contrast, the distances allocated to individual zones in the gliricidia+maize (GM) treatment varied because the distance between the trees and adjacent maize rows (0.38 m) was half that between maize rows further from the trees as the trees were essentially planted between adjacent maize rows within the sole cropping system. This reduced the space allocated to maize in the zone immediately adjacent to the trees (Table 1). Allocation of zones in the model is strictly limited since zone 1 can only be allocated to the trees, while zones 2-4 can only be allocated to crops. It was therefore impossible to mimic exactly the field layout of the GM treatment during modelling. In the model simulations, it was therefore assumed that there were three maize rows between adjacent tree rows. Thus, as the trees were planted between maize rows spaced at 0.75 m intervals, the unit distance occupied by the tree zone was assumed to be one quarter of 75 cm on either side of the tree row, giving a zone width of 0.5 x 0.75 m = 0.38 m. Zone 2, corresponding to the first maize row, was allocated 50 % of the 0.38 m space separating it from the neighbouring tree row plus 50 % of the 0.75 m space separating it from the maize row situated in zone 3, giving a total of 0.25 of 0.38 m + 0.5 of 0.75 m = 0.56 m. The maize in zone 3 was allocated half of the 0.75 m space on either side, giving a total of 0.75 m, while the maize in zone 4 was assumed to be adjacent to next tree zone, providing the same zone width as for maize in zone 2 (0.56 m). The total distance of 2.25 m within the simulation was therefore identical for the sole maize and GM treatments (Table 1).

Table 1. Distances (m) between different agroforestry zones designated for simulations using WaNuLCAS for the sole maize (SM) and gliricidia+maize (GM) cropping systems.

Cropping system	Zone 1 (tree)	Zone 2 (crop)	Zone 3 (crop)	Zone 4 (crop)	Total
SM	-†	0.75	0.75	0.75	2.25
GM	0.38	0.56	0.75	0.56	2.25

†Zone 1 in SM had no crop during simulation as the zone was designated for the tree component

Table 2. Soil layer thickness (m) in the agroforestry zones for the sole maize and gliricidia+maize cropping systems.

	Soil layer thickness (m)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Layer 1	0.05	0.05	0.05	0.20
Layer 2	0.15	0.30	0.50	0.30
Layer 3	0.10	0.30	0.50	0.50
Layer 4	0.10	0.30	0.50	0.50
Subsoil	2.00	3.00	3.00	3.00
Total depth[1]	0.40	0.95	1.55	1.50

[1]Total depth represents the sum of values for soil layers 1 to 4, and excludes the subsoil.

The soil layers were set to provide several scenarios involving changes in the depth of individual horizons and the overall soil profile to establish the sensitivity of WaNuLCAS to these factors. Scenarios 1 and 2 represent the likely rooting depths for maize and to some extent the pruned trees based on the assumption that the rooting density of both trees and crops is greatest in the surface horizons, as reported previously for repeatedly pruned trees (Ong and Leakey, 1999). Scenarios 2, 3 and 4 were used to establish the sensitivity of drainage and/or leaching patterns within the two cropping systems over the range for which field measurements of soil nitrogen and water content were made.

Climatic and soil parameters

Daily rainfall data at Makoka Research Station (latitude 15° 30′ S, longitude 35° 15′ E) for the period between 1996 and 2000 were entered into the WaNuLCAS Excel spreadsheet under the "Weather" options. WaNuLCAS also requires information on the relationship between soil water content and water potential to derive the root water potentials corresponding to specific soil water contents. As these relationships are often not available for soils to which WaNuLCAS is applied, pedotransfer functions are used (Arah and Hodnett, 1997). Parameters within the Van Genuchten equations describing soil physical properties were derived via a pedotransfer function based on soil texture, bulk density and soil organic matter content.

Tree and crop management

Tree and crop management data were entered into WaNuLCAS to give actual dates when activities such as tree and crop planting and tree pruning were carried out (Tables 3 & 4). The crop type under the 'crop type section' in the model is coded depending on the number given for a particular crop and the coded for maize is given as 2.

Table 3. Data entry format showing crop management activities for zones 2-4.

Number of previous crops	Year of planting[1]	Day of planting	Crop type Maize = 2
0	0	347	2
1	1	348	2
2	2	348	2
3	3	335	2
4	4	337	2
5	5	011	2

[1] WaNuLCAS assumes the first year of the simulation to be year zero (0).

Table 4. Data entry format showing tree management activities for zone 1.

Number of previous crops	Year of planting[1]	Number of previous prunings	Year of pruning	Day of pruning
0	0	0	1	238
1	0	1	1	309
2	0	2	2	16
3	0	3	2	249
4	0	4	2	330
5	0	5	3	26
6	0	6	3	247
7	0	7	3	351
8	0	8	4	29
9	0	9	4	258
10	0	10	4	325
11	0	11	5	26
12	0	12	5	78

[1] In the WaNuLCAS simulation, the trees were planted in Year 0 and the next planting within the simulation would have been in year 100, outside the 5 year simulation period.

Output results

Biomass production

The model was tested for the sensitivity of its simulation of biomass production by changing the soil depth and soil layer thickness parameters using scenarios Sn1 to Sn3 (Table 2). The model showed no effect of applying green leaf manure, even though this induced significant differences in total crop biomass between the gliricidia+maize and sole maize treatments in the field experiment (Fig. 2). This was consistent for all three scenarios, which basically involved changing the thickness of individual soil layers. Increasing the depth of the profile by increasing soil layer thickness generally increased predicted biomass yield in both systems, although the increase was greater for sole maize than in the gliricidia+maize treatment. In contrast to the field observations, there was no apparent decline in crop biomass production over the years for which the simulation was run for sole maize despite the elimination of fertiliser application within the simulation. The observed values for crop biomass in the agroforestry system were greater than simulated values obtained using scenario

1. Simulated values obtained using scenarios 2 or 3 were generally closer to the observed values, although the model tended to overestimate or underestimate during some years (Fig. 2). By contrast, the observed values for sole maize were lower than simulated values obtained using scenarios 1-3 during all seasons except year 2 for scenario 1, when the values agreed more closely (4.5 *vs.* 5.0 t ha^{-1}; Fig. 2). When scenarios 1 and 2 were run again after increasing the C:N-ratio of the litter pool, the output showed a general increase in crop biomass for both scenarios in both the gliricidia+maize and sole maize systems (Fig. 2), although this modification did not improve model sensitivity.

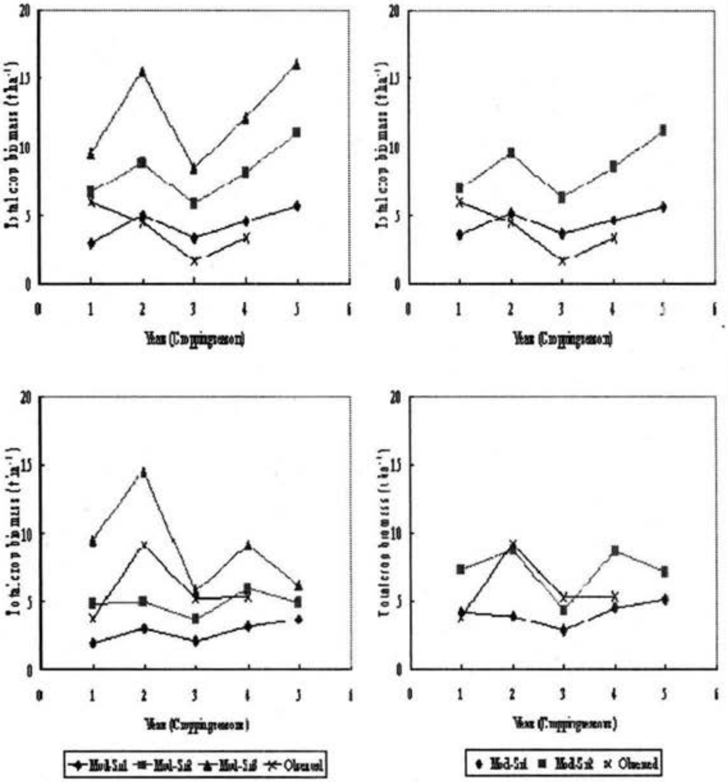

Figure 2. Comparison of observed above-ground biomass production at Makoka experimental site with output from WaNuLCAS.: (1) scenarios Sn1, Sn2 and Sn3 for the depth of individual soil layers for (A) sole maize and (B) gliricidia+maize & (2) scenarios Sn1 and Sn2 for the depth of individual soil layers with an increased C:N-ratio of 200:10:15:15 for the structural, active, slow and passive release pools, respectively for (C) sole maize and (D) gliricidia+maize.

Water use

As no direct measurements of water use by gliricidia or maize, soil evaporation or drainage were made. However, the values for overall water use by the different cropping systems were used (Chirwa 2002) as observed field data for comparison with those provided by the model simulations. Simulations of soil evaporation and water uptake using WaNuLCAS were based on Scenario 1 and two assumptions: (i) soil evaporation occurred mainly from the surface horizon; and (ii) water uptake during the cropping period occurred mostly from the 0-30 cm horizon as shown by the soil moisture profiles for the various treatments examined for 3 seasons at the study site (Chirwa 2002). Output from the simulations suggested that water use by the trees (270-384 mm) was greater during all cropping seasons than in maize grown either as a sole crop (SM; 160-305 mm) or intercropped with gliricidia (GM; c. 168-320 mm; Table 5). Simulated water use by maize was therefore similar in both cropping systems in all seasons examined. The simulation also suggested that soil evaporation was substantially greater under sole maize than in the gliricidia+maize system (260-300 *vs.* 95-125 mm; Table 5). Thus, soil evaporation accounted for over 50 % of total water use in the sole maize system, compared to c. 15 % in the gliricidia+maize treatment.

Table 5. Water use values obtained when WaNuLCAS was run using scenario Sn1. Results are shown for the gliricidia+maize and sole maize treatments.

	Water use (mm)				
	Gliricidia+maize			Sole maize	
Year	Crop	Tree	Evaporation	Crop	Evaporation
1	167.7	278.0	114.2	158.9	263.6
2	313.9	358.0	95.6	300.9	278.1
3	175.1	270.5	120.2	157.8	264.7
4	320.0	384.0	104.1	304.9	301.9
5	318.5	347.0	124.4	304.1	301.2

The model predictions suggest that total water use was greater in the tree-based system than in sole maize during all seasons (Table 6). Simulated values were consistently greater than observed values except during year 4, when both values were comparable for sole maize but the observed values were lower than the simulated values in tree-based system.

Table 6. Summary of simulated water use values obtained when WaNuLCAS was run using scenario Sn1 and observed water use at Makoka experimental site. Results are shown for the gliricidia+maize and sole maize treatments.

	Water uptake (mm)[1]			
	Gliricidia+maize		Sole maize	
Year	Modelled	Observed	Modelled	Observed
1	559.9	na	422.5	na
2	767.0	901.0	579.0	864.0
3	565.8	917.0	422.5	881.8
4	808.0	596.0	606.1	612.1
5	789.0	na	605.3	na

[1] Water use was calculated as the sum of the values for the different water balance components shown in Table 5 na = data not available as no measurements were made.

Simulations of drainage of water through the soil profile were run using scenarios Sn2, Sn3 and Sn4 (Table 7). Model output indicated that drainage during the cropping season was much greater under sole maize (390-460 mm) than in the tree-based system (150-240 mm). Drainage was greater in both systems when the simulation was run using scenario Sn2. Varying the thickness of the four soil layers prescribed by the model had differing effects on drainage in the two cropping systems; simulated drainage in the tree-based system increased when the thickness of layer 1 was increased from 0.05 to 0.20 cm, but decreased in the sole maize system.

Table 7. Water drainage values obtained when WaNuLCAS was run using scenarios Sn2, Sn3 and Sn4. Results are shown for the gliricidia+maize and sole maize treatments.

	Drainage (mm)					
Year	Gliricidia+maize			Soil maize		
	Sn2	Sn3	Sn4	Sn2	Sn3	Sn4
1	84.0	11.5	5.7	318.0	264.5	201.9
2	376.1	232.4	273.2	522.7	494.6	432.8
3	117.8	7.1	2.5	320.7	264.6	201.9
4	383.0	255.1	275.9	578.7	557.6	485.0
5	231.9	186.8	216.7	582.4	557.4	489.8

Nitrogen leaching

Simulations of nitrogen leaching using scenarios Sn2, Sn3 and Sn4 (Table 8) showed the same trend as for drainage, with a much greater quantity of nitrogen being leached from the sole maize system than from the tree-based treatment. The values for N leaching were lower in the tree-based system when the simulation was run using scenarios Sn2 and Sn3, with <20 kg ha^{-1} of N being leached during each season compared to 20-85 kg ha^{-1} N under sole maize. When the thickness of layer 1 was increased from 0.05 to 0.20 cm in scenarios Sn3 and Sn4, there was a substantial increase in nitrogen leaching in both systems, although leaching was still greatest under sole maize.

Table 8. Nitrogen leaching values obtained when WaNuLCAS was run using scenarios Sn2, Sn3 and Sn4. Results are shown for the gliricidia+maize and sole maize treatments.

	N-Leaching (kg ha^{-1})					
Year	Gliricidia+maize			Soil maize		
	Sn2	Sn3	Sn4	Sn2	Sn3	Sn4
1	1.3	1.3	1.7	40.2	53.5	63.3
2	4.8	16.6	78.3	47.3	84.7	137.7
3	1.4	0.1	0.4	22.4	36.0	61.4
5	2.6	3.6	57.9	36.2	62.5	135.8
5	2.3	5.0	42.0	40.8	54.6	108.1

Discussion

Validation of the model

The outputs from the simulation which indicate there was no response to the addition of prunings in the tree-based system suggest that the model has generally been set at high level of nutrient availability, in contrast to the conditions experienced in the field experiments reported here. Similar predictions were obtained when simulations were run with progressively increasing or decreasing C:N-ratios. The consistently high simulated values for crop production throughout the experimental period suggest that the quantity of soil organic matter assumed by the model is sufficient to sustain crop biomass production over several cropping seasons, which was clearly not the case under the prevailing field conditions, as indicated by the maize yields (Chirwa *et al.*, 2003). Increasing the C:N-ratio from 150 to 200 within the simulation also increased modelled crop biomass production values, implying that mineralisation rates were still very high, thereby maintaining sufficient nitrogen supplies. The most substantial effect on simulated crop production was obtained when the model was run with increased soil layer thickness values (Fig. 2). This observation suggests that the model assumes that increases in soil layer thickness increase dry matter investment in roots, resulting in enhanced uptake of below-ground resources. This has a bearing on the initial set up of the model, which should in practice reflect the actual rooting depths of both trees and crops. In the present study, excavations were not carried out to determine root distribution and the values used to define soil layers were based on estimates of the thickness of individual soil horizons.

Water use

Simulations using WaNuLCAS suggest that the gliricidia+maize treatment used more water than sole maize (Table 5), although this difference was not apparent from the field observations (Chirwa, 2002). It has previously been suggested that differences in water use between agroforestry and sole cropping systems may be masked under field conditions if the tree roots extend below the maximum measurement depth for soil water content or come in contact with the water table (Chirwa, 2002). In contrast to the field observations, the model outputs suggest that the tree-based systems used more water than sole crops as the simulation provided separate values for water uptake by the trees and/or crops and evaporation. This highlights the importance of measuring water uptake directly for each component of intercropping systems, as suggested previously (Trambouze *et al.*, 1998; Black and Ong, 2000). Estimates of water uptake provided by WaNuLCAS were lower than the observed values, perhaps due to differences in the depth of the soil profile used, as neutron probe measurements were made to a depth of 1.5 m compared to a simulation depth of 0.5 m. However, the use of the 0.5 m depth in the model was justified because the soil moisture distribution patterns showed that the changes in water content occurred mainly within the 0-30 cm horizon (Chirwa, 2002). Additionally, other studies have reported that systems where trees are subjected to repeated pruning tend they tend to develop a greater rooting density in the surface horizons (Ong and Leakey, 1999). The evidence provided by the simulations that soil evaporation was greater under sole maize than in the gliricidia+maize treatment concurs with previous field studies (Wallace, 1996; Black and Ong, 2000).

Drainage and nitrogen leaching

The lower drainage losses from the tree-based system than from sole maize imply that uptake by the trees may have increased overall water use. This decrease in drainage, coupled with a reduction in soil evaporation, supports earlier suggestions that water use efficiency was greater in the tree-based systems than in sole maize (Chirwa, 2002). Simulated losses of N by leaching showed a similar trend as estimates of drainage as leaching values provided by WaNuLCAS are based on drainage losses (van Noordwijk and Lusiana, 2000). The reduced losses of nitrogen by leaching in the tree-based system relative to sole maize support the hypothesis that tree roots provide a safety net which decreases nutrient losses but contrasts with previous findings that the roots of gliricidia are located mainly in the surface horizons and so cannot provide a safety net against leaching (Cadisch *et al.*, 1997; Rowe *et al.* 1999). However, Cadisch *et al.* (1997) also reported that, when WaNuLCAS was used to predict the effectiveness of the safety net effect provided by *Peltophorum*, which apparently provided a safety net role under field conditions, potential N leaching was reduced by only 5-10 % over a 60 day period. They attributed the low efficiency to the relatively shallow 40-60 cm soil layer used in their simulation and suggested that significant improvements in safety-net efficiency could be provided by the presence of much larger root length densities and deeper rooting. As earlier root excavation studies at Makoka showed that gliricidia roots may reach depths of 5 m (Anon. 1998), the simulations of leaching using soil layer depths ranging from 0.95 to 1.55 m using scenarios Sn2, Sn3 and Sn4 were within the acceptable range for the Makoka experimental site. Observations from the same study also indicated that rooting density for gliricidia was greatest in the surface horizon and decreased with depth in the soil profile, prompting the proposition that nutrient cycling may result from a 'nutrient pump' which enables nutrients in the subsurface horizons to be captured and brought to the surface horizons as a result of litter fall and incorporation of prunings.

Conclusions

Output from WaNuLCAS either underestimated or overestimated crop production compared to field observations and was particularly sensitive to changes in the soil layer thickness parameter. Model outputs were unaffected by applications of green leaf manure and assumed continuous availability of soil nutrients over several seasons, even when no fertiliser or green manure was applied. This suggests that adjustment of the initial model settings, especially the C:N-ratio of the litter pool and the initial C:N-ratio of the soil organic matter (SOM) litter pool, may be necessary as variation in these parameters had no significant effect on simulated crop production. In future, there will be a need to collect site-specific data for phenological and physiological tree and crop parameters as these are often based on observations made in a single agro-ecological zone. However, the model can be used to provide general trends for the nutrient and water balance when it is not possible to measure specific processes involved in resource capture. This was apparent in the present study, in which the modelling studies indicated that the tree-based system used more water and reduced drainage and leaching relative to sole maize. On the other hand the models have the potential to be used as decision making tools where knowledge of some of the phenological and physiological parameters of trees and crop varieties can provide an early indication of the potential of using a particular AF technology in a specific area thereby establishing recommendation domains for different technologies.

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PRECISION FORESTRY IN THE SOUTHEAST U.S.

Steven E. Taylor[1], Timothy P. McDonald[1], John P. Fulton[1], Joey N. Shaw[2], Frank W. Corley[3], and Christian J. Brodbeck[1]
[1]Biosystems Engineering Department, Auburn University, Auburn, Alabama, USA
[2]Agronomy and Soils Department, Auburn University, Auburn, Alabama, USA
[3]Corley Land Services, Chapman, Alabama, USA
E-mail: taylost@auburn.edu

Abstract
The U.S. forest products industry has undergone significant changes in recent years. Changes in workforce levels and ownership patterns have both had major influences on the implementation of precision forestry (PF). This paper defines precision forestry and describes the development of precision forestry in the southeast U.S. Early PF activities quantified impacts from harvesting operations and measured productivity of harvesting machines. Today, primary uses of PF techniques have started to focus on silvicultural operations and emphasize site-specific mechanical and manual herbicide and fertilizer application techniques. These are areas where PF can have an economic impact for landowners' providing spatial feedback to ensure services were performed correctly while providing environmental and worker assurance documentation. New technology is being developed for mapping yields in tree-length harvesting systems for site-specific feedback about production. Future developments in PF are also discussed.

Keywords: GPS, machine productivity, yield mapping, planting, herbicide.

INTRODUCTION

"Precision forestry" (PF) is a relatively new phrase that has become part of the vocabulary of the forest engineering - forest operations community. This term is similar to those frequently used in agricultural production circles, i.e. "precision agriculture," "precision farming," or "site-specific agriculture." Over the last 20 years, the concepts of precision agriculture have been refined into a definition that most people will accept. That is, precision agriculture can be defined as managing crop inputs, such as fertilizer, herbicide, etc. on a site-specific basis to reduce waste, increase profits, and maintain the quality of the environment.

Initially, one would think that the term "precision forestry" should have a very similar meaning to the frequently used "precision agriculture" term. Yet, as several international symposia and technical sessions at international meetings have attempted to synthesize, based on the current body of knowledge on PF, it is evident that the term PF has many different meanings depending on who uses the term (Becker, 2001; Dyck, 2003; Farnum, 2001). While many of the aspects of precision agriculture can be applied to forest management, the considerable differences between the two industries require a different, broader definition for precision forestry. Therefore, the objectives of this paper are to:

1. Discuss and define the term precision forestry in the context of forest operations, and
2. Discuss the development of precision forestry in the southeast U.S.

PRECISION AGRICULTURE CONCEPTS

Precision or site-specific agriculture techniques are centered on a database of geospatial information including soil fertility, soil variables, crop yield, in some cases crop quality, and different geospatial information on cropland. Many harvesting machines now have yield monitors that collect continuous geospatial data on the amount of the crop being harvested as a function of location in the field. When yield maps are combined with soil fertility and other soil type maps, management units within a field can be defined called management zones. Then, each management zone can have its own prescribed rates of fertilizer, herbicide, pesticide, and more recently, irrigation. Using variable-rate technology (VRT), the rates at which these inputs are applied can be changed as the applicator moves across the field based upon the rates assigned to these management zones. The ability to change fertilizer, herbicide, and irrigation application rates to suit the needs of each management zone leads to a more efficient use of these inputs, thereby possibly reducing production costs, reducing environmental impacts, or maximizing production in each zone.

PRECISION FORESTRY DEFINED

Since there are several differences between the forest products industry and the agricultural sector, all of the concepts of precision agriculture are not directly applicable to forest production systems. Moreover, there are different applications in forest management that can be considered part of PF. We choose to define PF as follows:

Precision Forestry - planning and conducting site-specific forest management activities and operations to improve wood product quality and utilization, reduce waste, and increase profits, and maintain the quality of the environment.

Further, we separate PF into three main categories:

1. Using geospatial-information to assist forest management and planning;
2. Site-specific silvicultural operations; and
3. Advanced site-specific technology to meet market demands for higher valued products.

The common thread in all three of these areas of PF is the emphasis on site-specific practices and geospatial technologies. Rather than conducting operations at the stand level, operations and activities are conducted in smaller management units or zones within the timber stand. The following text briefly defines each of these three PF categories.

FOREST MANAGEMENT AND PLANNING

This area of precision forestry encompasses a wide variety of activities that use geospatial information to assist in the site-specific management of forests and planning of future operations. This actually encompasses many current management and planning activities since many industrial and private landowners use geospatial tools to manage their land bases. Traditional examples would include using geographic information systems (GIS) to help develop management plans for forested areas; however, what makes these activities fit under the PF umbrella would be an emphasis on site-specific management.

New examples of this type of precision forestry include the use of information technology to optimize the transportation routes of wood products from the forest to their most appropriate processing location. Advances in wireless communication are at the point where much of this information can be shared from the harvesting machine directly to transportation dispatching services and to the manufacturing facilities. Another example of site-specific management and planning is the use of something similar to an agricultural yield map for collecting site-specific performance on a timber tract and using this information to develop site-specific management plans. Recent developments in forest yield mapping are discussed in the latter part of this paper.

SITE-SPECIFIC SILVICULTURAL OPERATIONS

Site-specific silvicultural operations involve the use of geospatial technologies, such as the global positioning system (GPS) and GIS, to improve operational efficiency and reduce the cost of wood fiber. This involves using much of the technology developed for precision agriculture. Example technology includes using GPS and variable-rate technology (VRT) to improve the efficiency of herbicide spraying or fertilizer application. Control systems and field computers are available to give real-time guidance information to the machine operator so they minimize areas of overspray and areas where they fail to spray along with assisting operators when navigating during operations. This technology is readily available and is currently being used in forest operations in the U.S.

Other examples of new technologies include radio frequency identification (RFID) and GPS-based steering systems have great potential for use in silvicultural operations. Temperature recording RFID tags can be used to track the conditions in which tree seedlings are lifted, processed, transported and stored before planting. This temperature data can be combined with information on who planted the tree, when it was planted, and where it was planted (using GPS data) to help landowners better understand tree seedling survivability. GPS-based steering systems are being used frequently for guidance of agricultural tractors. However, these systems also have the potential to provide guidance for forestry site preparation operations (both tillage and herbicide or fertilizer application). Rows can be more precisely established to minimize erosion and to maximize the number of trees planted on the site.

Site specific silvicultural operations will continue to expand because the development of precision agriculture technology continues to progress at a rapid pace and most of this technology can be readily adapted to silvicultural operations. Also, forest industry trends of consolidation and workforce reduction are encouraging more automation and data collection for verification of services.

ADVANCED SITE-SPECIFIC TECHNOLOGY TO MEET MARKET DEMANDS

Two of the largest components of the cost of wood when it is delivered to the mill are harvesting and transportation. These high costs directly impact forest landowners' bottom line by reducing the income they receive. Significant transportation costs and energy savings to the industry can be realized if a coordinated geospatial-technology-based harvesting and transportation approach is used. In such a system, it is possible to collect data on location and volume of trees as they are felled during the harvest. These data can be shared through the entire procurement and manufacturing chain to improve efficiencies. Example uses include optimizing the skidding or forwarding process using the product type and location data of logs on the ground, and optimizing trucking scheduling by knowing the inventory and location of logs harvested

Also, most current production systems are very inefficient in the methods employed to evaluate raw materials for future production. "Tree-length" harvesting systems, which are the most common in the southern U.S., cut trees and transport tree-length logs to mills, where logs are processed; however, this may not be the ideal location for any given log or part of it. The end result is multiple sorting and transportation steps before the final product is made (and even then, it may not have been the optimal use of the log). New sensors can be used in the woods or at the time of harvest to evaluate the quality of trees or logs and then determine the best use of that tree or log (Wang et al., 2003 and Murphy, 2003). After sensing the quality of a tree or log and determining its best future use, GPS and other information systems can monitor its location and schedule shipping directly to the best manufacturing plant. This type of system will eliminate unnecessary transportation steps, saving costs and energy while potentially maximizing profits for timber stands. For example, this type of system can identify higher value products, like veneer logs or high-stiffness lumber, in a given timber stand, so they can be segregated from other lower value logs to increase the return on the landowner's investment.

DISCUSSION

There are several key components in these three categories. The primary component that is common to all forms of precision forestry is the use of geospatial technologies such as GPS, GIS, remote sensing, LiDAR, etc. as tools to assist in site-specific forest management, planning, or silvicultural operations.

A second component in precision forestry is the development and use of an extensive information base to help make management and operational decisions. This information base could include data on product growth and yield, product quality, and environmental conditions as a function of location and time. A critical part of this use of information is the feedback mechanism that is possible. In other words, it is possible to take the geospatially attributed data on yield and product quality and use it to validate and refine growth and yield models so that future management strategies can increase return on investment for the landowner.

A final concept in precision forestry is that of defining the most appropriate management unit. As a start, this would involve examining stand maps, terrain information, soil maps, and soil fertility maps along with other information such as wildlife habitat, etc. Eventually, this should incorporate the development of yield maps but with additional information on product quality. Once the size or number of management units is determined, more focused management and operational decisions can be made on site-specific bases.

One of the primary goals of precision forestry is the gathering of site-specific information for various users. These users include forest landowners, forestry consultants, and forestry contractors. This information can be used ultimately by the landowner for verification of services provided by contractors, improving management decisions, and for certification purposes for programs like the Sustainable Forestry Initiative. Industry trends in the southeast U.S. that have influenced this need for more verification data include consolidation of the industry into fewer industrial landowners and the concomitant reduction in staffing levels. With fewer employees, these landowners are relying more and more on contractors to provide electronic data that verifies that the work was performed in a specific location and specific time.

Precision forestry should not mean that every operation is computerized or automated. Many site-specific silvicultural operations can be conducted in a cost effective manner without being automated. What it should mean is that the management process or operational activity is focused on making decisions for the smallest practical management unit area or number of management units within a given tract or management area. For example, this could determine how much fertilizer or which herbicide is applied at a particular location on a tract.

Using many of these concepts, we can envision that these geospatial technologies can help the forest products industry adopt scenarios similar to the following:

1. Develop yield maps during harvesting operations. From the yield maps, begin to quantify variability in wood quality and wood fiber production rates as a function of location.
2. Once variability is quantified, identify site conditions that contribute to that variability (e.g. soil type, soil fertility, moisture conditions, etc.).
3. Track the types and dates of operational practices and prescriptions that are carried out during the rotation (fertilization, herbicide application, seedling quality, planting methods, etc.). It may be possible to track tree growth during the rotation using remote sensing data or other methods on the ground.
4. With a record of these data, begin to conduct comprehensive analyses to determine what contributes to spatial and temporal variability in seedling survival rates, wood fiber growth rates, and final wood quality.
5. Using these conclusions, determine the most appropriate management unit size or number of management units for the operations.
6. Using these management units and the previously collected data, plan future silvicultural operations for the same rotation or the subsequent rotations. Fertilizer and herbicide application rates, planting density, etc. can be varied as a function of location depending on the site conditions.
7. At the time of the next harvest, product type and quality can be recorded and even used in determining the optimal use for the product as well as the optimal destination for further processing of the product.

PRECISION FORESTRY IN THE SOUTHEAST U.S.

The evolution of precision forestry techniques in the southeast U.S. began with the rapid use of GPS and other geospatial technologies in forestry in the early 1990's. Industry consolidation and increasing foreign competition since 2000 have forced the industry to reduce workforce levels and reduce other operational costs. These efforts at cost reduction have led to a greater reliance on contractors to provide mapping and GIS services and operational services for silvicultural operations such as site preparation, planting, etc. To provide verification of these services, the industrial landowners are relying more and more on electronic geospatial data supplied by the contractor. These data provide verification of the time at which the services were provided, location at which they were done, workers who conducted the work, chemicals applied at each location, and weather data during the operation at the site. These needs for data have led to increased development of precision forestry technologies in the southeast U.S. The following text describes initial work in using GPS for quantifying machine productivity, performance, and environmental impacts; implementation of precision technologies for herbicide and fertilizer application; and developing techniques for mapping growth and yield on a site-specific basis.

QUANTIFYING PRODUCTIVITY AND PERFORMANCE OF FOREST MACHINE SYSTEMS

Estimating Harvesting Impacts from GPS Machine Tracking

In the early 1990's, forest industry practitioners and researchers began to use the Global Positioning System (GPS) for forestry mapping activities. Early studies postulated that GPS could be used to track forest machines to help automate machine productivity determination. McDonald et al. (1998a) presented a method to use GPS tracking data to determine the area impacted by a machine as it traveled over a site. The method, which was similar to one presented by McMahon (1997), used pairs of x,y position data to represent sampled locations of a machine, then assumed that machinery moved linearly between adjacent location samples. These data were transformed into a map showing how many times the machine passed a given location. Final output of the transformation was a raster map, with cells in the raster having a value equal to the number of times the object, or machine, passed over a particular location in a rectangular region.

The model was tested initially by using data collected from a rubber-tired skidder working in part of a clear-cut harvest. Several features of the harvesting operation were discernable from the mapped paths: the deck or landing, the delimbing area, the main skid trail, and the return skid trails. Although they did not conduct any detailed position error determination, they concluded that overall the calculated travel patterns matched the true machine movements closely enough for stand-level assessments of operational productivity.

In a later study, McDonald et al. (1998b) and Carter et al. (2000a) used identical methods to map the travel paths of feller bunchers and skidders over an entire harvest tract. The output from this study was a traffic map of cumulative totals of traffic intensities and their distribution in the tract. Figure 1 shows the traffic intensity map resulting from this study. They found that 25 percent of the stand received no traffic, 25 percent received more than five tire passes, and 50 percent received one to five tire passes. When visual disturbance assessment methods were compared with GPS estimated traffic intensities, the visual methods overestimated the presence of heavily trafficked areas. They noted that the GPS-based method was superior to the traditional methods because it was less time consuming and presumably more accurate.

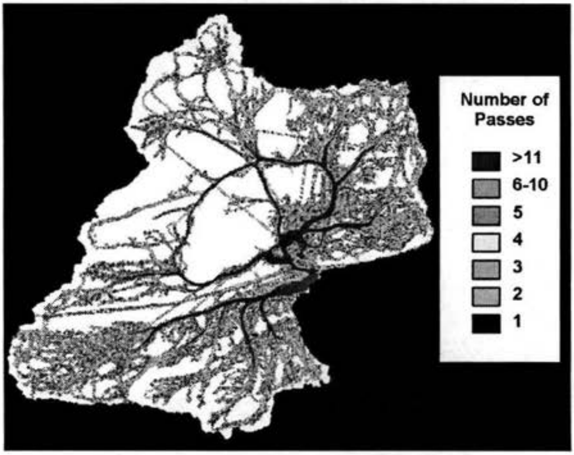


Figure 1. Harvest traffic intensities (number of machine passes indicated by different colors) as monitored by a GPS data logger during a clear-cut harvest of a loblolly pine plantation (adapted from Carter et al., 2000a).

Carter et al. (1999, 2000a, 2000b) presented detailed results of the soil physical responses measured during the study introduced by McDonald et al. (1998b). They assessed the impact of traffic intensity on spatial variability of soil physical properties by measuring changes in the properties at select points that corresponded to estimated traffic intensities within the harvest tract. They found that bulk density and cone index responded to increased traffic intensities and achieved peak values after a limited number of passes. This ability to compare detailed data on traffic intensities with soil strength properties would not have been possible without integration of GPS into the impact assessment process.

HARVESTING MACHINE TRACKING – AUTOMATED TIME STUDY

The machine tracking work begun by McDonald et al. (1998a, 1998b, 1998c) was extended to facilitate time and productivity study of harvesting machines by McDonald (1999), McDonald et al. (2000a, 2000b), and McDonald and Fulton (2005). The system to develop time study data solely from GPS position information was implemented using two components: 1) a feature extraction subsystem to identify characteristics of a machine path, given some site-level information, independent of the type of machine being tracked, and 2) an event processor that applied machine-specific knowledge to combine characteristic movements and sub-events into operational functions. The intention was to develop a system that was useful to analyze the functional performance of any type of machine where movement and position were important factors in its operation.

McDonald et al. (2000a) conducted further research using GPS for unattended time study of grapple skidders. The GPS data were reduced to movement-defined events, then movement events were combined into machine functions, and elemental times (travel loaded/empty, delimbing, positioning and grappling) were determined. For gross time study measurements, the data acquisition system performed well, recognizing over 90 percent of the time elements. These methods also have been applied to automating time study of wheeled feller bunchers (McDonald et al., 2000b). In addition to collecting GPS position data, a field computer in the machine monitored the states of two switches that indicated feller buncher activity: 1) cutting a tree as indicated by micro switches on the foot pedals that controlled the felling head grabbing arm, and 2) felling head tipping as indicated by a set of magnetic switches mounted on the felling head linkage. Figure 2 shows a map of feller buncher movements across a study plot as well as the locations of tree cut and head dump events as indicated by the data acquisition system. The system performed well in a gross time study, and for individual felling cycles the automated system agreed well with traditional time study methods. With more accurate information on the location of cut trees and with an additional system to measure tree size, it will be possible to measure yield across the site.

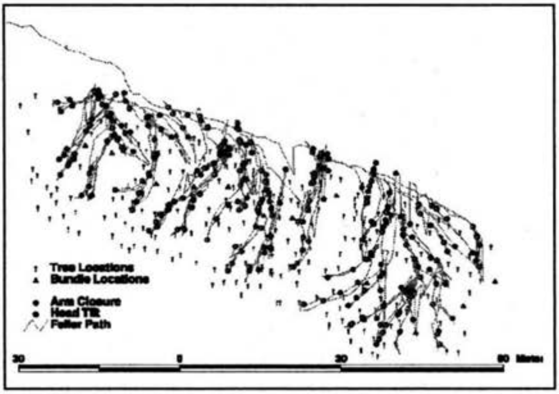


Figure 2. Map of feller buncher movements during harvest operations (adapted from McDonald et al., 2000b).

New GPS-based data collecting systems have since been developed for use in the forest products industry. Turcotte (2003) described the use of the MultiDAT system for determining harvesting machine utilization. This commercially-available data collection system is able to collect data similar to that described in the early studies by McDonald et al. but it has more flexibility and software tools than those used in the early machine tracking studies. These commercial systems will continue to develop and increase in functionality and geospatial accuracy and robustness.

SITE-SPECIFIC SILVICULTURAL OPERATIONS

Currently, most operational precision forestry activities in the southeast U.S. are in site-specific silvicultural operations. These silvicultural operations include site preparation, planting, fertilization, herbicide and insecticide application, thinning, pruning, and final harvest. This section will describe ground-based machines that are being used for herbicide and fertilizer application. Another paper being presented by McDonald et al. in this same proceedings, describes in detail new developments in GPS-assisted manual spraying and planting systems. These manual systems are proving extremely valuable in the certification of services conducted by the forestry contractor.

Regional Herbicide Applicator Trends

Site-specific application of herbicides and fertilizers is the most frequently used precision forestry technique. Noteworthy developments include more efficient ground-based machines for herbicide and fertilizer application, "smart" systems for aerial spraying, and "smart" backpack spraying systems. Informal surveys of forestry herbicide application contractors in the southeast U.S. indicate that there are approximately 400 contractors in the region that stretches from Virginia to Texas. Of these contractors, approximately 30 use ground based machines equipped with GPS-based guidance systems. Three contractors have implemented advanced GPS-based guidance and control systems for their equipment. Across the region, there are approximately 35 contractors who use aerial systems for chemical application. All aerial applicators use some form of GPS-based guidance system for their aircraft today.

Precision Ground-Based Spraying Machine Systems

One innovative silvicultural contractor in the southeast U.S., Woodlands Specialists Inc. has developed several ground-based machines that use GPS guidance and variable-rate controllers. Taylor et al. (2002) described one such machine that was configured for post-planting herbicide and fertilizer application. The machine, referred to as the WS Sprayer, is shown in Figure 3 and is constructed on the same chassis used for a wheeled feller buncher. Herbicides are not tank mixed; rather the machine contains one main 500 gallon water tank with chemicals injected at the nozzles. This design allows many different chemicals to be placed on the machine and used only when determined by the operator or the spray controller. Variable-rate pumps are used to deliver chemicals to the spray nozzles. An additional 250 gallon tank is mounted on the rear of the machine. This tank allows liquid fertilizer to be applied. When not in use for fertilizer, the tank can hold additional water for herbicide spraying.

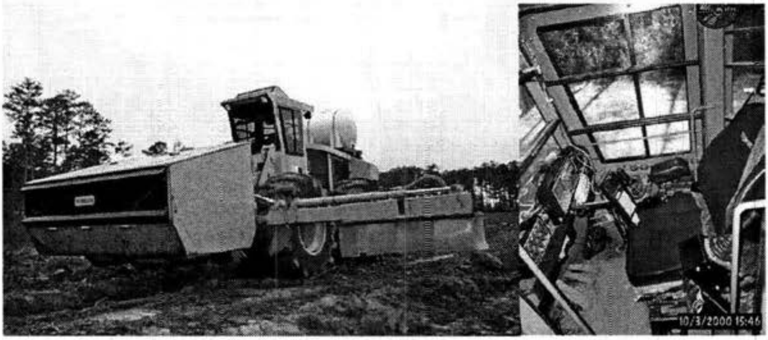


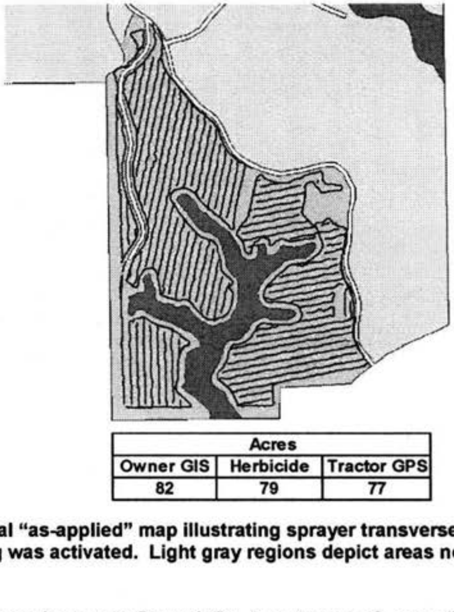
Figure 3. Photograph of WS sprayer configured for banded spraying. Inset shows the field computer and spray control equipment mounted in the cab.

A MidTech TASC spray controller, coupled to a field computer, was used to control chemical injection and monitor navigation of the machine. The controller uses GPS to determine machine location and speed. The controller also monitors water flow rate, band width, and herbicide application rate. Using these inputs, the control system can maintain the desired application rates by properly adjusting the amount of injected chemical based on ground speed fluctuations. This type of variable-rate control is critical to maintain efficient chemical usage as the ground speed of forestry sprayers can be highly variable.

Herbicides are injected in their original concentration from the manufacturer, except for dry flowable formulations such as Oust, Oustar, and Velpar by this control system. Using the injection system means that there is no measuring or mixing required of a chemical, which minimizes operator exposure to herbicides. Also, there is no leftover tank mix solution to dispose of at the completion of the tract; only the amount of product needed or the tract is applied. In its current configuration, the sprayer can inject three different products simultaneously;

however, up to six injection pumps can be used on the machine. Spraying prescriptions can be easily changed using the control console.

The spray control system provides a field computer display and a light bar so the operator can observe where they have sprayed and where they need to steer the machine. By comparing this real-time map to maps provided by the customer, the operator can insure that all designated areas are treated. There is also the capability to download a digital tract map from the customer to the field computer before beginning the tract. Finally, an "as-applied" map is stored in the controller that can be downloaded and provided to the customer for incorporation into a GIS database. A typical "as-applied" map is illustrated in Figure 4. This map shows the machine path as it is spraying and it indicates areas that were not sprayed.



Acres		
Owner GIS	Herbicide	Tractor GPS
82	79	77

Figure 4. Typical "as-applied" map illustrating sprayer transverse (blue lines) when spraying was activated. Light gray regions depict areas not sprayed.

The machine has been configured for two types of operation: 1) broadcast spraying and 2) banded spraying. In broadcast spraying, two Radiarc nozzles are mounted on the upper rear portion of the machine so that a 50-ft-wide strip can be sprayed during chemical site preparation or during understory release spraying. The Radiarc nozzles provide a uniform spray pattern and uniform droplets of large diameter to reduce drift. In banded spraying, booms with six TeeJet® spray nozzles on a common manifold are mounted on the front of the machine. These nozzles are shielded, positioned close to the ground, and operated at low pressures to also reduce drift when conducting a spraying operation. The booms are configured to spray a band of herbicide directly over three rows during a single pass by the sprayer. Also, liquid fertilizer can be applied along the row using the same booms.

By applying the herbicides and fertilizer in a band over the row, only those areas close to the trees are treated, thereby reducing approximately 2/3 of the total herbicide and fertilizer applied to a tract. Studies have shown that by applying the herbicide in a 4-ft-wide band around the tree, the growth response is the same as in broadcast herbicide applications. Also, by applying the fertilizer in a band, it is left in a concentrated area a few inches from the tree, providing a more effective burndown. In addition, by applying the fertilizer in a band, the total amount of fertilizer applied to the tract is much less than needed compared to the traditional broadcast application. The effect of this fertilization method on seedling growth rates has not been quantified.

Cost data for this new machine indicated that it can apply herbicide at a rate nearly half of that of aerial application methods. By performing a more site-specific application of herbicides and fertilizers, and by combining operations to limit machine passes, the cost of herbaceous weed control can be reduced significantly. Perhaps just as important as reducing cost, the use of herbicides and fertilizers can be reduced by two-thirds in this when implementing this type of management scheme.

An additional benefit of this type of operation is that the locations of the rows are established by the GPS track of the sprayer. This map can serve as the beginning of the complete geospatial history for a tract. In fact, the machine is capable of using a dye to mark the potential tree seedlings planting locations and geospatially document these sites for future mapping or analyses. This ability to mark the recommended tree location is important for manual tree planting operations since during winter planting operations, it is often difficult to distinguish the location of the herbicide treated rows, since all the surrounding vegetation is dead as well.

A second generation machine, constructed in 2003, was designed to apply banded both herbicides and liquid fertilizers simultaneously before planting seedlings. This sprayer (Figure 5) was constructed on a typical wheeled skidder carrier with water tanks mounted behind the cab and spray booms located at the rear of the machine. Since the sprayer is designed to apply herbicide in a band over the row before planting (i.e., the sprayer defines where the rows of trees will be planted in subsequent operations), additional equipment was installed on the sprayer to apply paint markings on the ground to identify row location. This row delineation indicates to manual or mechanical planting operators where the trees should be planted in order to take advantage of the herbicide and fertilizer. A GPS-based spray control system and field computer is used. As discussed earlier, the "as-applied" map provides a valuable product geospatially illustrating an activity completed. Since many industrial forest landowners have reduced staffing levels, the "as-applied map" produced by the contractor reduces the landowner's need to send personnel to the tract to ensure that the job was completed within contract specifications.

Figure 5. Second generation WS sprayer for pre-plant application of herbicide and fertilizers.

CONCEPTS IN FOREST YIELD MAPPING

Yield maps and the associated soil, fertility, and terrain maps are fundamental elements in site-specific or precision agricultural practices. The data available in these maps can assist the land manager identify sources of yield variation, which in turn help formulate strategies to improve yield and ultimately profit. The concept of a timber yield map is not quite as simple as in agricultural crops since the crop rotation length is much longer in forestry. Typically, agricultural producers can collect yield maps yearly for cropland; in some cases two per year in double-cropping situations. Additionally, forest management could conduct multiple thinning operations coupled with the impact of environmental and other management events over the life of the rotation can influence growth and the final yield of a timber tract. However, a yield map can provide valuable information to the management of a timber production system.

Many researchers and practitioners have investigated methods to use LiDAR and other remote sensing techniques to quantify timber stand volumes and growth (Andersen et al., 2001 and Andersen et al., 2003). Research at Auburn University has been focusing on developing yield mapping techniques based on using information collected by the harvesting machine at the time of felling and tree processing. Current work is centered on the platform of the feller buncher since tree length harvesting systems are the most common harvesting system in the southeastern U.S.

Research by McDonald and Fulton at Auburn University has been developing and testing various sensors that can be placed on the felling head to determine the diameter of the tree as it is severed from the stump. While the optimal sensing system has yet to be determined, an optical sensor device attached to the felling head has been tested in the laboratory and in the field and appears to be the most promising method. To validate these sensors and to help develop concepts of yield mapping in forestry, test sites have been established where detailed tree measurements have been made using traditional manual techniques combined with high accuracy GPS for geospatial location. Example results, from one test site, are illustrated in Figures 6 through 9. This particular test site, which has a total area of 3.6 Ha, has a stand density of 599 stems/Ha, a mean DBH of 14.0 cm, and mean tree height of 17.8 m.

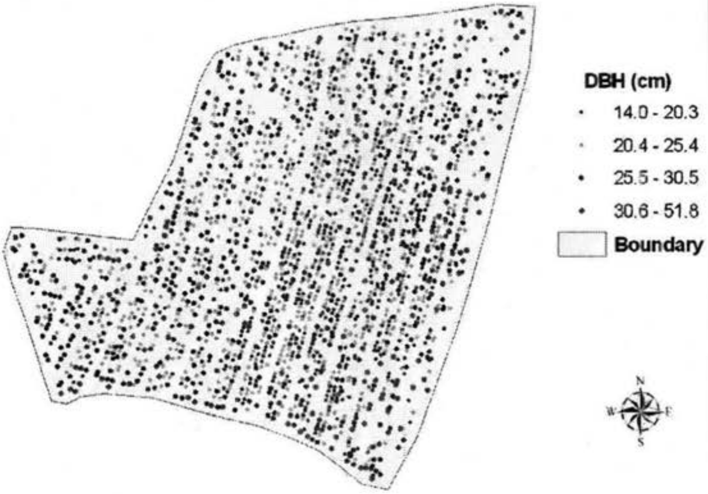


Figure 6. Tree diameter (DBH) map for the 3.6 ha test site.

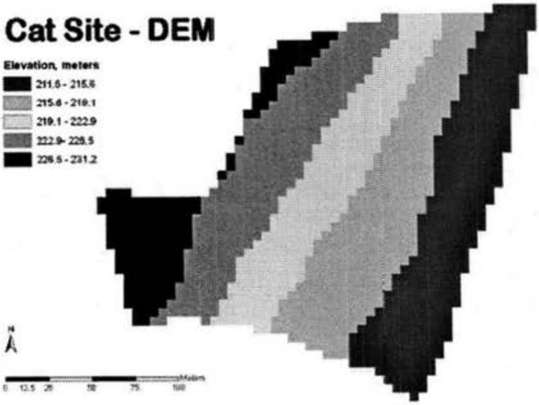


Figure 7. Generated digital elevation model for test site.

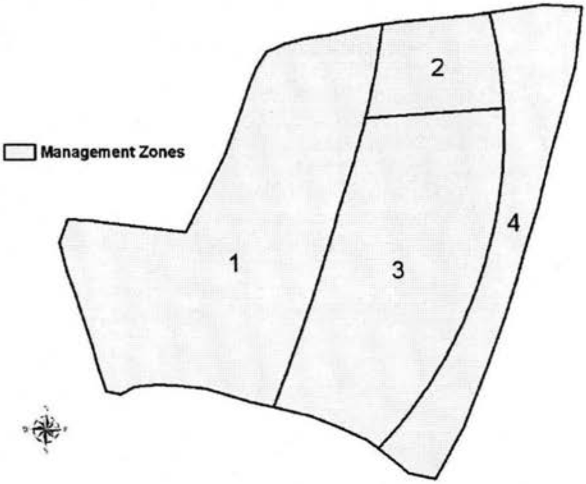


Figure 8. Proposed management zones for test site.

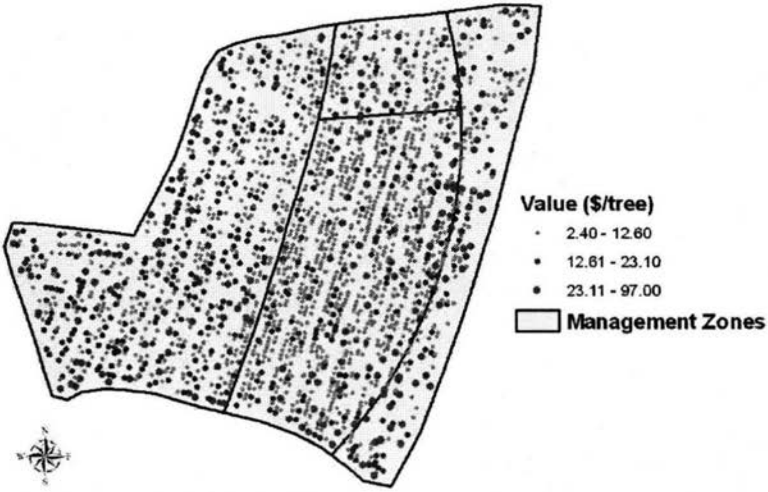


Figure 9. Generated value map (US dollars) overlaid onto the proposed management zone layer.

Figure 6 depicts the basic map of tree size and tree location. This map is indicative of what would be collected during a final harvest using a feller buncher equipped with a diameter sensing systems in a cut-to-length system. Figure 7 is a plot of the digital elevation model (DEM) generated for the site. The DEM shows how the terrain slopes downward when panning from left to right on the map. Along the right edge of the tract, the area starts to level out into a flood plane where a stream exists several meters away from the tract boundary. One can tell that the tree DHBs significantly differ within this area (Figure 6) and it could be considered as a unique zone to manage differently from other areas of the tract. Examination of the "yield map" in Figure 6 shows that other zones exist where tree size and density is distinctly different while these regions also vary with elevation changes. These differences in tree size and density may be related to soil fertility and soil moisture variability when moving down the slope. The map also reveals evidence of a previous fifth row thinning. After examining the yield map, one could segregate the tract into four different management zones based on the characteristics of the timber in each zone (Figure 8). Future decisions on thinning or final harvest may be varied now based on these management zones. More importantly, if this was information collected at the final harvest, it could be combined with other soil type and fertility maps to plan for the subsequent stand establishment which could be enhanced having this type of spatial data available at one's finger tips. One of the final output products of such a map is a value map (Figure 9). This map depicts how tree value varied across the tract. It also indicated that the overall total value of the stand is estimated at $ 28 034 USD. Table 1 provides details of area, density, basal area, and total value per zone for this tract. Providing site-specific data like these can assist landowners make more informed site-specific management decisions to help maximize profit and achieve long term stand goals.

Table 1. Inventory and value data for yield mapping test site.

Management Zone	Zone Area (ha)	Trees per Zone	Tree Density (trees/ha)	Basal Area per Zone (m^2/ha)	Value per Zone (USD)
1	1.53	791	518	416	$ 11 597
2	0.29	166	580	75	$ 1 977
3	1.17	971	830	409	$ 10 196
4	0.61	229	375	135	$ 4 265
Total	**3.59**	**2157**	**599**	**-**	**$ 28 034**

SUMMARY

Precision forestry is a rapidly developing field finding many applications in the forest products industry. We define precision forestry as planning and conducting site-specific forest management activities and operations to improve wood product quality and utilization, reduce waste, increase profits, and maintain environmental quality. Precision forestry can be categorized into three main areas: 1) using geospatial-information to help make forest management and planning decisions; 2) conducting site-specific silvicultural operations; and 3) advanced site-specific technology to meet market demands for higher valued products.

Researchers and practitioners in the southeast U.S. are applying these geospatial based technologies in many different areas. Early work used GPS-based systems to study the performance and productivity of harvesting and site preparation machines. Currently, the most common use of precision forestry is in site-specific silvicultural operations such as herbicide spraying and fertilizer application. New systems for GPS-assisted manual spraying and planting are increasingly being used for certification of services provided by contractors and compliance with environmental and labor regulations. Finally researchers are developing the concepts of yield mapping to help land managers make more site-specific management decisions to improve growth, yield, and ultimately profit. We see precision forestry continuing to advance in the southeast U.S. providing technologies and management systems to improve the productivity and efficiency of the forest products industry.

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COMPARISON OF DEM RESOLUTION FOR FOREST ROAD DESIGN WITH SOIL SEDIMENT EVALUATION

Kazuhiro Aruga[1], John Sessions[2] and Edwin S. Miyata[3]
[1]Department of Forest Science, Utsunomiya University, Japan
[2]Department of Forest Engineering, Oregon State University, USA
[3]Department of Industrial Engineering, University of Washington, USA
E-mail: aruga@cc.utsunomiya-u.ac.jp

Abstract

Recently, LiDAR has been widely used for mapping terrains. We have developed a program for optimizing forest road alignment with 1.5x1.5m grid DEM generated from LiDAR data. This paper discusses effects of DEM resolution on forest road alignment optimization. We first compared cross sections and ground profiles generated from 1.5m, 1.8m, 3.0m, 4.5m, and 10m grid DEMs. Except for 10 m grid DEM, cross sections generated from other DEMs are similar to those measured by Total Station. However, only cross sections generated from 1.5m and 1.8m grid DEMs showed the forest road template. When using DEM for forest road alignment optimization, total costs and soil sediments using 4.5m grid DEM are similar to those using 1.5m grid DEM. Although 4.5m grid DEM did not show the micro topography, it shows the relatively accurate ground profile and the program optimized forest road alignments based on the ground profile.

Keywords: Forest road design, Tabu Search, DEM resolution, LiDAR, vertical accuracy

Introduction

LiDAR is a remote sensing technology that is increasingly being used to map forested terrains. LiDAR has the ability to measure elevations more accurately than pre-existing mapping techniques and to create good quality terrain maps due to its small diameter laser beam footprint, even under forest canopy. Recently, there have been several studies to optimize forest road design using high resolution DEMs derived from LiDAR (Chung *et al.* 2004, Coulter *et al.* 2002, Akay 2003).

Aruga *et al.* (2004) have developed a program for optimizing horizontal and vertical alignments of forest roads with a high resolution DEM using Tabu Search, one of the modern heuristic techniques (Glover 1989). The application of the program indicated that the program successfully found better alignments than manually selected initial alignments. However, the accuracy of generating ground profile and forest road alignments depends on resolution and accuracy of DEM. Low quality of DEM causes less accuracy of generated ground profile and forest road alignments. Low quality data would not produce useful and satisfying solutions. On the other hand, cost of high quality DEM is higher than that of low quality DEM. Therefore, this paper compares the vertical accuracy of DEMs on forest roads and discusses forest road design generated by the program using DEMs.

Methods and Materials

Model

Once a series of IPs (intersection points) are selected manually, the program generates alternative horizontal and vertical alignments (Figure 1). The program precisely generates ground profile and cross sections using a high resolution DEM derived from LiDAR. It accurately calculates earthwork volumes for curved roadways using the Pappus-based method (Easa 2003). The program estimates construction and maintenance costs using the USDA Forest Service Region 6 Cost Estimating Guide (1999). The program also estimates total soil sediment delivered to streams using the "Standard methodology for conducting watershed analysis" manual (Washington State 1997). Tabu Search optimizes forest road alignments based on the total costs (Aruga *et al.* 2005).

Study Site and Data

The study site was a part of Capitol State Forest in Washington State. The site was covered by 70-year-old coniferous forests such as Douglas-fir, western hemlock, and redcedar. Dominant tree height was approximately 50 m. As part of a forest management study, the canopy of the 70-year-old forest stands was partially harvested in 1998. As a result, four different residual canopy density classes, which included clear cut areas: 0 tree/ha, heavily thinned areas: 88 trees/ha, lightly thinned areas: 385 trees/ha, and uncut areas: 616 trees/ha, were made (Figure 2).

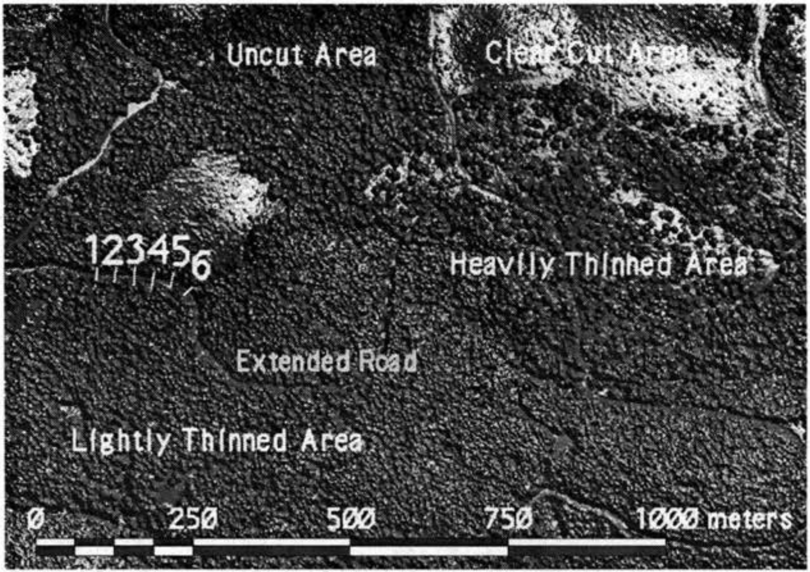

Figure 2 Shading map of Digital Surface Model generated from LiDAR data in 2002 (numbers indicate Total Station survey points).

This site was measured by a small footprint LiDAR system in the spring of 1999 and the LiDAR data was converted into a 1.52x1.52 m grid DEM and 4.56x4.56 m grid DEM (Reutebuch *et al.* 2003, Table 1, Figure 3, 4). Reutebuch *et al.* (2003) compared the vertical accuracy of 1.5 m grid DEM with 348 points surveyed by Total Station. Because the LiDAR data was converted into a 1.5 m grid DEM, a bilinear interpolation was applied to compute the elevation at the horizontal position of each survey checkpoint. As a result, the root-mean-square error was 0.43 m.

Table 1 Flight parameters and scanning system setting in 1999.

Flying height	200 m
Flying speed	90 km/h
Scanning swath width	70 m
Forward tilt	8 degrees
Footprint diameter	40 cm
Laser pulse density	4 pulses/m^2
Laser pulse rate	7 000 points/sec

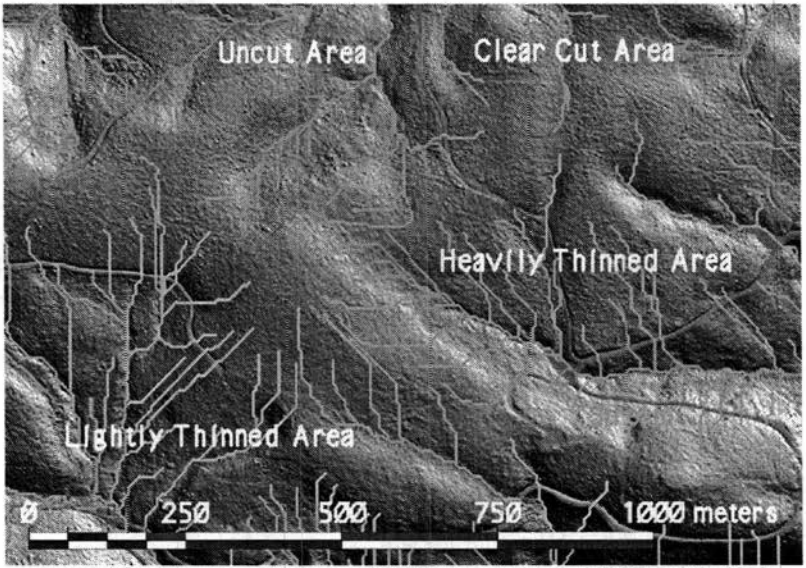

Figure 3 Shading map of 1.5 m grid DEM generated from LiDAR data in 1999.

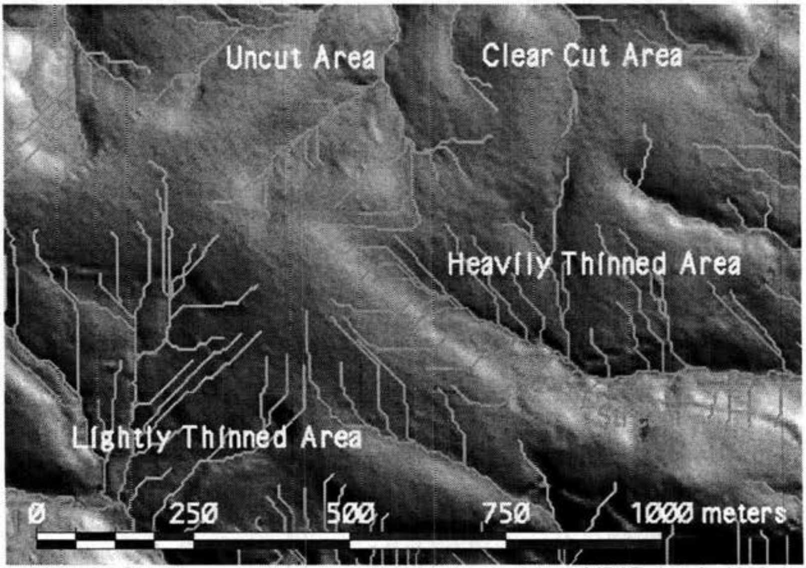

Figure 4 Shading map of 4.5 m grid DEM generated from LiDAR data in 1999.

In addition, 1.83x1.83 m grid DEM was obtained from Puget Sound LiDAR Consortium (PSLC, Table 2, Figure 5). 1/9 arc second (3.43x2.35 m) and 1/3 arc second (10.36x7.08 m) grid DEMs were obtained from National Elevation Dataset (NED) developed by the U.S. Geological Survey (USGS, Figure 6 and 7). PSLC measured the site by LiDAR system in 2002 (Table 2). PSLC indicated that the vertical accuracy is 30 cm or less on flat open surfaces although a small sample of points is evaluated. Since PSLC is supported by USGS and so on, PSLC provides LiDAR dataset to USGS. USGS converts them to 1/9 arc second grid DEMs and includes them in NED. The vertical accuracy of 1/9 arc second grid DEM is 41 cm or less on flat open surfaces although a small sample of points is evaluated.

Table 2 Flight parameters and scanning system setting in 2002.

Flying height	1 000 m
Scanning swath width	650 m
Footprint diameter	90 cm
Laser pulse density	1 pulses/m^2
Laser pulse rate	30 000 points/sec

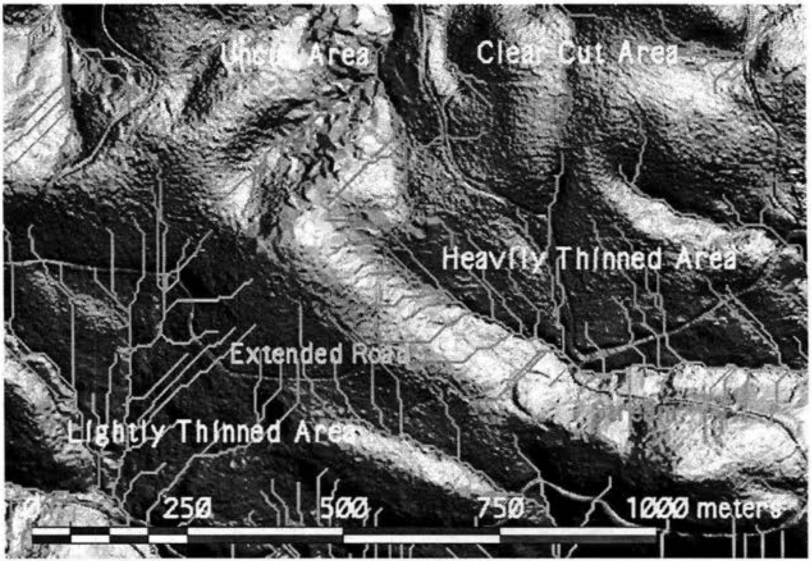

Figure 5 Shading map of 1.8 m grid DEM generated from LiDAR data in 2002.

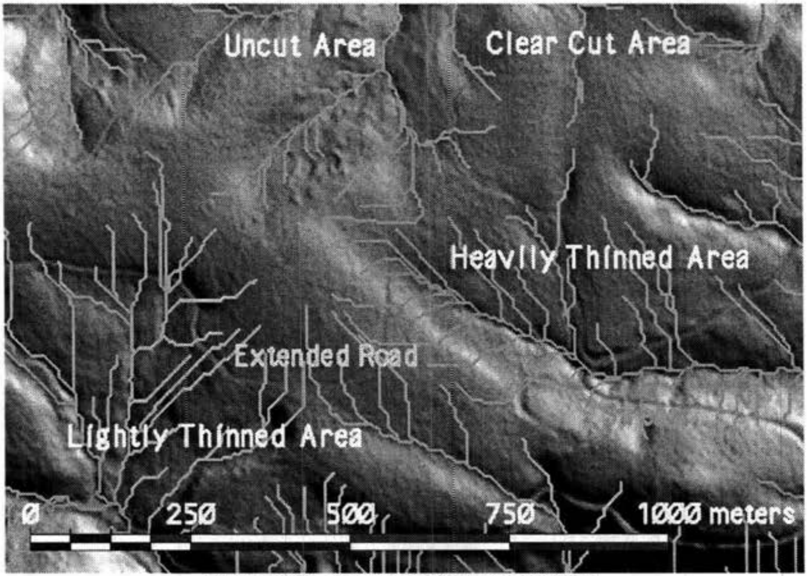

Figure 6 Shading map of 3.0 m grid DEM.

After the study site was measured by LiDAR in 1999, the forest road was extended. We can see the extended road on the shading maps generated by LiDAR data in 2002 (Figure 2, 5 and 6). The extended road was located in lightly thinned areas, uncut areas, and heavily thinned areas (Figure 2). The IPs for the new model were decided along the extended road on a horizontal plane manually and the model generated an initial horizontal alignment based on geometrical constraints (Figure 8). Its length was 827 m, with 27 sections of 30 m. Ground heights along the horizontal alignment range between 340 m and 352 m (Figure 9). The average of ground slopes in Figure 8 is 9.8 degrees and its standard deviation is 5.3 degrees.

We first compared the vertical accuracy of cross sections on Line 1-6 (Figure 2) and ground profiles on the initial alignment (Figure 8, 9). 165 points on cross sections generated from 1.5 m, 1.8 m, 3.0 m, 4.5 m, and 10 m grid DEMs were compared with those measured by Total Station. Because we did not measure the actual ground profile, ground profiles generated from 4.5 m and 10 m grid DEMs were compared with that generated from 1.5 m grid DEM. Ground profile generated from 1.8 m and 3.0 m grid DEMs were not compared with others because it was measured after road construction.

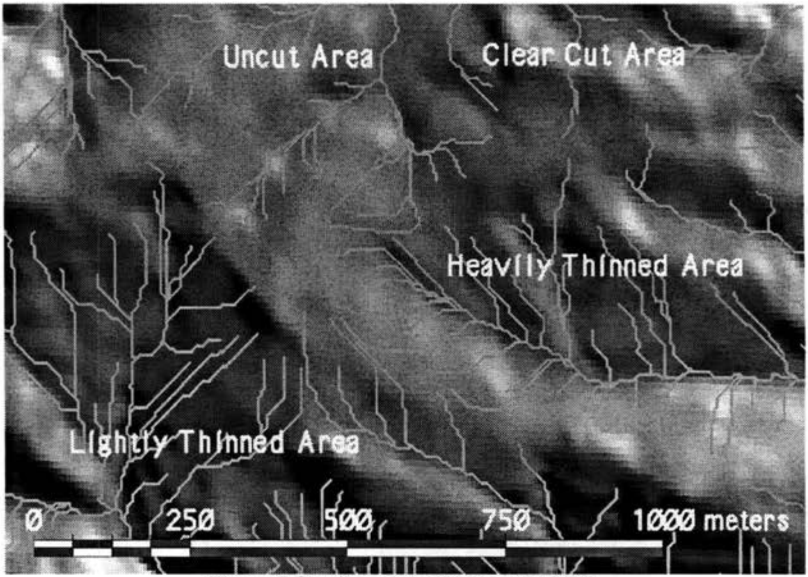

Figure 7 Shading map of 10 m grid DEM.

Figure 8 Forest road plane showing contour intervals, horizontal alignment, and 30-m road stations (= and = indicate an existing road and an extended road, respectively).

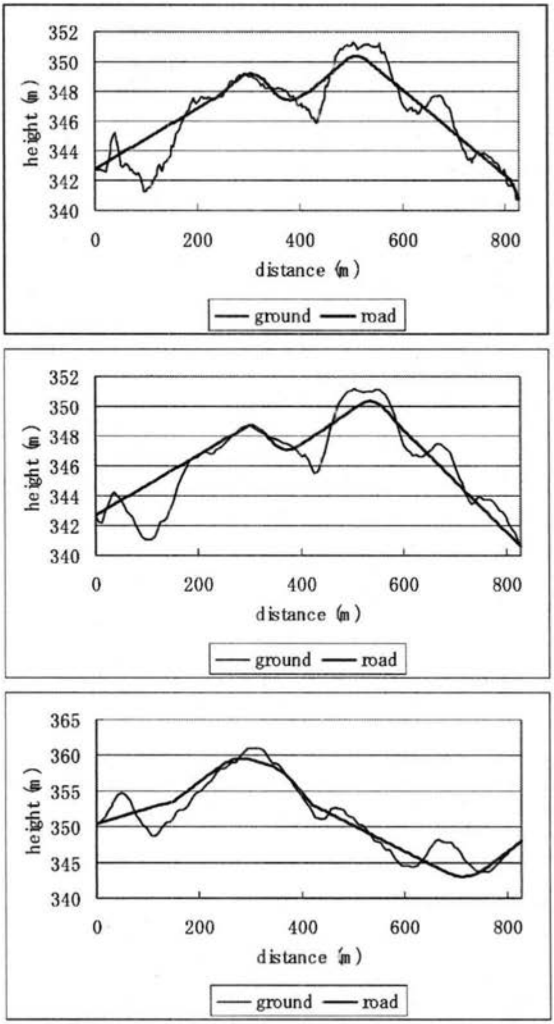

Figure 9 Forest road profile with five grade change points on the three initial alignments: 1.5 m, 4.5 m, and 10 m grid DEM.

Results and Discussion

Comparison of DEM resolution for cross section and ground profile

The cross section on Line 2 is shown in Figure 10 as an example. The cross section generated from 10 m grid DEM is quite different from other cross sections. The root-mean-square error of its difference from Total Station Survey is 7.32 m (Table 3). The root-mean-square errors of cross sections generated from 1.5 m, 1.8 m, 3.0 m, and 4.5 m grid DEMs are relatively small. Those are 0.14 m, 0.25 m, 1.12 m, and 0.70 m. However, we can see the forest road template on only the cross section generated from 1.5 m and 1.8 m grid DEMs (Figure 10). We cannot see the cut slope, road surface, and fill slope on other cross sections clearly. Therefore, we should use the same level of DEM with 1.5 m and 1.8 m grid DEMs in order to identify forest roads.

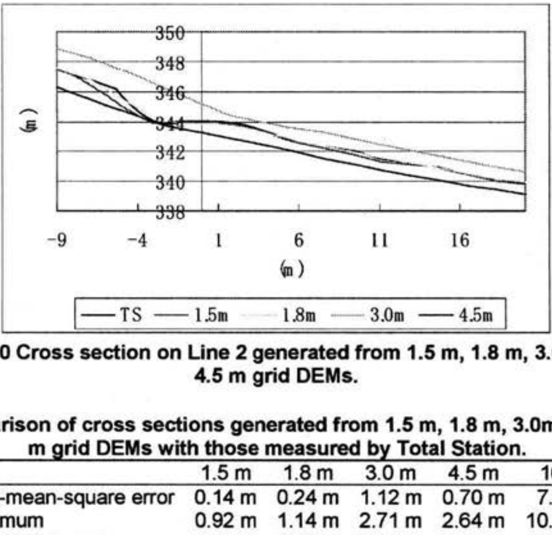

Figure 10 Cross section on Line 2 generated from 1.5 m, 1.8 m, 3.0 m, and 4.5 m grid DEMs.

Table 3 Comparison of cross sections generated from 1.5 m, 1.8 m, 3.0m, 4.5 m, and 10 m grid DEMs with those measured by Total Station.

	1.5 m	1.8 m	3.0 m	4.5 m	10 m
Root-mean-square error	0.14 m	0.24 m	1.12 m	0.70 m	7.32 m
Maximum	0.92 m	1.14 m	2.71 m	2.64 m	10.65 m
Standard deviation	0.11 m	0.19 m	0.65 m	0.43 m	1.38 m

Then, we compared DEM resolution for ground profiles on the initial horizontal alignment. Similarly, the ground profile generated from 10 m grid DEM is quite different from other ground profiles (Figure 9). The root-mean-square error of its difference from the ground profile generated from 1.5 m grid DEM is 5.70 m (Table 4). The root-mean-square error of the ground profile generated from 4.5 m grid DEM is 0.37 m. The ground profile generated from 4.5 m grid DEM is similar to that generated from 1.5 m grid DEM (Figure 9). Although we cannot identify micro topography with 4.5 m grid DEM, it is much more accurate topography than 10 m grid DEM.

Table 4 Comparison of ground profiles generated from 4.5 m and 10 m grid DEMs with 1.5 m grid DEM.

	4.5 m	10 m
Root-mean-square error	0.34 m	5.70 m
Maximum	0.92 m	12.34 m
Standard deviation	0.23 m	3.86 m

Comparison of DEM resolution for forest road alignment optimization

We first compared total unit costs and total soil sediments with five grade change points on the initial alignments (Table 5). Total unit costs and soil sediments using 4.5 m grid DEM are similar to those using 1.5 m grid DEM because the program generated the similar vertical alignments on the similar ground profiles with 1.5 m and 4.5 m grid DEMs (Figure 9). According to 10 m grid DEM, total unit cost was a little larger than those with 1.5 m and 4.5 m grid DEMs. However, total soil sediment was double of those with 1.5 m and 4.5 m grid DEMs. Moreover, the vertical alignment is quite different from those with 1.5 m and 4.5 m grid DEMs because the ground profile is quite different from those with 1.5 m and 4.5 m grid DEMs.

Table 5 Costs ($/m) and total soil sediment delivered to streams (ton/year) with five grade change points on the initial alignments generated 1.5 m, 4.5 m, and 10 m grid DEM.

Element	Sub element	1.5 m	4.5 m	10 m
Staking		1.06	1.05	1.05
Clearing and Grubbing		8.29	8.38	8.69
Earthwork allocation		16.01	18.29	21.46
Surfacing	Base course	12.60	12.59	12.59
	Traction surface	5.81	5.81	5.80
Watering	Excavation	1.99	2.25	2.34
	Surfacing	3.66	3.66	3.66
Seeding and Mulching		0.71	0.73	0.83
Drainage and Riprap	Culvert	2.90	2.70	1.75
	Riprap	0.04	0.05	0.04
Maintenance		8.35	8.46	8.25
Total unit cost		61.42	63.97	66.46
Total soil sediment		0.452	0.439	1.076

Simultaneous optimization of horizontal and vertical alignment has been shown to successfully reduce total construction costs with 1.5 m grid DEM (Aruga et al. 2004). Similarly, Tabu Search with seven grade change points found the best solution in each of the two other DEMs. Unit construction and maintenance costs were reduced to 79.3%, 71.1%, and 69.5% of unit costs of the initial alignment with 1.5 m, 4.5 m, and 10 m grid DEMs, respectively (Table 6). These reductions occurred due to earthwork allocation cost reduction. The amounts of materials moved from borrow areas were 2 573.25 m^3 with 1.5 m grid DEM, 3 143.76 m^3 with 4.5 m grid DEM, and 541.69 m^3 with 10 m grid DEM, respectively. On the other hand, after optimization, the amounts of materials moved from borrow areas were negligible; 1.75 m^3 with 1.5 m grid DEM, 4.24 m^3 with 4.5 m grid DEM, and 5.51 m^3 with 10 m grid DEM, respectively. Optimized horizontal alignments generated smoother ground profiles and the model could generate vertical alignments that more closely followed ground profiles (Figure 11). Therefore, optimization of horizontal alignments successfully balanced cut and fill volumes and reduced earthwork costs. However, soil sediment on the optimized horizontal alignment increased by about double on the initial alignment (Table 6). These increases occurred due to steeper gradients. Therefore, we should optimize forest road alignments considering total costs as well as soil sediments.

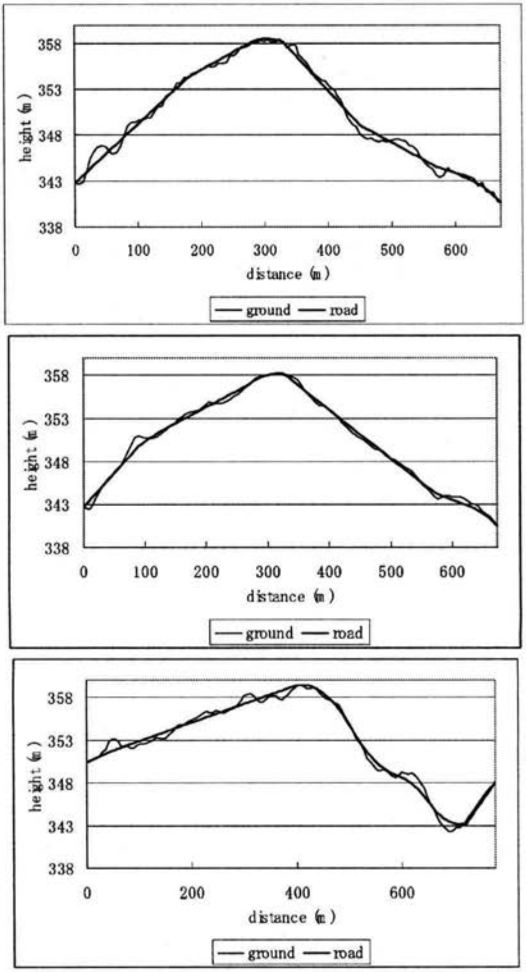

Figure 11 Forest road profile with seven grade change points on the three optimized alignments: 1.5 m, 4.5 m, and 10 m grid DEM.

Table 6 Costs ($/m) and total soil sediment delivered to streams (ton/year) with seven grade change points on the optimized alignments generated 1.5 m, 4.5 m, and 10 m grid DEM.

Element	Sub element	1.5 m	4.5 m	10 m
Staking		1.07	1.06	1.05
Clearing and Grubbing		7.89	7.64	7.40
Earthwork allocation		6.51	5.10	5.77
Surfacing	Base course	12.18	11.90	11.60
	Traction surface	5.61	5.47	5.33
Watering	Excavation	0.78	0.61	0.69
	Surfacing	3.54	3.45	3.37
Seeding and Mulching		0.67	0.65	0.63
Drainage and Riprap	Culvert	2.24	1.48	2.37
	Riprap	0.04	0.03	0.04
Maintenance		8.21	8.08	7.97
Total unit cost		48.74	45.47	46.22
Road length (m)		670	671	776
Total cost ($)		32 701	30 554	35 885
Total soil sediment		1.053	1.157	0.651

Lastly, we compared DEM resolution for horizontal and vertical alignments (Figure 8, 11). The horizontal alignment generated from 10 m grid DEM was quite different from those generated 1.5 m and 4.5 m grid DEMs. Subsequently, the vertical alignment generated from 10 m grid DEM was quite different from those generated 1.5 m and 4.5 m grid DEMs. Although the number of our application was small, we concluded that we could use 1.5 m and 4.5 m grid DEMs for forest road alignment optimization.

Conclusions

In this study, we first compared cross sections and ground profiles generated from five different sizes of grid DEM. Except for 10 m grid DEM, cross sections generated from other DEMs are similar to those measured by Total Station. However, only cross sections generated from 1.5 m and 1.8 m grid DEMs showed the forest road template. Therefore, if we need to identify forest road or micro topography, we should use the same level of or more accurate DEM than 1.5 m and 1.8 m grid DEMs. When using DEM for forest road alignment optimization, total costs and soil sediments using 4.5 m grid DEM are similar to those using 1.5 m grid DEM. Although 4.5 m grid DEM did not show the micro topography, it shows the relatively accurate ground profile and the program optimized forest road alignments based on the ground profile.

We used 1.5 m grid DEM measured by helicopter which could measure the ground profile more precisely than by airplane due to its slower speed. However, its measurement cost per unit area was higher. Therefore, we could use 4.5 m grid DEM for forest road alignment optimization cost-effectively. 4.5 m grid DEM used in this study was created from LiDAR data measured by helicopter due to its measurement year in 1999. Now, new LiDAR equipment has been developed. It can emit more laser pulses than pre-existing LiDAR equipment. Therefore, an airplane with new LiDAR equipment can measure ground profiles more precisely than 4.5 m grid DEM used in this study which was created by helicopter with pre-existing LiDAR equipment. This makes it possible to reduce the cost of LiDAR measurement and to increase the availability of LiDAR data.

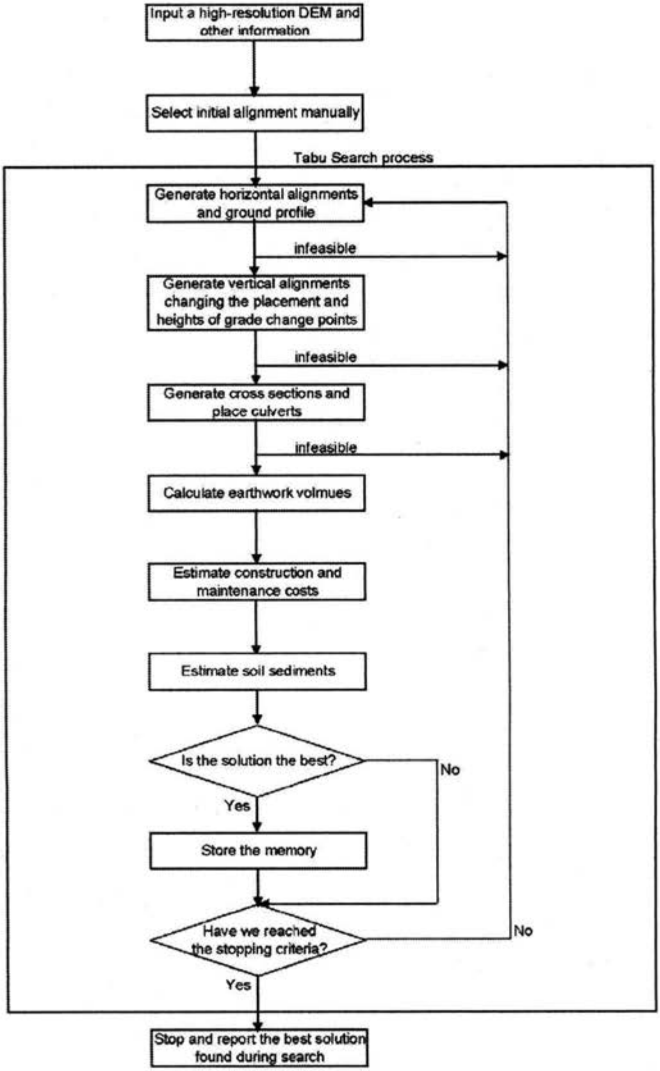

Figure 1 Flowchart of the model.

Acknowledgement
LiDAR data in 1999 were provided by the USDA Forest Service, PNW Research Station, Resource Management and Productivity Program. LiDAR data in 2002 were provided by Puget Sound LiDAR Consortium (PSLC). 3 m and 10 m grid DEMs were provided by USGS, EROS Data center. We express our appreciation to the Washington State Department of Natural Resources for letting us use the study site in Capitol Forest.

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HIGH-END GPS vs. LOW-END GPS: COMPARING GPS POSITIONAL ACCURACY IN THE FOREST ENVIRONMENT

Tetsuhiko Yoshimura, Mitsuhiro Nose and Tetsuro Sakai
Graduate School of Informatics, Kyoto University, Japan
E-mail: yoshimu@bre.soc.i.kyoto-u.ac.jp

Abstract

It is known that high-end GPS receivers work well even under adverse conditions, but their cost is definitely a hurdle for forest owners and managers. To make more use of low-end GPS receivers in the forest environment, we proposed three methods, i.e., use of a height-adjustable GPS antenna pole, filtering out GPS data of low quality and differential correction of carrier phase data. We used Pathfinder Pro XR and Blue Logger GPS as high-end and low-end GPS receivers, respectively, and compared the performance of these GPS receivers in the forest environment. As a result, positional errors of Blue Logger GPS were larger than those of Pathfinder Pro XR. However, they were improved by raising a GPS antenna of Blue Logger GPS over forest canopy. It was also found that neither filtering nor carrier phase data always improved precision and accuracy errors of Blue Logger GPS.

Keywords: positional accuracy, forest canopy, GPS

Introduction

We know that GPS receivers cost only 100-500 USD while high-end ones often cost more than 3,000 USD or more. It is known that performance of high-end GPS receivers is high even under adverse conditions, but their cost is definitely a hurdle for forest owners and managers in Japan, who are struggling with the difficult market environment. To make more use of low-end GPS receivers in the forest environment, we proposed three methods, i.e., use of a height-adjustable GPS antenna pole, filtering out GPS data of low quality and differential correction of carrier phase data. In this study, we compared the performance of high-end (or high-cost) and low-end GPS (or low-cost) receivers through field experiments under different canopy conditions.

It is well known that forest canopy adversely affects GPS positional accuracy due to signal attenuation when GPS is used inside forests. Many studies have been conducted to determine the performance of GPS positional accuracy under different canopy conditions. Mori and Takeda (2000) showed the effects of SA removal on positional accuracy of the DGPS. Martin et al. (2001) evaluated DGPS positional accuracy and precision on Irish forest roads with typical peripheral canopies and discussed the relationship between position dilution of precision (PDOP) and the percentage of open sky. This study also showed that both DGPS accuracy and precision improved with decreasing peripheral obstruction. Sawaguchi et al. (2001) discussed the effect of stand conditions on positioning precision with real-time DGPS and found factors that affected positional precision by using multiple regression analysis. However, these studies have not shown any proactive methods of improving accuracy of GPS positioning.

There are some existing studies in which a GPS antenna was raised up to 4.0-4.2 m. D'Eon (1996) concluded that GPS positions obtained within 5 min under mixed forest canopies were better at an antenna height of 4 m than at an antenna height of 2 m, and also pointed out that raising the antenna completely above the canopy would be ideal, but was not operationally practical in situations where the canopy is 10 m or higher. Gandaseca et al. (2001) also tried to improve the accuracy of GPS positioning by increasing GPS antenna height up to 4.2 m. The results showed that there was slight improvement in GPS positional accuracy. As for differential correction of carrier phase data, Næsset (1999) showed that the accuracy of GPS positioning was significantly higher with the 12-channel GPS receiver than with the 6-channel GPS receiver and was significantly higher with the combined use of the C/A code and carrier phase than with the use of the C/A code only. Kobayashi et al. (2001) evaluated five GPS receivers' performance by comparing the positional accuracy of the autonomous GPS, real-time DGPS and carrier phase GPS. Results indicated that the autonomous GPS, real-time DGPS and carrier phase GPS produced positional errors of 15.4–48.6, 1.1–7.3 and 0.1-5.1 m, respectively, which were based on the condition that SA was on.

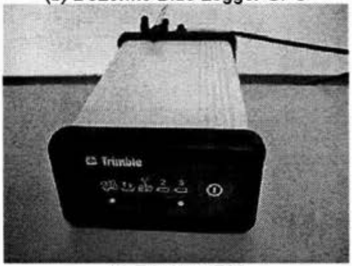
Materials and methods

We conducted field experiments inside the forest of the Kamigamo Experimental Station, Field Science Education and Research Center, Kyoto University on October 30, November 1, 3 and 4, 2005 to determine GPS positional accuracy under different canopy conditions. The GPS receivers used in this study were

Trimble Pathfinder Pro XR (Figure 1(a)) and DeLorme Blue Logger GPS (Figure 1(b)) for rovers and Trimble 4700 (Figure 1(c)) for the base station.

(a) Trimble Pathfinder Pro XR

(b) DeLorme Blue Logger GPS



(c) Trimble 4700

Figure 1. GPS receivers used in this study.

Pathfinder Pro XR is a high-end GPS receiver for mapping and GIS data collection, and widely used for research and field work in the forest environment. It has multipath rejection technology called EVEREST that was reported to work well in the forest environment (Tachiki et al, 2005). Blue Logger GPS is a low-end GPS receiver for navigation and recreation. It is equipped with Bluetooth that enables wireless communication with a controller, that is, laptop computer or PDA. Besides Bluetooth communication, one of the most notable features of this receiver is its capability of data collection of L1 carrier phase, which can be differentially corrected by DeLorme GPS PostPro 2.0 software. On the other hand, 4700 is a high-end GPS receiver for professional surveying, and is being operated as a CORS (continuous operating reference station) in the campus of Kyoto

University, which was about 5 km away from the two observation points in the Kamigamo Experimental Station. The rovers were set up at two points, that is, A5 and K2, inside the forest during field experiments. A5 was located on a forest road, and surrounded by natural forest stands consisting of Japanese cypress (*Chamaecyparis obtusa*) and broad-leaved species with a thick shrub layer. K2 was located at the top of the hill inside the forest with few trees around it. Figure 2 shows fisheye photos taken at these points using NIKON E4500 with a fisheye converter (NIKON FC-E8).

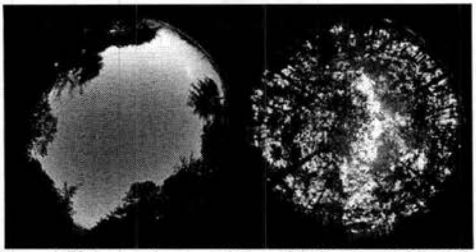


Figure 2 Fisheye photos taken at K2 (left) and A5 (right).

At each point, GPS measurements were conducted for 2 hours 14 minutes with an antenna height of 2 and 12 m. In order to set up a GPS antenna at a height of 12 m, we experimentally produced a height-adjustable GPS antenna pole (max. 15m), which was made of carbon to reduce its weight and to enhance its portability. We raised a GPS antenna over forest canopy to change a positional relationship between a GPS antenna and forest canopy (Figure 3). The settings of the GPS receivers used in this study are shown in Table 1. The default settings were used for DeLorme Blue Logger GPS because they were unchangeable by users. Table 2 shows the schedule of the field experiments. We started each GPS measurement four minutes earlier on the next day because the same constellation of GPS satellites appears four minutes earlier day by day. Figure 4 shows that there were always 8-10 available GPS satellites during field experiments. The weather was fine except on 3 November 2005 when it was cloudy with slight rain around 13:30 (JST).

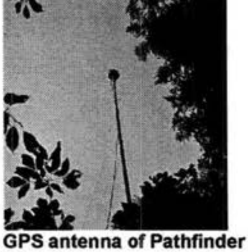


Figure 3. GPS antenna of Pathfinder Pro XR raised over forest canopy using the GPS antenna pole.

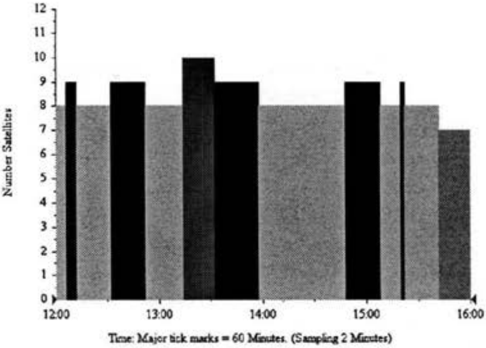


Figure 4. Available number of GPS satellites on 30 October 2005 with the elevation mask of 10 degrees.

Table 1. Receiver settings.

Type of GPS receiver	PDOP mask	SNR mask	Elevation mask (degree)	Logging interval (sec)
Pathfinder Pro XR	99	0	10	2
Blue Logger GPS	Unknown	Unknown	Unknown	2
4700	25	0	10	1

Table 2. Schedule of field experiments.

Date	Starting time (JST)	Ending time (JST)	Type of GPS receiver	GPS antenna height (m)	GPS observation point
30 OCT 2005	12:52:00	15:06:00	Pro XR	2	A5
			Blue Logger	12	K2
1 NOV 2005	12:44:00	14:58:00	Pro XR	2	K2
			Blue Logger	12	A5
3 NOV 2005	12:36:00	14:50:00	Pro XR	12	K2
			Blue Logger	2	A5
4 NOV 2005	12:32:00	14:46:00	Pro XR	12	A5
			Blue Logger	2	K2

JST, Japan Standard Time (UTC+9 hours).

In this study, horizontal positional errors were calculated and compared in terms of precision and accuracy. Accuracy refers to the closeness of the sample mean to the true value, and precision refers to the closeness of repeated observations to the sample mean (Leick 1995). We used the methods of calculation as shown in Yoshimura and Hasegawa (2003).

Results and discussion

All GPS data collected during the field experiments were differentially corrected by using Pathfinder Office 3.0 for Pathfinder Pro XR and GPS PostPro 2.0 for Blue Logger GPS.

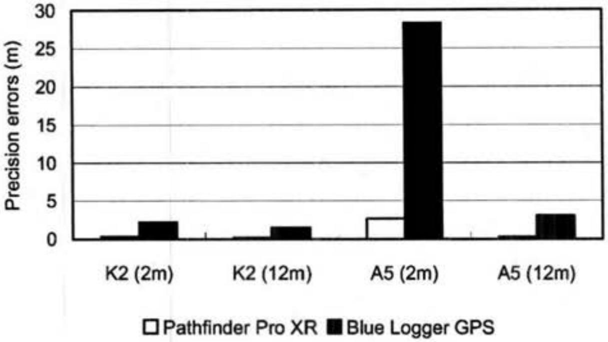


Figure 5. Comparison of precision errors among locations, antenna heights and types of GPS receivers.

Figure 5 compared precision errors among locations, antenna heights and types of GPS receivers. As shown, Pathfinder Pro XR produced better results than Blue Logger GPS in terms of precision errors. This result shows that multipath rejection technology of Pathfinder Pro XR worked well under forest canopy. On the other hand, precision errors were by far the largest (28.3 m) when Blue Logger GPS was used at A5 with antenna height of 2 m. This means that precision errors of Blue Logger GPS increased due to disturbance by forest canopy. It should be noted that precision errors of Blue Logger GPS were greatly improved at A5 when antenna height was raised to 12 m over forest canopy.

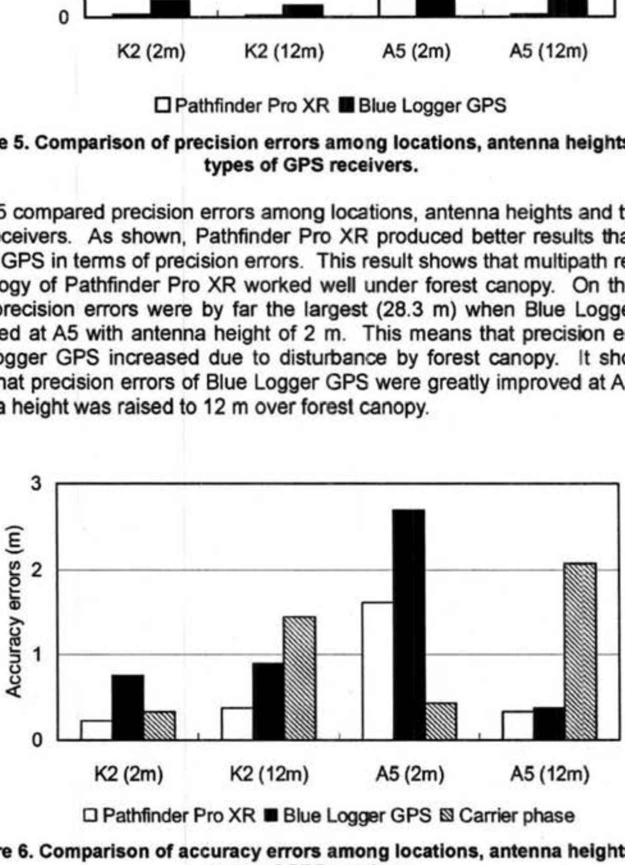


Figure 6. Comparison of accuracy errors among locations, antenna heights and types of GPS receivers.

Figure 6 compares accuracy errors among locations, antenna heights and types of GPS receivers. As shown, Pathfinder Pro XR produced better results than Blue Logger GPS in terms of accuracy errors as well as precision errors although accuracy errors of Pathfinder Pro XR were relatively larger (1.6 m) at A5 with antenna height of 2 m. On the other hand, accuracy precision errors were the largest (3.1 m) when Blue Logger GPS was used at A5 with antenna height of 2 m. As a result, accuracy errors increased due to disturbance by forest canopy, especially when Blue Logger GPS was used under forest canopy. However, it was also found that raising a GPS antenna over forest canopy by using the GPS antenna pole effectively reduced accuracy errors greatly.

In order to reduce large precision and accuracy errors when Blue Logger GPS was used at A5 with antenna height of 2 m, we tried to filter out GPS data of low quality. GPS PostPro 2.0 outputs indicators, in which green, yellow and red show good, questionable and bad data, respectively, and GPS data with yellow and red indicators were filtered out prior to precision and accuracy calculation. As a result, accuracy errors improved from 28.3 to 18.6 m. However, precision errors went slightly worse from 2.7 to 3.1 m. We also used carrier phase data of Blue Logger GPS for differential correction. As shown in Figure 6, carrier phase data did not always improve accuracy errors of Blue Logger GPS.

Conclusions

We tried to achieve the precision and accuracy of a high-end GPS receiver (Pathfinder Pro XR) by using a low-end GPS receiver (Blue Logger GPS). Through field experiments, it was found that precision and accuracy errors of Blue Logger GPS were larger than those of Pathfinder Pro XR, especially under forest canopy. Then, we used a GPS antenna pole to raise a GPS antenna up to 12 m to change a positional relationship between a GPS antenna and forest canopy. The result showed that precision and accuracy errors of Blue Logger GPS were improved to the same level as Pathfinder Pro XR. Furthermore, we filtered out GPS data of low quality based on indicators of GPS PostPro 2.0, but this filtering did not fully improve precision and accuracy errors of Blue Logger GPS when it was used under forest canopy. It was also found that carrier phase data did not always improve accuracy errors of Blue Logger GPS. In conclusion, Blue Logger GPS achieved the same level of precision and accuracy errors as Pathfinder Pro XR only by using the GPS antenna pole that raised a GPS antenna over forest canopy.

Acknowledgement

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A MODEL FOR EVALUATING FOREST ROAD LOAD BY FOREST OPERATIONS

Janez Krč
Department of Forestry and Renewable Forest Resources, University of Ljubljana, Slovenia
E-mail: janez.krc@bf.uni-lj.si

Abstract

In this paper, a simulation algorithm for determining gravity fields (skidding and hauling units linked to specific forest road or its sections) used in forest operations planning is presented and applied. We developed a procedure for identifying ridge points using Digital Elevation Model (DEM) data. Ridge points contribute to the accuracy of gravity field delineation. The procedure uses GIS data in raster format and the terrain friction, which is determined from micro-topography and forest stand conditions, to determine wood flow impact zones on forest roads. We used IDRISI GIS software with the ALLOCATE module, which assigns each raster cell to the nearest designated feature – in our case, a forest road section. For each raster cell, the shortest distance to the forest road is chosen. Different types of terrain friction may also influence the distance. The ridges designate points with a high friction value that can impede the movement (skidding) of timber. Data on the size and location of gravity fields can be used in a sample calculation of timber transport load for the forest road. The transport load exerted upon the forest road network by transportation and skidding was calculated from data on planned wood extraction volumes. The forest road transport load data can be used in assessing forest openness, costs of road maintenance, required road construction quality, and other factors related to forest operations.

Key words: load of forest road, gravity fields, forest operations, GIS, wood skidding

Introduction

Forest planning considers a number of factors related to work organization. A viable, efficient and rational plan of forest operations, however, is closely connected to the availability of relevant data affecting the working process (felling, skidding, hauling of wood). In this respect, data on the terrain and its accessibility is of particular importance. Forest road network is a crucial element of road infrastructure as it represents the backbone to which the system of secondary and tertiary roads is linked (tractor skid trails and cable lines). The system of roads is also an important factor in determining impact zones or gravity fields which serve as an indicator of the selection the most suitable methode of felling and transportation of wood from forests. Gravity field data can be used as the basis for creating a timeframe for the operational plan, which in addition to covering the technical, technological, personnel, ecological, safety and economic aspects of forest operation also deals with the need for additional opening up of forests with forest communication. Besides, public road infrastructure strongly affects location of forest roads, selection of skidding method used and the forest operation (Krč 1999, Krajčič 1996).

Therefore, the objective of the research was to assess the forest road load imposed by timber harvesting operations. First, DEM and forestry GIS data was analyzed. As planned, GIS database contains forest road data, including the productive and connecting road section lengths, road elements, structures and signalization systems (Beguš 2002). The research, conducted with the use of spatial analysis tools, produced some of original algorithms. Impact zones for certain forest road sections were derived from terrain characteristics, primarily terrain friction affecting timber skidding to forest roads. In most cases, ridge points were used to delineate gravity fields of individual forest roads. Ridge points were determined with a programme which analyses DEM data and classifies it according to location (ridge point, non-ridge point). Ridge point extraction led to an improvement in the precision of gravity field delineation and, consequently, helped form a basis for distributing planned wood cut quantities among forest roads. Forest road load data is required to ensure satisfactory preparation of work and organization of road maintenance activities and to provide an assessment of forest openness and road network density.

State-of-the-art methods

The problem of identifying water catchment areas is not of recent origin – numerous authors have presented and described algorithms and/or software tools for extracting topographic structures and water catchment areas from DEM data (Jenson and Dominguem 1988, Mark 1983). The results generated by these modules have been and are still being used in many scientific fields: agriculture (Ahamed et al. 2002), hydrology (Voinov et al. 1999) and forestry (Zhu et al. 2003). Research often focuses on optimization and localization of habitats for endangered animal and plant species. Even more popular are studies into the impacts of forest management (tree felling) on erosion, ecohydrology and development of individual tree species (Wattenbach et al. 2005).

Similar issues are also addressed by research projects dealing with road network density, location of roads in the environment (Newnham 1995, Tucek 1995, Yoshimura 1997) and the choice of skidding (mainly tractor skidding and cable yarding) (Tucek 1999). We did not find research so far which would focus on the issue of forest road load or study models predicting the system of forest road usage for timber harvesting operations.

Input data

The selection of data used to determine the load exerted upon forest roads by forest operations is adapted to the requirements of the task and data available in digital format. To perform an analysis into forest openness and forest road load, the following data is needed:

- Digital Elevation Model (DEM),
- vector database of forest roads,
- digitised and vector delineation of forest compartments,
- data on allowable cut by forest compartment or forest section,
- skidding direction (point of exit from analyzed area).

Digital Elevation Model of Slovenia (DEM 100) has been available for almost 20 years. It was created by digitizing and further interpolating elevation points in a 100 x 100 m grid. Topographic maps TTN 5 and TTN 10 were used as the basis for data collection. State-of-the-art techniques for generating a DEM grid of higher density are closely connected with photogrametric methods and radar interferometry. The state of Slovenia has also generated a Digital Elevation Model with a grid spacing 25x25m. For the purpose of the research presented in this paper, however, only DEM 100, interpolated on a 50x50m grid, was used.

Vector database of forest road network can be obtained by digitising topographic maps of different scales. State-of-the-art forest road mapping techniques explore the possibilities of combining digitized ortophoto and satellite navigation or GPS (KOPŠE/HOČEVAR 2001). Measurements have a position error which is more significant when the measurement is taken under the canopy of trees or vegetation, in the event of poor satellite constellation and if the period of measurement at individual points is short. Nevertheless, position error magnitude does not impose any serious limitations upon most types of forestry land use and has no significant effect on the accuracy of gravity field delineation.

Computer-aided spatial representation of allowable cut requires digitized delineation of individual forest sections which are the basic data support media in the forestry information system. The data needs to be in digital form. To that purpose, a vector polygon database is created that represents forest sections and is marked with a series of identification numbers. Section identification number must correspond with database information (in our case, forest survey data or forestry information system data) on the section concerned. If not, a transformation file is needed which contains a key to the connection.

Data on allowable cut volume and the scope of forest production was obtained from the forest management plans published in a digital collection of Forest Survey by Forest Section (Slovenian Forest Service). Annual allowable cut is set for a 10-year period. Consequently, we were only able to obtain aggregate data for a 10-year period covering forest road load and planned forest cutting volume. Data was presented in raster format, in a file of raster cells the value of which is equivalent to allowable cut per plot of a forest section represented by a raster cell. A raster cell of size 25x25m represents 1/16 ha of a section and 1/16 of allowable cut for that section per area unit (m^3/ha). Raster cells marking the forest section area bear uniform values that are equal to the quotient of growing stock per hectare and the share of the area represented by a raster cell in relation to 1 ha.

Gravity field extraction method

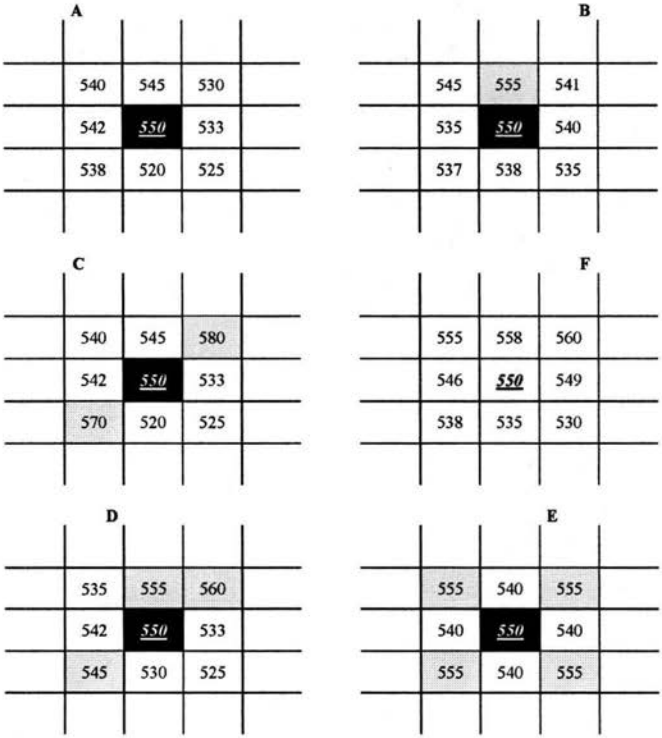
Determination of limitations in terrain openness

The gravity field of a certain forest road is primarily defined by the distance of certain points from the nearest road point. Potential barriers on the way to the roadside can have varying effects on log extraction. Influential factors to be considered are slope and terrain shape, ridges in particular. Often enough, ridges separate different gravity fields, forming timber skidding delineation lines. Timber skidding delineation lines are apparent lines which separate forest areas according to the direction of wood skidding to a particular forest road. For the research, extraction of ridge lines or ridge points was of utmost importance. As we would not settle for ridge point extraction results provided by GIS software packages (e.g. module TOPOSHAPE, Idrisi), we developed an original computer-aided algorithm for extraction of ridge points which analyses DEM data and assigns it with regard to the position of neighbouring points (Figure 1). A DEM point is classified as a ridge point if:

- All the neighbouring points are lower (Figure 1, Example A),
- any of the neighbouring points is higher than the point observed, yet all the other points are lower (Figure 1, Example B),
- only a pair of opposite neighbours is higher than the point observed, and all the other points are lower (Figure 1, Example C),
- points higher than the point observed take the shape of the letter S (Figure 1, Example D),
- points higher that the point observed take the shape of the letter Y (Figure 1, Example E).

If the point does not meet the above requirements, it cannot be extracted as a ridge point (Example F).

Extracted ridge points are listed in a new file. The data in the new file is made available for a visual presentation on a 2D or 3D elevation model (Figure 3) where the accuracy of ridge lines can be verified.



A

540	545	530
542	550	533
538	520	525

B

545	555	541
535	550	540
537	538	535

C

540	545	580
542	550	533
570	520	525

F

555	558	560
546	550	549
538	535	530

D

535	555	560
542	550	533
545	530	525

E

555	540	555
540	550	540
555	540	555

Figure 1: Decision-making steps in ridge point determination

The computer programme for ridge point determination uses Ms FoxPro environment and writes extracted ridge points in IDRISI vector-file format. The algorithm of program operation is presented in Figure 2. A pre-condition for successful operation of the programme is availability of DEM data in the format of an MS FoxPro data file which contains longitude, latitude and altitude fields (XYZ co-ordinates) for each DEM point. After that, the algorithm performs a serial verification of all DEM points, assigning them to the position of neighbouring points (relative height compared with the point concerned) into two classes (ridge point, non-ridge point).

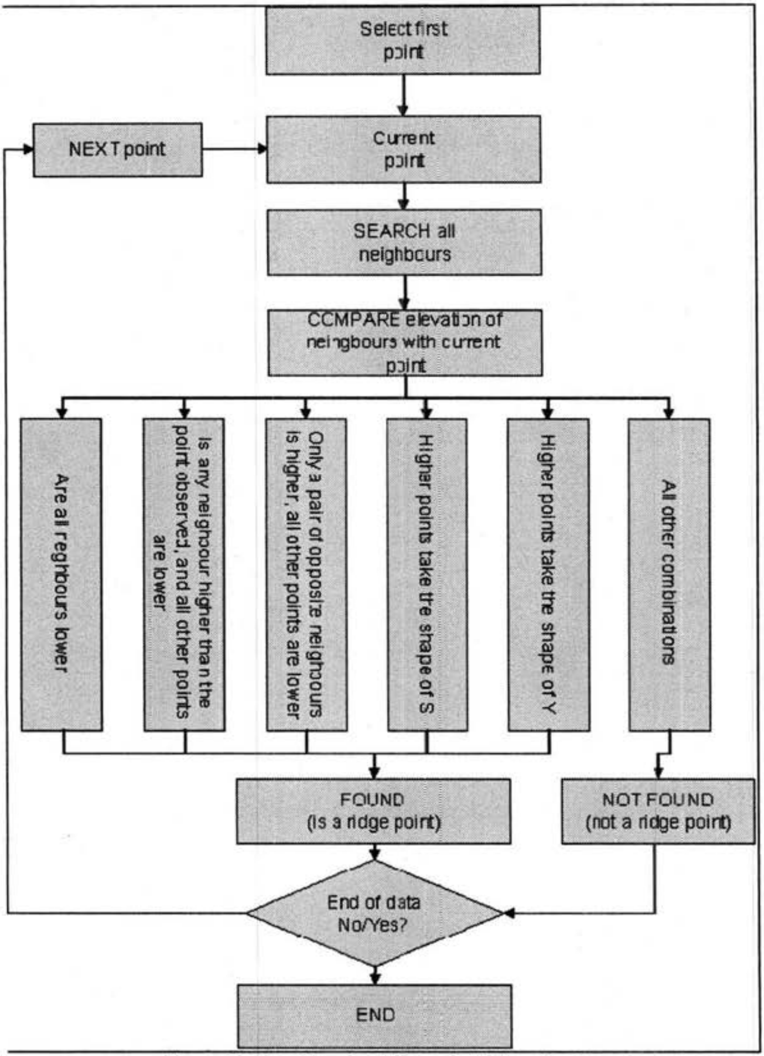


Figure 2: Algorithm for ridge point determination

Further steps in the procedure for determining the limitations which arise from wood skidding over certain terrain are closely connected with the use of tools for digital spatial data analysis. DEM data can also be used to calculate the slope of terrain, which is an important factor in evaluating potential skidding methods. Terrain slope data was derived by using the IDRISI module SURFACE, which calculates the terrain slope in % for each DEM raster cell.

Next, a raster file was created. Values assigned to the raster file present the force size or the energy created by friction in timber skidding over the terrain or terrain unit represented by a raster cell. In the given case, the force or energy produced was equated with a cost item which depends upon the friction to be overcome in timber skidding. Skidding costs were assumed to increase in line with terrain friction. Furthermore, a prediction was made that timber was transported from the felling site to the truck road along tractor skid trails and cable lines. Selection of the most appropriate traffic route (skid trail or cable line) depends on terrain characteristics and on the skidding distance and cost as well as suitability of various skidding methods regarding the ecological requirements of the forest. Initial minimum costs were defined (e.g. skidding over flat and smooth terrain). Taking account of the characteristics of the area and procedure (log skidding) concerned, raster cell multiples of the minimum cost were assigned for all raster cells in the area concerned. Terrain slope and extracted ridge points were used as influence factors affecting costs and skidding friction. It was assumed that skidding costs increase in line with terrain slope, as higher slope results in longer and costlier hauls or, consequently, in the decision to apply a costlier timber extraction method (cable yarding). Ridge points present a specific limitation in this respect. Skidding delineation lines commonly run along ridges and their identification in the terrain helps improve the accuracy and precision of the computer model for determining the gravity field(s) of a truck road. It was established that in comparison with terrain slope, ridge points represent extremely large friction valued at 20 times the value of 100% terrain slope. In this way, an indirect influence was imposed on the selection of a skid trail which should only exceptionally run over a ridge line or a series of extracted ridge points.

Road selection procedure for individual raster cells

In order to be able to select an appropriate forest road, we should have raster data form or an input file on forest roads and an input file on terrain characteristics affecting timber extraction.

The first step to provide the required data is to calculate weighted distances from the road to each raster cell. A pre-prepared file of terrain slopes with ridge points is used as weights on the route from raster cells to the roadside. These values are calculated with the DISTANCE module which creates a new raster file on the basis of the input forest road file and input slope-and-ridge file. In the new file, raster cells are assigned values that are equal to the sum of cell values in the slope & ridge file on the way from this cell to the nearest road or the road to which the sum of cells in the slope & ridge point file is the lowest.

Idrisi software module ALLOCATE is then used which creates a new file of the area, assigning new values to all raster cells. This value is identical to the value of the nearest destination, in our case, the identification value of a forest road. The road is selected with a previously created distance file. This procedure has provided a new classification of the forests and the terrain. The classification regards timber extraction, as the raster cells for which skidding distance had already been calculated were assigned the same identification value of road in the new file. The surface is divided into a number of spatial units that corresponds to the number of roads or forest sections that had been digitized to create the forest road file. Every unit represents the gravity field of a certain selected road (Figure 4).

Road load in timber harvesting

Calculations of mean 10-year forest road load in timber harvesting are derived from spatial data on the position of gravity fields and allowable cut data by forest section. Raster files have been prepared for both sets of data. The first file has been created in line with the described procedure of gravity field determination, and the second file has been created on the basis of input data on allowable cut per forest section, translated into a raster format. The IDRISI module EXTRACT allows the planner to combine statistical data from two input files, one of which is required for determining spatial data - feature definition file and the other represents the value pool for feature data. The first file is in our case called Gravity Field File, and the second file is Allowable Cut File. Instead of simply summarizing statistical data, data can be used to generate a spreadsheet that summarizes data by analyzed spatial unit.

Data is included in absolute quantities which can also be expressed in cubic meters of wood per a meter of a forest road. The procedure can be written as a programme that analyses road distances from the number of raster cells and raster file resolution and uses the data to calculate the load per meter of a forest road. This value only presents a partial load which results from felling operations conducted in the gravity field opened by a road section.

A road section, however, is not only affected by wood felled in its gravity field, but also with extraction of wood from gravity fields or areas located in the catchment area of the forest section. It is therefore crucial to determine the extraction section of a road network at the end of which there is a point over which all the wood is transported or all truck loaded with wood felled in the selected area supported by road network (Figure 5).

The position of this point (we shall call it EXIT) is recorded as the new data plane (raster file) where only the geographic position of the exit point is stated. The file is used in the procedure of adding up road load data per road section, which is best conducted by using the IDRISI module COSTGROW. The module adds up relative friction in complex examples (in our case, a forest road network), where absolute barriers (all surface outside roads) on the friction surface are assigned the value -1.

Thus acquired road load seems to increase from the point of exit towards the inside of the forest opened up by a road network. Absolute road load values can then be divided into several groups (as has been done in our case – see Table 1) or the mean road load is calculated by comparing the number of truck rides with its carrying capacity.

Results

Model testing site

A sample calculation of forest road loads resulting from timber harvesting operations has been conducted in the Forest Management Unit (FMU) Jelendol. The FMU Jelendol covers over 3,000 ha of forests growing on relatively steep slopes in the area of the Karavanke mountain range in the vicinity of the state border between Slovenia and Austria. The altitude in the FMU Jelendol ranges from 750 to 2065 m above sea level. In 1999, forest openness was measured at 23 m/ha. As for growing stock, conifers account for 80 % of the mean growing stock estimated at 311 m^3/ha.

Calculation of road network load following wood extraction for the FMU Jelendol

For the described case of the FMU Jelendol we have acquired the necessary input data to determine terrain openness as required by skidding. The main improvement of the procedure lies in the identification of ridge points, ensuring a higher degree of reliability of ridge point extraction for certain forest road sections.

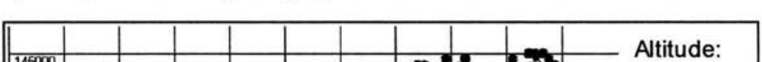


Figure 3: DEM (model base 100x100 m, interpolated on 50x50 m) for the FMU Jelendol with model-defined ridge points and forest road locations.

Figure 3 presents a raster file of elevation heights, that is the Digital Elevation Model. Its colour palette clearly indicates the topography of the terrain and position of contour lines. The file of extracted ridge points and the file of forest roads were overlay onto the raster DEM image. The accuracy of ridge point extraction can be verified by studying the position of extracted points as the number of ridge points densifies along locally highest contour lines. Forest roads can be classified as valley, sloping and ridge roads.

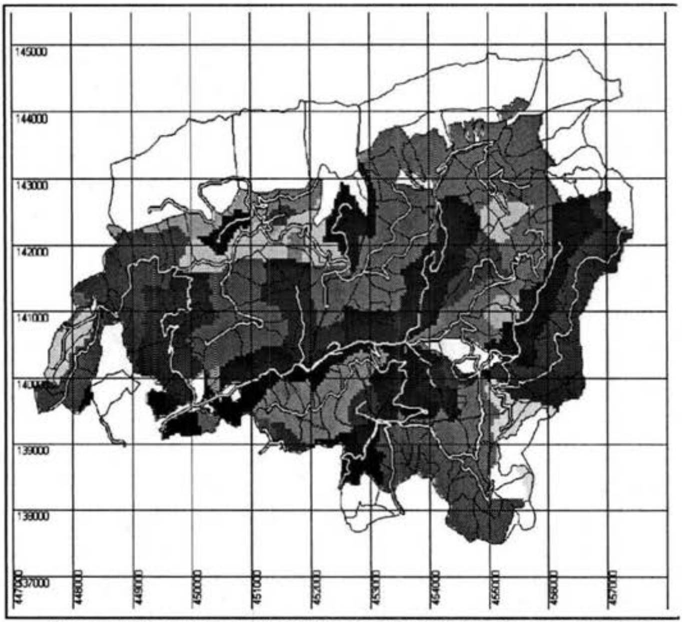


Figure 4: Model of gravity fields used in skidding for road sections in the FMU Jelendol

In Figure 4, sections of roads for which gravity fields have been determined are marked with one colour that differs from the colour of the corresponding extracted gravity field. Certain road sections open up forest areas of differing surface sizes, dependent primarily upon the course and density of roads, their slope and terrain topography. Areas of lower slope generally form larger gravity fields than steep forest areas. No provision has been made for forest production in the protective forests in the northern and eastern part of the FMU. All the roads have an exit towards the southwest of the FMU which also represents the point of lowest elevation in the area concerned. With a view to transport routes, the FMU can be divided into as many spatial units as there are possible timber removal routes from the area in question (KRČ 2000).

The potential road load in the FMU Jelendol has been calculated on the basis of 10-year allowable cut figures (Table 1). First, data on road section length was derived from the information on the number of raster cells for each extracted forest road section. Then, the allowable cut file was searched for data on the sum of raster cell values in the areas of corresponding gravity fields. Raster cells in the allowable cut file are assigned values which are equivalent to allowable cut per surface unit represented by a raster cell. Final road load value was calculated per road length unit represented by a raster cell.

The last step of the procedure was to apply the option of summing up section load values resulting from the transport of wood cut in the catchments area of the section, and obtain cumulative values for the loading of individual raster cells which represent the road network (Figure 5).

Table 1: Load classes for forest road sections with 10-year allowable cut for FMU Jelendol

ID Road section number	Number of raster cells per road section	Maximum section load class	Minimum section load class	Average section load class
2	79	1	3	1.45
1	93	1	5	2.12
21	4	3	3	3
22	6	3	3	3
13	23	3	5	3.86
3	53	3	6	4.28
14	91	3	6	4.48
19	7	4	5	4.57
18	35	4	5	4.6
16	83	4	5	4.63
17	16	4	5	4.81
20	4	5	5	5
44	1	5	5	5
37	18	5	6	5.27
15	56	4	7	5.48
23	67	4	9	6.11
39	16	6	7	6.12
28	28	6	7	6.32
38	73	6	7	6.45
5	23	6	7	6.56
24	94	5	9	6.58
34	95	5	8	6.7
33	64	5	9	6.75
4	38	6	8	6.76
30	14	6	7	6.85
6	4	7	7	7
27	53	7	8	7.32
26	40	7	8	7.45
36	21	7	8	7.57
35	3	8	8	8
25	12	7	9	8.16
31	38	7	10	8.47
40	61	6	11	8.65
45	7	8	9	8.71
41	8	9	9	9
43	22	9	10	9.22
29	144	6	13	9.89
42	101	8	16	11.7
32	7	13	14	13.14

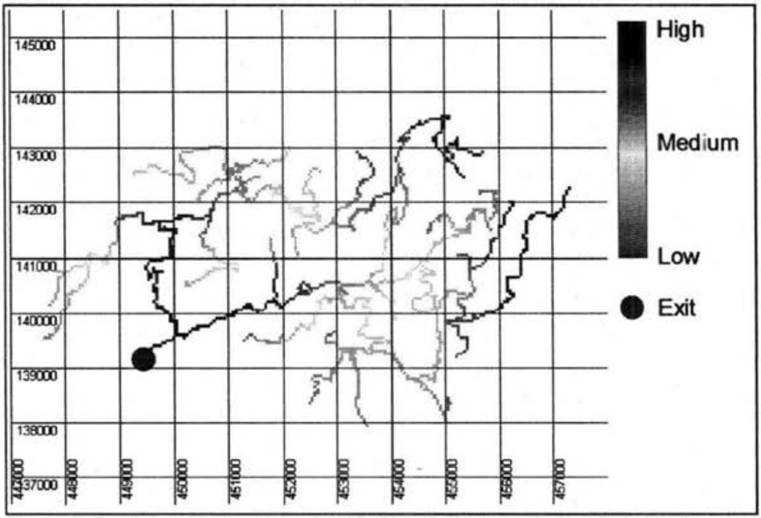


Figure 5: Spatial representation of road network by degree of loading resulting from timber extraction in the FMU Jelendol

Discussion

The research presents the procedure for determination of forest road loading that results from forest operation. The procedure requires spatial data in digital format. In the research, an IDRISI software packet was used which enables a series of standardized analyses of spatial data. The determination procedure enables fast computations of road load resulting from forest production activities for relatively large surface areas. The information acquired is useful in the analysis of forest openness and in keeping records of the differentiation in forest road maintenance works.

Data on forest road load caused by forest production can be applied in various levels of forest management planning. In addition to serving the needs of wood production, forest roads perform a number of other functions (POTOČNIK 1997) that influence the effectiveness, quality of construction and maintenance system of forest roads. This research does not cover other functions of forest roads. There are certain sections of forest roads that are under severe pressure from forest production. Generally, we are speaking about several rather short road sections leading to extensive forest areas characterized by high growing stock and high allowable cut. If these road sections were not intended for forest production in the first place (e.g. farm driveways), it is sensible to assign them the same mark as the roads to which they connect. In this way, the driveways are not treated as independent gravity fields.

Assessment of catchments area at a particular point of a forest road constitutes an important aspect in determining the loading of a forest road. It confirms the existence of several road sections that are stressed with forest production also in their initial parts in the direction opposite to wood transport flow. The model generates cumulative sums by successive road in the direction of wood transport flow and is useful at this stage of development for evaluations of direct road load and for analyzing the productive length of a road for skidding purposes as well as for calculating cumulative road network load, actually imposed on a forest road by timber extraction.

Conclusion

Information on road loading is extremely important for forest operations, as it is needed by forest managers at the strategic level and by forest production managers, spatial analysts and silviculture workers at the tactical and operational levels. Road loading and transit volumes play a significant role in determination of forest management goals and silviculture objectives that are the base for most forest operations. Road loading also provides information necessary for fair and differentiated allocation of funds for forest road maintenance and information on the need for technical and technological development of forestry enterprises which have to adjust to production conditions and limitations. The presented model enables relatively fast and consistent assessment of the loading of large forest road complexes, conducted with the help of spatial data and spatial data analysis tools. Applying a determination procedure, we can calculate the allowable cut volume per length unit of a forest road, which is critically dependent upon accurate delineation of gravity fields belonging to certain forest road sections.

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COST-COMPETITIVENESS OF HARWARDERS IN CTL-LOGGING CONDITIONS IN FINLAND – A DISCRETE-EVENT SIMULATION STUDY AT THE CONTRACTOR LEVEL

Kari Väätäinen, Harri Liiri & Dominik Röser
Finnish Forest Research Institute, Joensuu Research Centre, Finland
E-mail: kari.vaatainen@metla.fi

Abstract

Harwarders, in which the work of a one-grip harvester and a forwarder is combined into one machine in CTL-loggings, are starting to compete for some logging operations with conventional machines. This new logging concept has opened a way to reduce logging costs for the contractors by allocating the logging sites to different machine concepts in a cost-effective way and thus reorganizing the entire structure of logging operations. Compared to conventional machines, the main advantages of harwarders are mostly related to time savings since some work elements are combined into the same working phase or working cycle. Additional time and cost savings are achieved through reduced machine translocations between logging sites. At this stage, the total number of harwarders in forest operations in Europe; particularly in Scandinavia and Central-Europe, is close to 200 units.

So far, there is no clear concept, how to utilize harwarders cost-effectively as part of the contractors' harvesting fleet. The aim of this study was to find cost-effective working patterns of harwarders for forest machine contractors in different logging structures and conditions. A discrete-event simulation model was used as the study method. The initial material of the logging sites consisted of detailed stand characteristics, removals and location information of nearly 7 000 real logging sites cut in the year 2003 in South-Eastern Finland.

According to preliminary results based on the existing harvested stand structure, harwarders are more feasible to allocate to the cutting sites, where either the removal per stand or per hectare is small. Additionally, if the annual harvested volume of the harvester-forwarder chain is less than 20 000 m^3, harwarder concepts can compete better in economy.

Keywords: CTL-logging, harwarders, discrete-event simulation, logging cost

Introduction

Several logging concepts, which differ both in machine and logging technique, are available for cut-to-length (CTL) loggings. At present, depending on the scale and operation and risk preparing strategy, forest machine contractors have more options to choose and build a suitable fleet of forest machines from different machine concepts. During the past years, the interest of both the scientific community and practitioners in Europe has been focused on the feasibility of harwarders in CTL-loggings.

Harwarders, in which the work of a one-grip harvester and a forwarder is combined into one machine in CTL-loggings, are starting to compete for some logging operations with conventional machines. This new logging concept has paved the way to reduce logging costs for the contractors by allocating the logging sites to different machine concepts in a cost-effective way and thus reorganizing the entire structure of logging operations. Compared to conventional machines, the main advantages of harwarders are mostly related to time savings since some work elements are combined into the same working phase or working cycle (Hasselryd 2003, Asikainen 2004). Additional time and cost savings are achieved through reduced machine translocations between logging sites (Talbot et al. 2003, Hasselryd 2003, Asikainen 2004). At this stage, the total number of harwarders in forest operations in Europe; particularly in Scandinavia and Central-Europe, is close to 200 units (Affenzeller 2005).

So far, there is no clear concept, whether it is more cost-effective to utilize harwarder in CTL-logging operations as a one machine independently or as part of the contractors' harvesting fleet. The Finnish Forest Research Institute investigated the operational and economical feasible use of harwarders in different logging structures and conditions in co-operation with three forest machine manufacturers (John Deere Ltd., Komatsu Forest and Ponsse Ltd.) and the National Association of Machine Contractors in a TEKES (Finnish Technology Development Agency) funded project. A discrete-event simulation model is used as the study method.

The focus of this paper is on the utilization of discrete-event simulation as the main method to compare the economy of different CTL-machine concepts in different logging conditions in Finland. The studied harwarder concepts were Ponsse Dual and a Valmet Combi 801 with a fixed and a rotating load space compared to a mid-weight harvester-forwarder chain. Some preliminary results of the project are presented below.

Material and methods

The study was carried out by building discrete-event simulation models for each machine concept using the WITNESS simulation software and making simulation runs with the models. Background information for the simulation was logging site data of harvested sites, work methods of different machines, time consumption models and the cost calculation.

Logging site data

Stand data was acquired from Stora Enso's database of Finland's South-East logging operations in 2003. From the initial logging site material 9 different logging site categories were produced, each including 201 logging sites (Table 1). Characteristics of each logging site were derived from genuine stand data (removal of main tree species, site area, average stem size of tree species, average forwarding distance, location in co-ordinate values, cutting time etc.) The first logging site category with normally distributed logging site types represented the average distribution of different logging site types in the South-Eastern part of Finland. The three main types were clear cuttings 58 %, second (or third) thinnings 22 % and first thinnings 8 %. The average stem size, area, forwarding distance and removals were 0.257 m^3, 3.1 ha, 361 m and 100 m^3/ha, respectively in this pine dominated (52 % of pines) logging site category (first category).

Table 1. Logging site (bank) categories of the simulation study.

Logging site category	logging sites, pieces	Harvested volume, m^3	Average removal		Share of the total stand removal
			m^3/site	m^3/ha	
1. Normally distributed logging site types	201	62 200	311	100	-
2. Clear cuttings	201	82 500	413	203	58
3. Thinnings	201	47 600	238	54	28
4. Seed tree removal	101	11 300	113	52	2.5
5. First thinnings	201	31 800	159	46	7
6. Normally distributed site types below 50 m^3 removal	201	6 900	34	36	1,5
7. Normally distributed site types below 100 m^3 removal	201	11 650	58	52	6
8. Normally distributed site types below 100 m^3 removal	201	20 500	102	72	18
9. Thinning sites below 100 m^3 removal	201	11 650	58	47	3.5

The same values, and the order of values in translocation distances between sites were used for all the logging site categories. The empirical distribution of translocation distances between two sites in successive logging order was analyzed from the initial logging site bank, where the average translocation distance was 12, 6 km.

Models, functions and distributions

In this study two alternate harwarder concepts were examined, namely the Valmet Combi 801 and the Ponsse Dual. The Valmet Combi harwarder is a genuine combi machine with the possibility to use it as a harvester or a forwarder at any time during the work cycle. It has a turning cabin and it is equipped with either a fixed load space or a rotating load space. The combi harvester head of the Valmet Combi concept can undertake both cutting and loading of timber. The Ponsse Dual uses a forwarder as a base machine. It has two interchangeable heads for the crane: a normal harvester head for cutting of timber and a grapple for loading the timber. Additionally an interchangeable bunk system with pillars is used in this concept so that during cutting the bunk system is removed. In the Ponsse Dual's simulation model the average time consumption of the machine transformation was set to 20 minutes.

The simulation study of the Valmet Combi case was concentrated on both load space concepts (fixed and rotating load space). There are several different working techniques for both load space concepts. The chosen technique for the fixed load space concept was a mix of all main techniques. In the mixed technique there is part of both "loading during cutting" technique and "cutting the amount of presumed load space size and then loading" technique. Depending on the site conditions and characteristics, in all of the techniques are relevant.

In the Valmet Combi's concept with a rotating load space two methods were applied. These methods differed in the share of direct processing to load space and the addition of extra time to cutting work phases. In the first method 50 % of the stems in thinnings and 80 % in all other cuttings were processed straight to load space and time addition to cutting was +15 % when direct load space processing was used. In the second method, the corresponding values were 90 %, 99 % and +5 % in respective order. Otherwise, the base logging technique, when direct load space processing was not used, was similar to that of the fixed load space concept.

The Ponsse Dual's working technique corresponded to the commonly used techniques of harvester work in cutting and forwarder work in forwarding. The only difference was the additional machine transformation from harvester to forwarder or vice versa. In this study, the transformation was done two times per logging site; after cutting the whole area and after forwarding all timber to the road side.

All the cut log assortments were loaded from the strip road during the same forwarding cycle, so mixed loading was used in this study. The size of the load space was the same for all of the machine concepts in the same logging site type. In first thinnings load space was 12 m^3, in other thinnings 14 m^3 and in other cuttings 15 m^3.

The used time consumption models were gathered from large time and follow-up studies of mid-weight harvesters and forwarders made mostly in Finland. Some modifications to the basic modes were made to the harwarder concepts. These modifications were based on the literature, field studies carried out during this project and machine operator interviews. The time consumption models will be presented in further publications, but the share of every work element's duration can be observed from figure 3. Interruption/break times of harwarders were acquired from Metsäteho's yet unpublished surveillance and follow-up study of harwarders. Theoretical probability distributions were formulated from the follow-up data to estimate the duration of interruptions/breaks and the interval of interruptions/breaks, which were used in the simulation models. All time consumption elements needed for the simulation are presented below.

- Driving during cutting (Harwarders & Harvesters)
- Positioning the harvester head and felling the stem (Harwarders & Harvesters)
- Delimbing and cross-cutting (Harwarders & Harvesters)
- Driving unloaded (all machines)
- Loading (Harwarders & Forwarders)

- Driving during loading (Harwarders & Forwarders)
- Driving loaded (Harwarders & Forwarders)
- Unloading (Harwarders & Forwarders)
- Auxiliary time (all machines)
- Interruptions/breakdown time divided below and above 15 min (all machines)
- Machine transformation (Ponsse Dual)
- Driving time to next site (all machines)
- Loading machines and driving time (low bed truck)

Structure of the simulation model

Four different simulation models were made for this study. They are: "Ponsse Dual", "Valmet Combi fix", "Valmet combi rot." and "harvester-forwarder chain". The simulation models have been built in the WITNESS simulation software environment. The software has a graphical interface in which the programming can be made according to the harvesting cycle's layout. The models have been built by imitating the work method of each machine concept as close as possible. Using discrete-event simulation in studying logistical problems has widely been used in previous forest technology research projects (Asikainen 1995, Asikainen and Nuuja 1999, Väätäinen et al. 2000, Asikainen 2001, Väätäinen et al. 2005). The models accuracy was verified by running the models step by step, checking the intermediate outputs and by comparing the results to an Excel-sheet cost calculator, based on the deterministic system analysis model.

An example of the flowchart of the Ponse Dual concept is presented in figure 1.
A screenshot of the simulation of the Valmet Combi Harwarder is presented in figure 2.

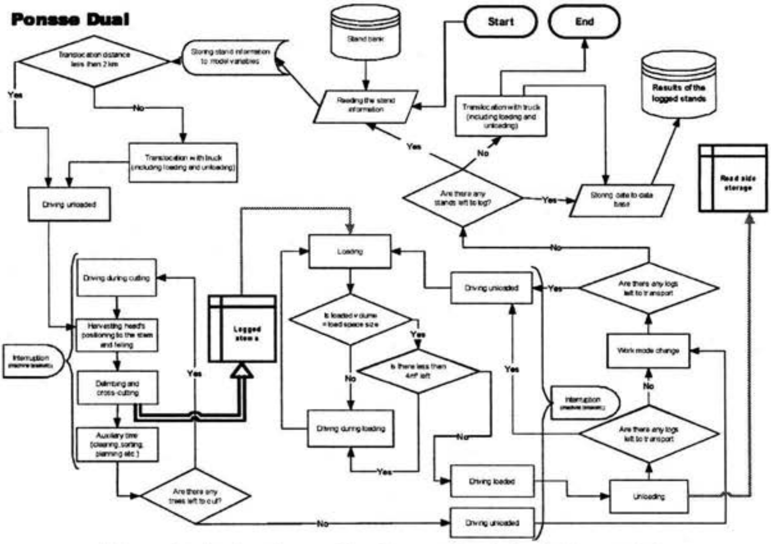

Figure 1. The flowchart of the Ponsse Dual simulation model.

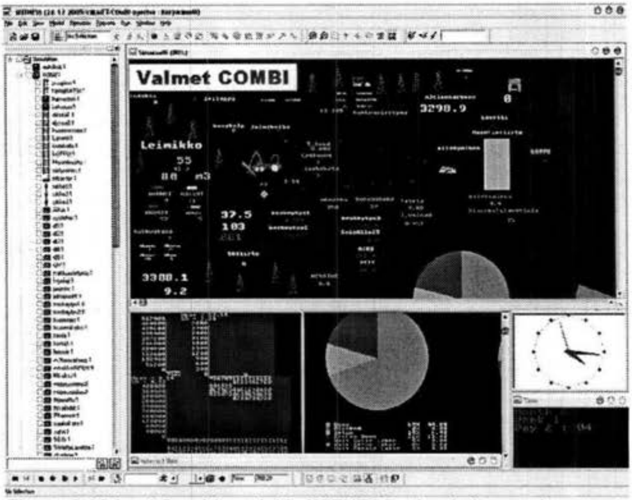

Figure 2. Valmet Combi model in WITNESS -simulation environment.

In the beginning of the simulation all the logging site data was entered in all models. After that machine/machines were transported to the roadside of logging site's storage area. The site was then cut and the timber forwarded to the roadside. After that, all the logging information data was stored to the logging results database. Then the cycle started again by transporting machines to the new logging site.

In the "Valmet Combi fix." model the harwarder cut the amount equal to the size of its load space. After that, it loaded the cut volume of logs and forwarded them to the roadside storage. In the Ponsse Dual model the entire site was cut first. After that the machine transformation was done and the cut logs were forwarded to the roadside storage. After the site was logged the log grapple was switched back to the harvesting head. In the harvesting chain model the limitation was set that the harvester can go at maximum, two sites ahead of the forwarder. For example, if the harvester had already cut the third site, the harvester was idling time until the forwarder had finished forwarding of the timber in the first site. If the harvester's productivity was smaller than the forwarders, it manifests in the forwarders waiting time (especially in first thinnings). In all of the models an extra allowance of maximum 4 m^3, was added to the last forwarded load to avoid a final unusual small pickup. Also, if the transport distance to the next logging site was less than two kilometers, the machine relocation was carried out by driving the machines to the next logging site.

Cost calculations

At the end of each logging site, the simulation model recorded intermediate outputs to a file (current time consumption distribution, logged volume, transported volume etc.). After all of the logging sites were logged, the model recorded also the final cumulative output of all logging sites to a file. The final output files of all simulation runs were imported to Excel, where the calculation of unit costs was derived.

The cost calculation was based on a common method of forest machine accounting. Machine's capital cost was calculated with a straight line depreciation. Hourly costs of machines are presented in euros per operating hour (€/E_{15}). Cost calculation values are presented in appendix 1. This report's study results are based on the unit cost calculations, where the annual operating time is set to 2 500 hours for all machines except forwarder, which value depends on the annual removal cut by harvester. The hourly costs of machines can vary a lot among logging site categories, because of the current machine utilization of each site category. The purchase price of the machines is presented in the table 2.

Table 2. The list prices of the machines, excluding VAT. Prices include standard equipment: 15 000 € in both harwarders and harvesters and 10 000 € in forwarders.

Purchase prices of machines	
Valmet Combi 801 (fixed load space)	400 000 €
Valmet Combi 801 (rotating load space)	425 000 €
Ponsse Wisent Dual	345 000 €
Ponsse Buffalo Dual	360 000 €
Harvester mid-weight class (Valmet 901, Ponsse Beaver, John Deere 1070)*	331 667 €
Forwarder mid-weight class (Valmet 840, Ponsse Wisent, John Deere 1110)*	221 333 €

* An average price from the prices of presented models of manufacturers

Results

The focus of this report is on the results of three logging site categories. The three categories are; normal distribution of site types, first thinnings and logging sites less than 100 m³.

Table 3. Machine utilisation (MU-%), productivity and hour cost of studied machine concepts in three logging site categories. Annual operating time for machines (forwarder excluded) was 2 500 hours (E_{15}).

	Ponsse Wisent Dual Buffalo Dual*			Valmet Combi 801 (fixed load space)			Valmet Combi 801 (rotating load space) O1, O2*			Harvester-forwarder chain without idling time with idling time*			
												€/ E_{15}	
Site types	MU-%	m^3/E_{15}	€/ E_{15}	MU-%	m^3/E_{15}	€/ E_{15}	MU-%	m^3/E_{15}	€/ E_{15}	MU-%	m^3/E_{15}	harv	forw
1 Normally distibuted logging site types	84.9	8.3	70.3 71.6*	86.5	8.0	74.6	85.8 85.9*	8.8 9.8*	77.1 77.3*	86.9 75.6*	8.5	77.4 82.4*	54.4 56.9*
5 First thinnings	84.3	4.1	72.6 73.9*	86.1	4.1	76.8	85.8 84.7*	4.1 4.7*	77.0 79.7*	85.2 65.0*	4.3	75.9 75.9*	64.4 87.2*
7 Logging sites less than 100 m³ removal	77.0	7.1	79.3 80.6*	82.3	7.3	82.5	80.2 80.5*	7.9 8.9*	86.0 87.1*	78.0 71.0*	7.2	91.9 94.6*	70.5 73.2*

- O1 (option 1) Valmet Combi 801 with rotating load space: Processing straight to load space 50 % in thinnings and 80 % in other site types. Additionally 15 % extra time for cutting work
- O2 (option 2) Valmet Combi 801 with rotating load space: Processing straight to load space 90 % in thinnings and 99 % in other site types. Additionally 5 % extra time for cutting work.

In table 3 general machine operation information of different concepts is presented. If all idling times resulting from the simulations are included in the harvester-forwarder chain operation, the machines' hourly costs can increase drastically. If the Valmet Combi with a rotating load space would process most of the cut stems straight to the load space (Option 2), the productivity would even be 23 % bigger than the lowest productivity value of machine concepts in normally distributed logging site types.

Figure 3 presents the total working times and the structure of work time among the machine concepts in different logging site categories, when 201 sites were harvested in each category. The amount of harvested stem volume is presented in table 1. Idling time illustrates the productivity unbalance of the two machine concept, which could be diminished with effective work scheduling of both harvester and forwarder.

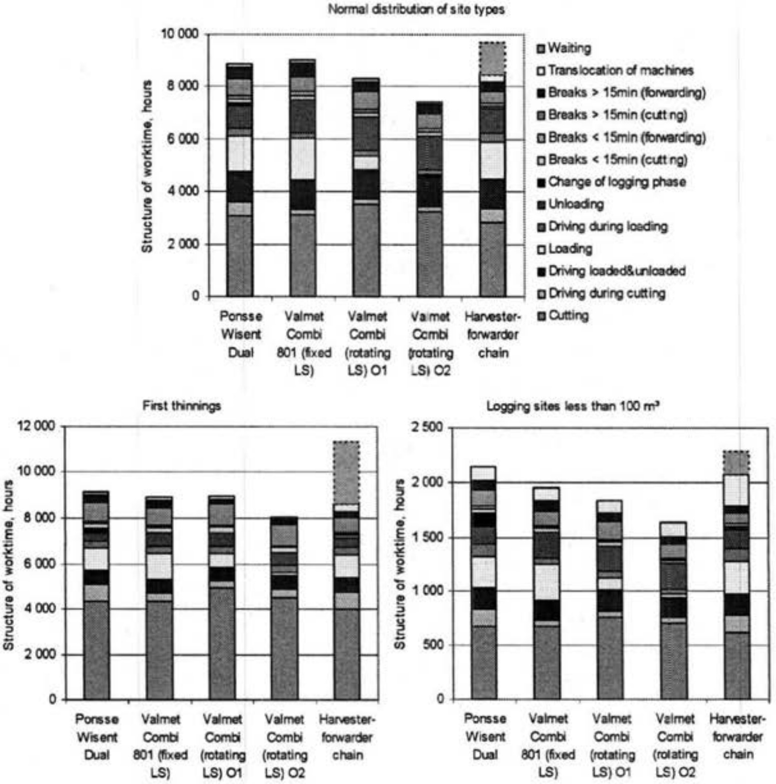

Figure 3. Work time structures of machine concepts.

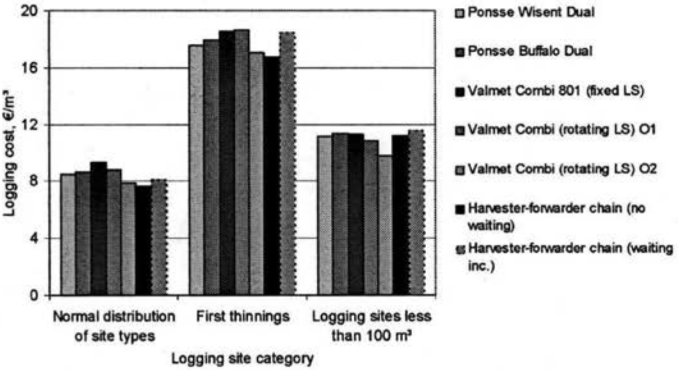

Figure 4. Machine concepts' average logging costs in different logging site categories.

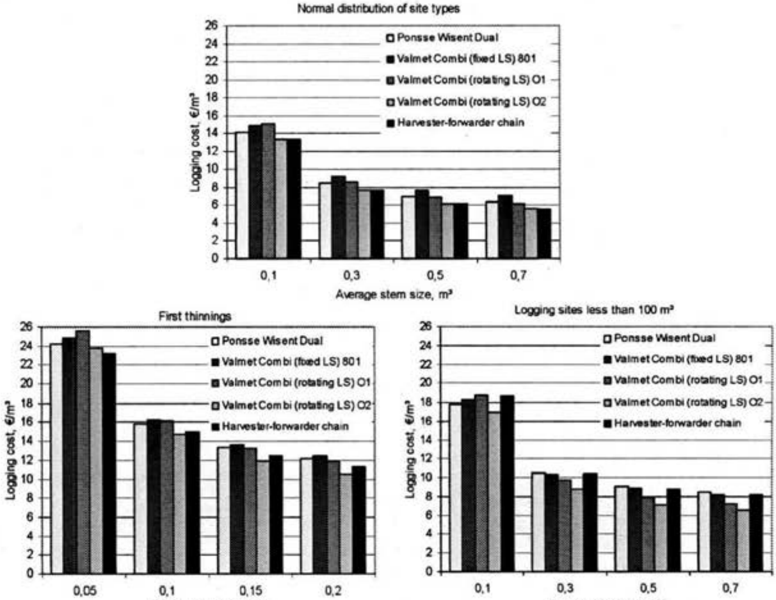

Figure 5. The effect of stem size in logging cost among machine concepts.

In figure 4 the average logging costs among machine concepts is presented. With a normal distribution of logging site types the most economical concept is the harvester-forwarder chain along with the Valmet Combi with a rotating load space (Option 2). If the Valmet concept equipped with a rotating load space could be used with the fastest work technique (major processing method straight onto the bunk), it is the most economical concept on harvesting sites with less than 100 m^3 removals. Additionally, the effect of the higher purchasing price is apparent in the case of the Ponsse Buffalo Dual.

Figure 5 shows the effect of stem size on the logging costs for different machine concepts. The effect of stem size is similar for all of the machine concepts. An exception is the Valmet Combi with a rotating load space in first thinnings, where the increase in stem size improves the cost-competitiveness.

Figure 6 illustrates the effect of annual logging removals for each harvesting concept on logging costs. In these calculations the maximum lifespan of machines is either 15 years or 15 000 operating hours depending on which value is reached first. Additionally, during the lay-days of machines the machine operator's salary is paid normally. The minimum annual salary cost (including indirect costs) is 30 000 € per machine. When the harvester-forwarder chain's annual logging amount goes below 20 000 m^3, the cost-competitiveness is decreasing compared to the harwarder concepts. This is essential information, when bigger forest machine contractors adjust their logging fleet and operations' scale to specific annual cutting removals.

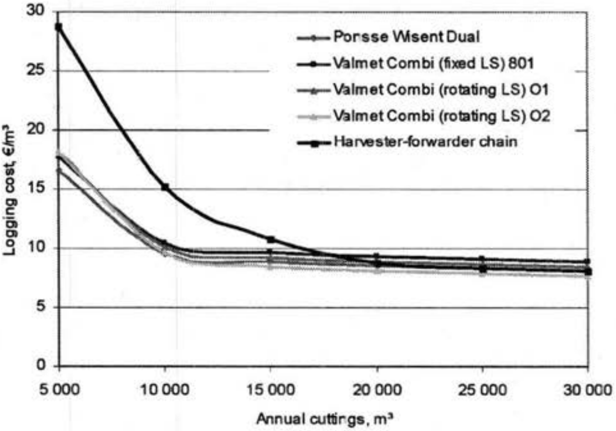

Figure 6. The effect of annual cutting amount on logging cost among machine concepts.

Conclusions

The presented results are preliminary but the simulation method has already provided evidence of it's usability to illustrate the situation in a real environment of logging operations. The utilization of detailed, real logging site data with spatial information improves the accuracy of results towards more general comparison with real logging cost data. This paper's logging costs, compared to Finnish logging cost publication values in the year 2004 (Anon. 2005), reveals similarities of values in different cutting type categories. It also proves the reliability of the used time consumption models from work studies with broad study material.

Additionally, the possibility to use probability distributions, randomization and machine interaction activity in logging simulations helps to understand the function of different harvesting concepts in varying simulation set ups (Asikainen 1995).

It can be concluded, that harwarders are suitable for logging sites both with small removals (less than 100 m^3) and with long translocation distances, when translocation costs play a big role in total costs. Similar findings have also been made by Björnheden and Dahlin (1999), Talbot (2003), Von Bodelschwing (2003), Asikainen (2004) and Emer (2005). The Valmet Combi concepts' benefit is the simultaneous cutting and forwarding of the logs during the same cycle. The smaller the removal per hectare, the bigger the benefit in time savings, due to less driving (both in driving during cutting and during loading). Therefore, in these conditions, the harwarder concept is more suitable compared to other concepts as was also shown by Emer (2005). Additionally, direct processing onto load space can save a lot of time compared to separate log loading (Hallonborg and Nordén 2000, Bergkvist et al. 2003). The Ponsse Dual harwarder concepts' logging costs represent the average cost values for harwarders in most study cases.

Sensitivity analysis will be made for the functions of the factors having the largest effect on the logging site characters. These factors include removal per hectare, removal per site, stem size, forwarding distance and stand density. Moreover, additional adjustments and sensitivity analysis on machine concepts' time consumption functions are carried out to reveal the effects of varying time element durations on final logging costs. Additionally, the balancing of harvester-forwarder chain's productivity gap using harwarders as the third machine will be studied further.

Further studies concentrate also on finding the suitable combination of machines for forest machine contractors in varying annual cutting removals and logging circumstances. The influence of the share of different logging site types in different parts of Finland on the harwarders optimal use will also be investigated in the future.

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Appendix 1. Cost-calculation values of machine concepts.

Capital factors		
	Base machine	Harvester head
Service life	15 000 hours	7 000 hours
Depreciation-% of purchase price	27 %	27 %
Salvage-% of purchase price	23 %	20 %
Consumption values		
Fuel (Harwarder, **H**arvester, **F**orwarder)	**w** 11 , **H** 12 , **F** 10 liters/hour	
Motor oil	0.1 liters/hour	
Transmission oil	0.1 liters/hour	
Hydraulic oil	0.2 liters/hour	
Chainsaw oil	0.43 liters/hour	
Marking color	0.3 liters/hour	
Chainsaw chain	0.055 pieces/cutting hour	
Chainsaw disc	0.02 pieces/cutting hour	
Operating costs		
Fuel	0.55 €/liter	
Motor oil	1.3 €/liter	
Transmission oil	2 €/liter	
Hydraulic oil	1.35 €/liter	
Chainsaw oil	1.35 €/liter	
Marking color	1.3 €/liter	
Chainsaw chain	15 €/Chainsaw chain	
Chainsaw disc	53 €/Chainsaw disc	
Repair and maintenance costs (Harwarder, **H**arvester, **F**orwarder)	**w** and **H** 35 %, **F** 30 % annual depreciation	
Translocation cost with truck	1.5 €/km	
Labor costs		
Hourly wage to an operating time (E_{15}) (Harwarder, **H**arvester, **F**orwarder)	**w** and **H** 10.9 €/h, **F** 10.1 €/h	
Hourly wage to non operating time	**w** and **H** 10.9 €/h, **F** 10.1 €/h	
Evening shift extra	0.75 €/h	
Indirect wage costs	63 % from the base salary	
Work trip driving distance (average per shift)	60 km	
Work trip compensation	0.38 €/km	
Meal compensation days	20 days/year	
Meal compensation	6.4 €/day	
Fixed costs		
Depreciation of purchase price	(*) €/year	
Interest rate	5 %	
Insurance (traffic, fire etc.) (Harwarder, **H**arvester, **F**orwarder)	**w** and **H** 2 200 , **F** 1 750 €/ year	
Administrative costs (computer, phone, education, accounting etc.)	4 000 €/year	
Maintenance costs (washing, storage, spare parts)	1 500 €/year	
Risk extra	5 %	

(*) Depreciation of purchase price = (Purchase price - Salvage value)/ Service life in years

THE PRECISION OF PRODUCTIVITY MODELS FOR THE HARVESTER – DO WE FORGET THE HUMAN FACTOR?

Thomas Purfürst, Jörn Erler
Institut of Forest Utilization and Forest Technology, University of Technology Dresden, Germany
E-mail: thomas.purfuerst@forst.tu-dresden.de

Abstract

To calculate the time and costs for a technical forest production system - productivity models are needed. Though we know a lot mostly of them disregard one of the main factors. Practical experience indicates that the machine driver is a decisive factor for the system's performance; therefore all those productivity models that do not consider this factor contain an error not yet quantifiable. To qualify and quantify the influence of the human factor in productivity models for the harvester, a new method for more precise and objective time studies is created. Different sensors automatically record movements of the harvester during standard operations in the field. The time studies in the forest are compared with certain tests (simulator, standard field test) to the separate individual performance of the driver. This data can be mathematically converted into a standard performance level. In future productivity models the influence of the human factor can be normalized to increase the precision and comparability of results. The standard field test is an indicator to measure the standard performance of the driver. The smaller the variance in data in this test, the better the harvester driver performed under real conditions.

Keywords: Time study, harvester, productivity models, operator performance

Introduction

Productivity models indicate the performance that can be expected using a specific procedure, under specific conditions. In theory, the performance of a technical forest production system depends on various independent factors, which have already been tested in many studies. One has to distinguish between five types of influences. Included are the working environment, the environmental factors, stand conditions, the machine as well as the human factor (see fig. 1). The attention paid to and the weighting of these influencing factors are however different depending on the region. In the mountains more weight is given to the slope angle as compared to the lowlands. HEINIMANN already mentioned in 1998: „The importance of a consistent collected pool of data which is in accordance with standardised methods cannot be emphasised enough to make future productivity models become more reliable."(translated by the authors) In the past, the aspect of the driver as an influencing factor has been identified; however, it has not been further examined or evaluated. Over the past years a rethinking has been taking place and it is recognised that "...the characteristics of the operator may be regarded as the most important factor related to harvester productivity" (OVASKAINEN et al. 2004)

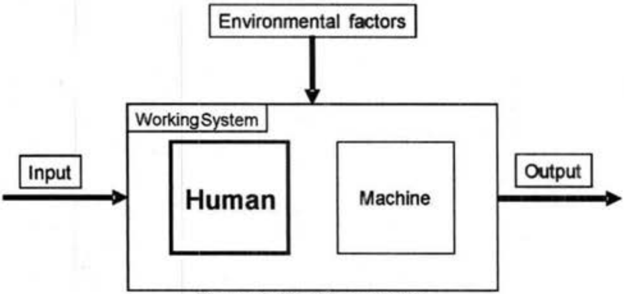

Figure 1: Working system

Looking at manual forest labour one assumes that the differences in performance derive from the fact that a person works more or less efficient and quick. It means that the efficiency is nearly 100% reflected in the productivity of the system. With regard to mechanical labour, the influence of the driver decreases and the productivity is mainly determined by the performance of the machine. This factor is often underestimated and should be stronger taken into account. VÄÄTÄINEN & OVASKAINEN (2004) found that: „The differences of the operators' time consumption in the thinning varied from 40 to 55 percent". Practical experience, however, indicates that the machine driver is a decisive factor for the system's performance, so that all these productivity models that do not consider for this fact include an error not yet quantifiable. The basis of the data of most of the productivity models has been conducted with experienced but randomly chosen drivers. This complicates the comparability of different productivity models.

The aim of this research project is to develop a specific time-study procedure or a certain test to measure the individual performance of the driver. This data can be converted mathematically into a standard performance level. That does not mean the average efficiency but a performance, which is experienced as "balanced, harmonious and natural" (REFA) and in most cases it is lower than the average efficiency. Thereby productivity prognoses, which are comparable among themselves, become possible.

Methods

To attain a performance index, five different data collections will be harmonised (see fig. 2). First of all, a semi-automated forest-time-study is conducted. Furthermore, a test under ideal conditions without the influence of other factors is carried out (Laboratory Conditions Test - LCT). Many harvester drivers are analysed in a simulator as the third possibility. The data of the performance in the past give additional information's as a forth source. As fifth hint a certified expert estimate visually the level of work performance. Drivers of different shifts will be examined and directly compared with each other. The time study in the forest and the LCT are conducted as follows:

- In the morning time: a „field-time study" in the forest is conducted for the first driver
- At noon: During shift change the LCT is conducted on the „plain field"
- In the afternoon: the field-time study is conducted with a second driver

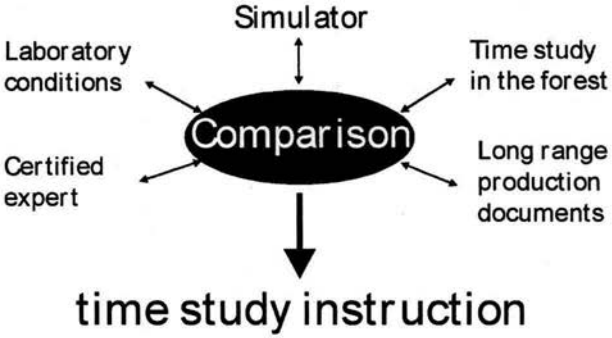

Figure 2: Comparison if different measurements

Herewith drivers of different shifts will be directly compared with each other. There are only two different factors, human factor and time of day. The influence machine can be excluded while the driver is on its "own" machine. Until now 24 different drivers have been tested, some of them several times. It's planned to test about 40 drivers more.

Laboratory Conditions Test - LCT

For a test under laboratory conditions the following requirements have been set:
The test should:

- be possible everywhere under the same conditions. So it cannot be run in the forest but on a plain field like a meadow or a parking place.
- not take much time, a maximum of 30 minutes should be applied to each driver.

- feature the human performance as the only variable. This means that all other factors are set ceteris paribus. To assure these only drivers on the same machine who are familiar with this individual machine can be compared.

To satisfy these conditions, a test as illustrated in figure 3, has been developed. This LCT bases on a test plot of BEYER and SCHIECK (2003). 36 discs are placed on a standard field (meadow) and are marked with labels on the edges. The base of the harvester's crane is set at the position zero and the head is positioned at a start disc. The driver moves on a virtual skid road (red line – fig. 3). Via radio communication, the driver is told to which disc he has to move the harvester head and return to the starting disc. During this process the harvester head must not to be dropped at the ground because this would damage the aggregate. After a learning period of 20 trails the measurement starts: In a random sequence, which has been fixed once and is used in every study, the driver is asked to hit each disc twice. So this LCT collects data of 72 movements and takes about 25 minutes.

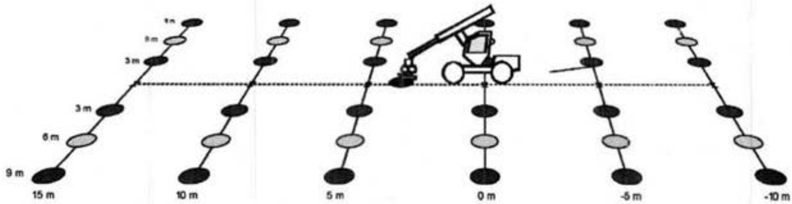

Figure 3: Plot of the Laboratory Condition Test (LCT)

The call of the disc is automatically affected by a computerized voice (see fig. 4). At the end of each call the time measurement is started. Once the aggregate has reached the starting disc, the time is stopped manually. Furthermore, the test is being filmed to revise subsequent problems or discrepancies in the evaluation. In addition of the time, the movement of the harvester and the resulting pivoting angle is measured. Mistakes such as wrong or poorly approached discs are noted.

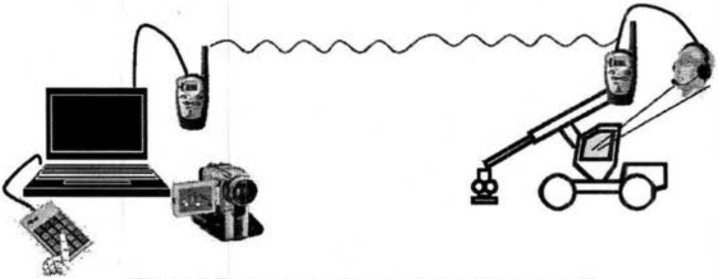

Figure 4: Data communication to the driver on LCT

The times measured are put in relation to the distance to move to the discs. Furthermore, the pivoting angle of the harvester is presented and evaluated.

Semiautomatic Forest Time Study

In order to measure the performance of the driver with satisfactory precision, an accurate collection of data is necessary. A new time study method has been developed for the harvester. A combination of sensors and intelligent software is recording data of motion. This sensor system is in contrast to others, for example the system used by PELTOLA (2004), independent of the type of harvester.

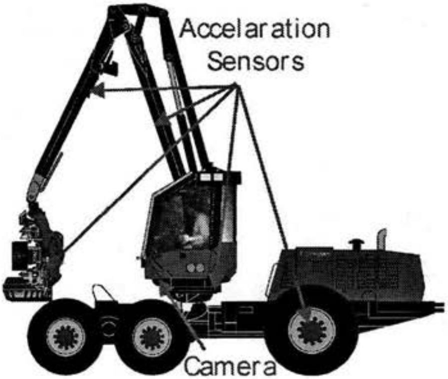

Figure 5: Installed sensors on the harvester

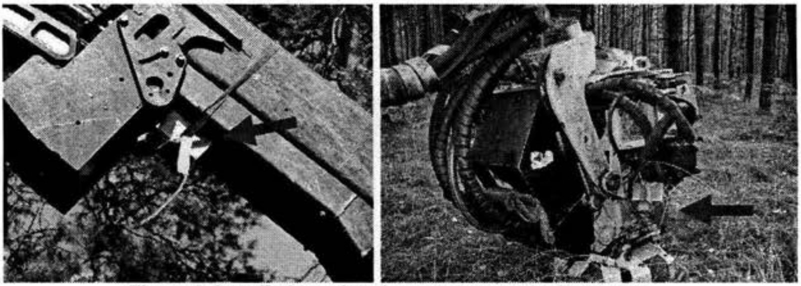

Figure 6: Installed acceleration sensors on the harvester

Several sensors are installed on the harvester as can be seen in figure 5 and 6. Sensors on the wheel register the motion of the entire machine. The sensors on the harvester crane enable the recording of the motion as well as the angle of the boom and the resulting distance of the harvester head. A further sensor on the harvester head is used to register the felling and the motion of the saw. This sensor is connected to the time study computer via Bluetooth. A wireless data communication is thereby made possible. This acceleration sensor, which are 3 dimensionally located can measure six degrees of freedom. Intelligent pattern recognition software calculates various data from the processing of the sensor values (see fig. 7). To verify the data there are also sensors on the rotating assembly that register the pivoting angle of the harvester crane. All sensor data are collected simultaneously. The times for the work time phases, delays and breakdown, the efficiency and various features of the motion pattern for each driver can be deduced. The measurement of simultaneous motions is also possible.

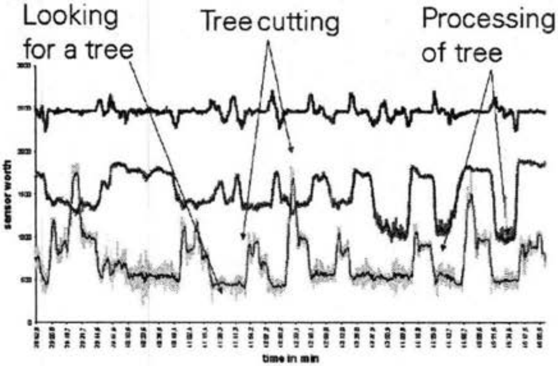

Figure 7: Acceleration sensor data of the working machine

In edition a webcam which is installed on the machine films the harvester head. These films serve to verify data as well as the clarification of inconsistencies. The diameters of the processed trees can be taken from the board computer; when the software does not export single tree the diameter can be recorded by a separate webcam.

Simulator

As the third test the drivers are tested on different harvester simulators. The advantage of the simulator compared to the Laboratory Conditions Test is that one does not have to every driver can be tested under the same conditions, in a short period of time.

After some preparation times the drivers have to run various courses. At the same time the data of the simulator are evaluated. Interview questions are further put to each driver regarding the suitability of the simulator. For the test, only drivers with practical experience can be used. In each case the drivers are tested for one day. A lengthy examination is the question of being out of touch with reality.

Results

Comparison of Field-Time-Study and Laboratory Conditions Test

To evaluate the tests and the Field-Time-Studies, primarily the drivers of different shifts but in the same machine and in the same stand are compared with each other to achieve ceteris paribus conditions. The measured time values in relation to the distance of the discs (LCT) and in relation to the volume of the log of the trees respectively (Field-Time-Study) are presented in figures 8 and 9. Both illustrations are typical for the tests.

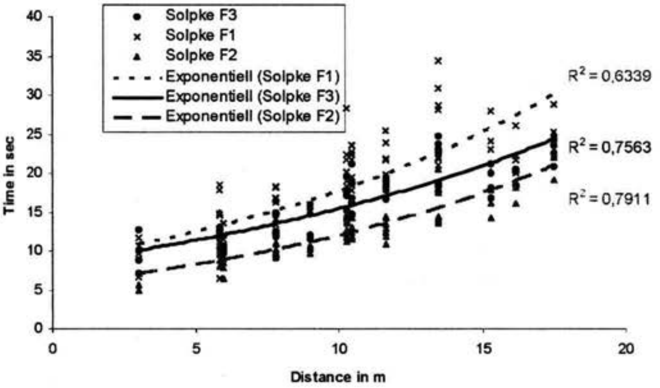

Figure 8: Time consumption on the LCT

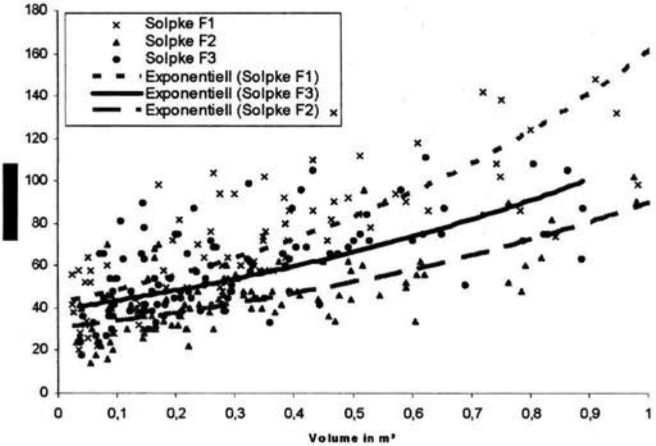

Figure 9: Time consumption on the field-time-study

Figure 8 describes a result of the Laboratory Conditions Test. The times of three drivers are illustrated. Drivers F2 and F3 both possess approximately the same hours of harvester experience. Driver F1 in contrast is an experienced forwarder driver who conducts the harvester only occasionally when the others are impeded. Figure 9 shows the times of the same drivers in time studies in the forest. It can clearly be seen that the message of both diagrams is similar. The forwarder driver F1 has the poorest performance in the forest and on the trial course. However, also the experienced drivers substantially differ to each other. The higher the difficulty the higher is the distance between the drivers: The driver F1 who is not as well experienced has its worst results under conditions of thicker trees which hit the limits of the harvester head. This is the reason why the LCT by which only the distance variable does not express the differences under extreme conditions as well.

In general, one can say that the drivers who showed a better performance in the Laboratory Conditions Test, also performed better under real conditions and vice versa.

The sequence of performance of the drivers in the Laboratory Conditions Test is in total the same as the sequence of performance of the drivers in the field-time study. But due to the different influencing factors the quantitative relations between the performances in the field-time-study are not he same as in the Laboratory Conditions Test.

A further characteristic is the variation of the time consumption which can be indirectly measured by the coefficient of determination. A driver with a higher performance under real conditions usually works more harmonically and approximately needs the same time for every disc in the same distance. To generalise: the steadier a driver works in the Laboratory Conditions Test; the higher is the performance in the time-study in the forest.

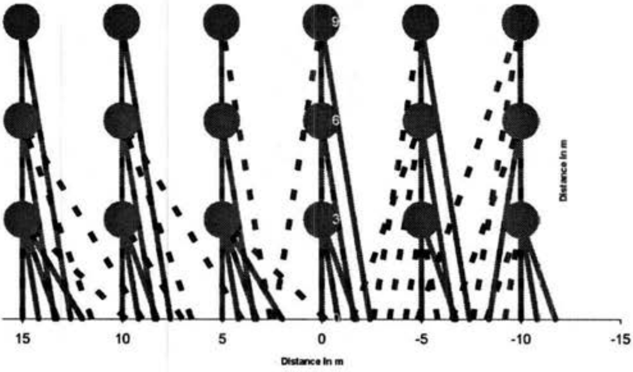

Figure 10: Pivoting Angle on the LCT

In the Laboratory Conditions Test the different drivers have different behaviour in the way they approach the discs. The way of movement indicates approximately the final performance. Figure 10 shows 2 extreme examples. The pivoting angles to reach the various discs are presented. The driver who has been marked with the solid red line is very inexperienced. In contrast the dashed line shows the experienced driver. It points out that the inexperienced driver moves significantly more by means of the chassis and chooses his pivoting angle near to the direction of 90°. When a disc is located behind the starting point of the aggregate, he travels backwards and grabs forward with the harvester head. The experienced driver on the other hand recognises that there are no interfering trees around. He thereby uses the smallest possible pivoting angle and increases the extension of the boom. To reach the discs which are located behind the aggregate, he hardly drives with the harvester but instead prefers to move the crane. This shows that due to experience, typical behaviours can be set in relation to the real performance of the driver.

The evaluation of mistakes and errors show a negative correlation with the performance, the driver shows on the trial course and in the forest.

Simulator

Following numerous tests and interviews with the harvester drivers it has emerged that the drivers struggle to get familiar with the simulator and are unable to show similar performance like they would have under real life conditions. Drivers also had problems with the different handling of harvesters. Over the years the seats and the handling respectively have further developed. It is therefore rare that the equipment and fittings to which the drivers are used to are the same as they find in the simulator. The setting of the movements in the simulator is also different to the reality. Furthermore, criticism has been expressed regarding the limited visibility and the lack of vibrations of the simulator. A further factor is that high costs arise to get the driver to the simulator.

Discussion

PELTOLA (2004) asked at the International seminar ProForSim "Is the simulator the only a way to measure operator' skills?" The clear answer to this question given by this research project is: no. The simulator has been described by many authors as the universal tool. With the assistance of the simulator one can train the drivers and increase productivity (FERNANDES 2004). In contrast to OVASKAINEN (2005) this simulator tests are tried on different simulator types. However as a result of the shortcomings listed above, it has not proven target-orientated as a quick test of the driver's performance. This may however change in the future due to the further development of simulators. It could possible to reduce the cost by using a mobile simulator such as the SIMAGO – Mobile Simulator Unit.

Each driver has his own working method which can be measured by various features. This research is in accordance with ANONYMUS (2003) and comes to the conclusion that the difference in performance between drivers is bigger under more difficult conditions and at the performance limit of the aggregate. A lot can be automated in normal forest stands as the trends of technical development suggests at the moment (LÖFGREN, 2004). Therefore it is not possible to directly relate the results of the Laboratory Conditions Test to the real life performance. However, the ranking of drivers in tests is equal so that the Laboratory Conditions Test can be use as a assessment of the performance of the driver within a short period of time. The results of the Laboratory Conditions Test can and should only be used as an indicator of the rough performance level of the operator (NIMZ, 2002). Despite the different influencing factors, the close relationship between the results of the Laboratory Conditions Test and the results of the field-time study coincide with RANTA's (2004) findings. "An effective driver can operate efficiently in all phases of the work cycle."

There are high variations in performance between the drivers. Also among high drivers we recognize high variations. The differences in the fluctuation of the performance between the drivers are made up of 1/3 day-to-day differences within operators and 2/3 due to differences between operators (FREEDMANN, 2004). This conclusion in this thesis could neither be confirmed nor disproved until now because there is no sufficient pool of data yet.

It will become important in the future to analyse in more detail the different abilities and features of the drivers such as the pivoting angle and the movement of the crane. RANTA (2004) found that: "Statistically significant positive correlations were found between productivity and the use of extension of the boom and for simultaneously used boom joints and negative correlations were found between productivity and vertical boom movements". This allows for the assumption that in order to determine the performance, the compilation of human profiles could be important.

The advantage of the semi-automatic time-study used in this research project is the possibility to conduct continuous data recordings over a long period of time. The recorded data have been accomplished objectively. As no human being is observed as a time keeper close to the machine, this proven falsifying factor has been minimized. The personnel and cost-intensive investment can be minimized. The sensors do not cause any harm to normal operation as compared to a human being as time keeper.

The analysis only concentrates on the productivity of the harvester as such. It is important to pay attention to dependent operations. „By optimizing the size of the pile the harvester operator can improve the productivity of the harvester-forwarder chain"(ALA-FOSSI et al. 2004). It means that there could be different basis for the determination of the productivity.
In the future the pool of data will be expanded from 24 tested drivers to about 60 in order to improve the description of the influence of the driver. As long as the „Vision for mechanisation in Sweden" described by LÖFGREN (2004) as „No hand on the logs; No man on the ground; No man in the machine" has not yet become reality, the influence of man must be regarded as an important factor for time and cost in forestry.

Acknowledgements

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FOREST OPERATIONS PLANNING BASED ON HIGH RESOLUTION WET AREAS MAPPING: VERIFICATIONS

Paul Murphy, Mark Castonguay, Jae Ogilvie, Trevor Connors, Paul A. Arp
Nexfor-Bowater Watershed Research Centre, University of New Brunswick, Canada
E-mail: pmurphy@unb.ca

Abstract
High resolution (5 and 10 m) watershed, flow channel and wet areas maps generated much positive feed-back from forest operations planners and field practitioners. These maps were derived using a GIS process from digital elevation models (DEMs) and hydrographic data. The maps were ground-truthed using a number of methods in two Canadian case studies: one in New Brunswick (an area of mixed wood Acadian forests) and another in Alberta (a hilly area of boreal forest). 88 % of stream culvert locations predicted by the map fell within 40 m of actual locations in New Brunswick and 94 % in Alberta. The index used to map wet areas was found to be positively related to water table depth along transects adjacent to wetlands in New Brunswick and this index was related to the *sphagnum* boundary around wetlands. In Alberta, rutting was found to occur during summer harvest in areas predicted to be wet.

Keywords: Digital elevation model, forest operations planning, surface hydrology, flow accumulation, wetland mapping.

Introduction

This paper focuses on the verification of surface drainage networks and wet areas derived from digital elevation models (DEMs) and hydrographic data. Accurate and comprehensive spatial hydrographic information is an important first step in forest operations planning (Andison 2003). Planning tools incorporating this information offer the potential to move forest operations towards best management practices (BMPs). Such information improves the ability to reduce environmentally detrimental effects, and offers potential cost savings by avoiding operational 'surprises' in road layout and construction, culvert location and size, cut-block and harvest trail lay-out, site preparation and re-generation, and navigation.

DEMs can be used to derive flow direction and flow accumulation in landscapes where surface topography is the primary determinant of surface water flow (Moore *et al.* 1991; Strager *et al.* 1998; Fall and Morgan 2000; Gessler *et al.* 2000; Case *et al.* 2005). The derived drainage network can be improved by incorporating pre-existing hydrographic data. DEMs can also be used to derive indices related to soil wetness (Moore *et al.* 1991; Gessler *et al.* 2000; Ryan *et al.* 2000). The method discussed in this paper uses both the DEM and the improved drainage network to derive a soil wetness index (SWI), allowing wet areas to be mapped.

The reliability of the derived drainage and wet areas map was tested for two areas in Canada: one for the University of New Brunswick Forest in New Brunswick (an area of mixed wood Acadian forests subject to a cool temperate, maritime climate and gentle to flat topography) and another for the Swan Hills area in Alberta (a hilly area of boreal forest subject to a semi-arid continental climate) (Fig. 1).

Figure 1. Location of the two study areas in Canada.

Deriving the maps

A very brief description of the process used to derive the surface drainage and wet areas map is given here. Pre-existing hydrographic information was incorporated into the DEM by lowering the elevation of grid cells corresponding to stream channels to produce a "hydrologically corrected" DEM for which the derived flow conforms with all the known flow paths (Olivera 1996; Saunders and Maidment 1996; Simley 2004). DEM resolution was 5 m. The FILL function of ArcView was used to create a depressionless DEM. The flow direction algorithm D8 (deterministic-8 node algorithm) (Hornberger and Boyer 1995) was then used to derive a flow accumulation network. The resulting flow network was merged with the already mapped stream coverage to produce a single improved hydrographic layer.

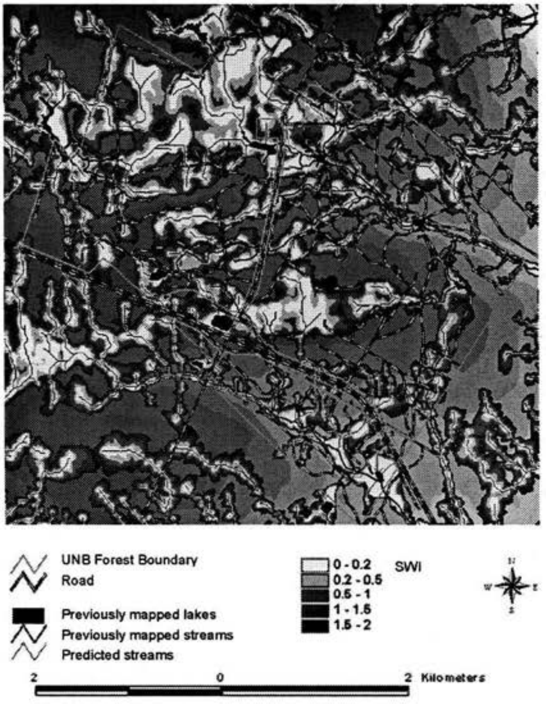

Figure 2. Map of surface drainage network and wet areas for the UNB Forest study area. DEM is given as background.

Large depressions were derived from the DEM and the improved hydrographic layer was combined with these depressions to produce a source layer. A SWI value was determined for each cell in the landscape using an iterative function which finds the cumulative slope value associated with the least slope path from the cell to a source cell. The index value reflects both the distance from a source (surface water feature or depression) and the slope of the land surface between the landscape cell and the source. Lower values indicate wetter soils. Values tend to increase away from the source into the landscape, indicating drier soils. It increases more rapidly in steeper terrain (higher slope values) and more slowly in flatter terrain (lower slope values). The final map is shown for the New Brunswick study area in Figure 2 and a part of the Alberta study area in Figure 3.

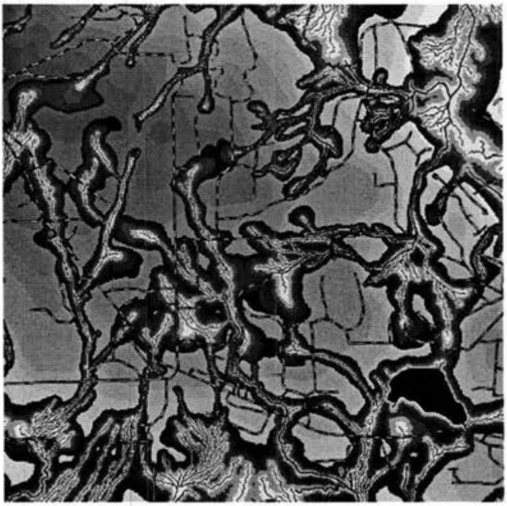

Figure 3. Map of surface drainage network and wet areas for a section of the Alberta study area. DEM is given as background. Area shown is equal to that of Fig. 2.

Verifying the maps

The reliability of the map was investigated using a number of methods:

(i) Culverts were located in the field using GPS and distance between map-predicted and actual stream culvert locations were derived for 62 locations in the New Brunswick study area and 17 in Alberta.

(ii) Three transects, with a total of 14 points, were installed in the New Brunswick area adjacent to wetlands. Three perforated tubes (0.6-1.5 m in length) were installed at each point. Depth to water table was monitored using a water meter, mean depth at each transect point was calculated, and these values were compared to the SWI.

(iii) Wetland boundaries were mapped out by tracing the limit of *sphagnum* moss distribution using GPS. SWI values for the mapped wetland boundary points were analyzed to identify a SWI value which might correspond to the wetland boundary.

(iv) Evidence of rutting resulting from recent forestry operations was sought in areas predicted to be wet.

Results and discussion

Predicting culvert location

The process allowed previously unmapped, low-order streams to be mapped with reasonable reliability: 88 % of predicted stream culvert locations fell within 40 m of actual locations for the New Brunswick study area (n = 62) (Fig. 4) and 94 % for the Alberta study area (n = 17). Total channel length increased 11.7 times over the pre-existing drainage network for the New Brunswick study area (Fig.5) and 5.3 times for Alberta.

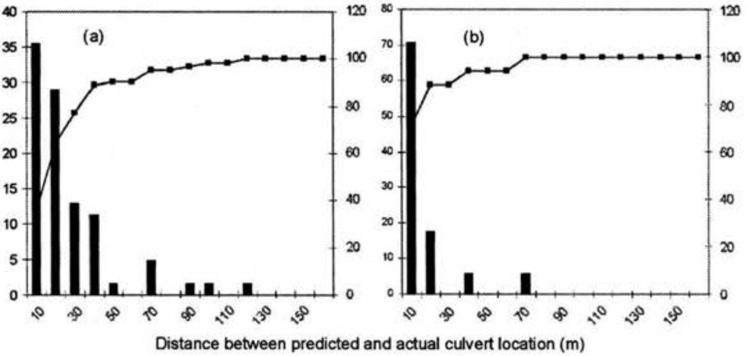

Figure 4. Percentage frequency distributions (incremental and cumulative) of distance between predicted and actual culvert locations for (a) the New Brunswick study area, and (b) the Alberta study area.

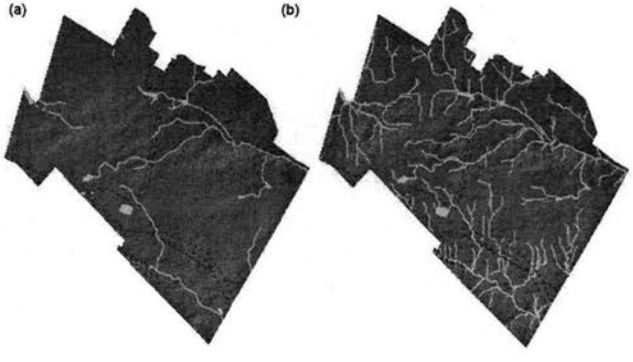

Figure 5. Comparison of the already mapped stream network (a) with that derived from the hydrologically corrected DEM (b) for the New Brunswick study area.

Figure 6 shows a detail of the flow channels from the pre-existing hydrographic layer (a), and those derived from the DEM (b). Note the failure of the pre-existing hydrographic layer to correctly predict culvert locations along the low-order streams in the left half of (a). These locations, however, were correctly predicted by the hydrologically corrected DEM (b).

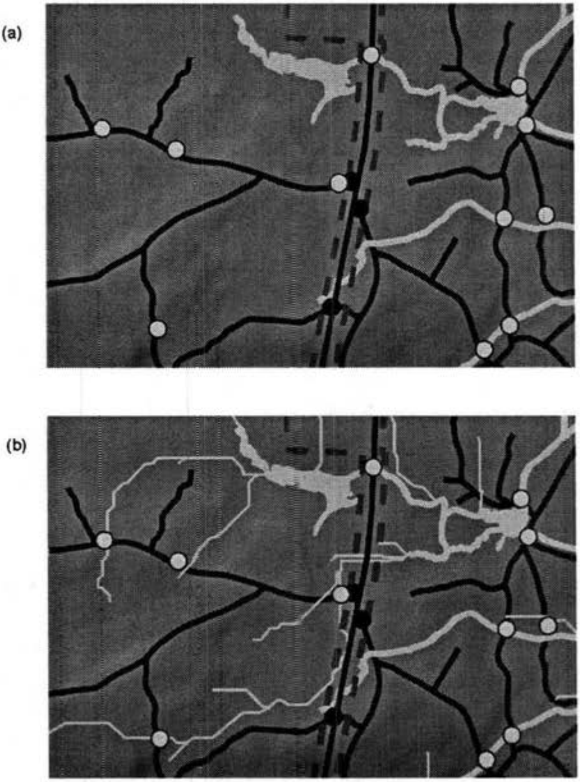

Figure 6. The improvement in prediction of stream culvert locations in the New Brunswick study area with the improved hydrographic layer (b), compared to the pre-existing hydrographic layer (a). Note the failure of the pre-existing hydrographic layer to predict stream culverts on lower order streams in the left half of (a) which are predicted in (b).

In all cases, the accuracy of flow accumulation patterns derived from corrected DEMs would be strongly dependant on the accuracy of the already mapped hydrographic features. Reliability and extent of the pre-existing hydrographic layer varies considerably between regions and this affects the reliability of maps produced. The pre-existing hydrographic layer for the Alberta study area was more extensive than that for New Brunswick, incorporating more of the low order stream channels. Therefore, the improved hydrographic layer for Alberta was less dependant on derivation of low order stream channels from the DEM. Reliability might be further improved by using a more complex, multi-directional flow accumulation algorithm such as FD8 or DEMON (Hornberger and Boyer 1995), which allow for the simulation of dispersive flow, as opposed to the D8 algorithm which only permits cumulative flow in a single direction.

Predicting depth to water table

SWI was found to be positively related to water table depth. Figure 7 shows this relationship is best described by a non-linear power function (R^2 = 0.41):

$$\text{water table depth} = 39.4(\text{SWI})^{0.36}.$$

This relationship was used to predict water table depth from SWI at points along a transect, shown in Figure 8 as a cross-section. These results suggest that SWI may be a good indicator of water table depth, which is an important silvicultural parameter. The change in vegetation along the transect demonstrates this.

The relationship between SWI and water table depth (Fig. 7) suggests that there may be a threshold value of SWI which can be defined, above which water table depth increases only very slowly with SWI. Such a pattern is consistent with the general observation that water table surfaces rise with topography. It should be noted that this relationship will be dependant on soil and parent material hydraulic properties and the hydrologic regime of an area. It may also differ seasonally. Two outlying data points were removed from the data set for this analysis.

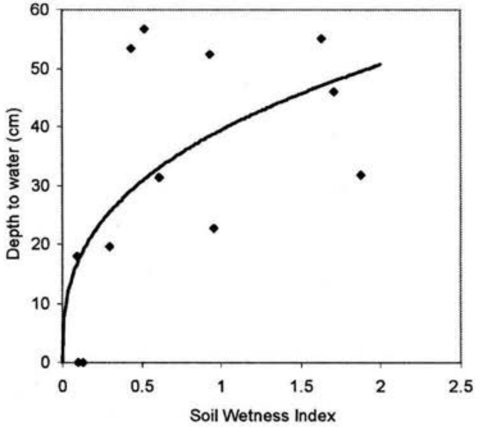

Figure 7. Depth to water table increases with Soil Wetness Index (R^2 = 0.41).

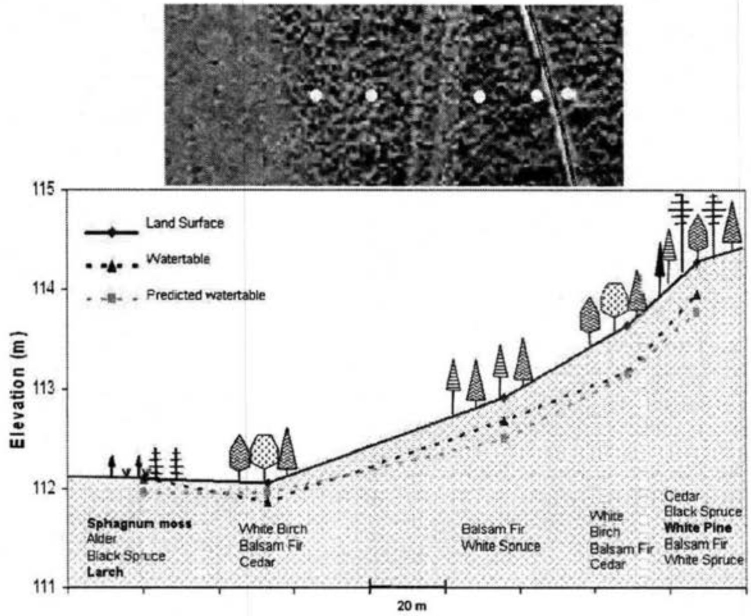

Figure 8. Cross-section along a transect in the New Brunswick study area (vertical exaggeration x 22.5), showing the observed water table and that predicted by the SWI values. The upper image is a digital aerial orthophotograph showing the vegetation change along the transect and the transect points.

Predicting wetland boundaries

The SWI values associated with the *sphagnum* boundary in the New Brunswick study area showed marked differences between wetlands (Fig. 9). Four of the smaller wetlands had mean boundary values of SWI > 1.5, while the other wetlands, which tended to be larger in extent, had SWI values < 0.6. The larger wetlands tended to be bogs with no tree cover, dominated by sphagnum, whereas the smaller wetlands tended to be located in small depressions along ephemeral watercourses with forested cover. For those wetlands with a mean boundary SWI value < 0.6, the mean SWI boundary value was 0.2 (S = 0.34, n = 248), and 87 % of boundary points had SWI values < 0.5. This would suggest that a SWI value of 0.5 should give a good approximation of the *sphagnum* boundary around these kinds of wetlands. Therefore, the SWI has potential as a means to map wetlands across large areas, based on a DEM and hydrographic information. Further work needs to be done in defining this relationship.

For the wetlands in the second group the mean SWI at the *sphagnum* boundary was 2.5 (S = 1.77, n = 152). However, the data set showed a much wider distribution of boundary SWI values, with a flatter cumulative distribution curve. Any boundary SWI value for such wetlands would be very unreliable. This suggests that the SWI may not be a reliable predictor of boundaries for these smaller wetlands.

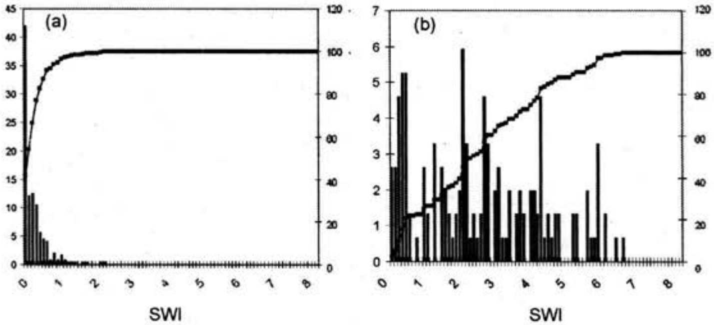

Figure 9. Percentage frequency distributions (incremental and cumulative) of SWI values at points on the *sphagnum* boundary of wetlands for (a) larger wetlands and (b) smaller wetlands.

Rutting and wet areas

Rutting was found to occur in areas indicated as wet soils by the SWI map. Figure 10 shows this for a harvested cut block in the Alberta study area.

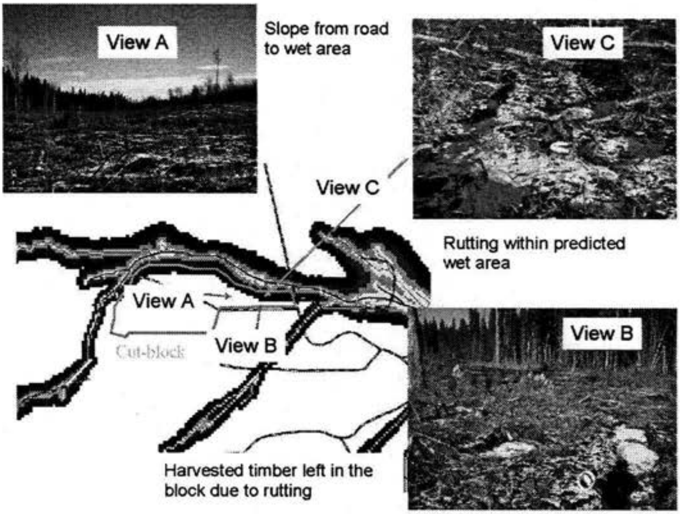

Figure 10. Rutting in a predicted wet area during summer harvest in the Alberta study area. As a result, skidding was abandoned and harvested timber was left in the block until the winter when soils would be frozen. Rutting could have been avoided by altering the cut-block layout according to the predicted wet area.

The block was cut as a summer harvest, but skidders created ruts in the wet area and the timber was left in the block until winter when soils are frozen and rutting can be avoided. Application of the wet areas map might help reduce such environmental impacts and costs in forest operations by allowing cut-block layout and operations timing to account for these wet areas.

Conclusions

Improved maps of surface drainage networks and wet areas were found to be reliable, in terms of the positional accuracy of stream channels and the relationship between a soil wetness index and wetland boundaries. The index was also found to be related to water table depth. These maps have potential as planning tools in forestry operations to reduce environmentally detrimental effects, and increase cost savings by avoiding operational 'surprises'.

Further work needs to focus on establishing the relationship between SWI and wetland areas more reliably. The SWI may also be related to soil type, particularly soil drainage conditions, and stand cover type. Drainage networks derived from the DEM might be improved by the use of multi-directional flow accumulation algorithms which allow for the simulation of dispersive flow. The reliability of the derived network is heavily dependant on the quality of the DEM and hydrographic layer used as input. Improved hydrographic information and DEMs (e.g. high resolution LiDAR DEMs) could increase reliability.

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GPS-BASED DOCUMENTATION OF MANUAL SILVICULTURAL OPERATIONS

Timothy P. McDonald, John P. Fulton, Matt Darr, Steven E. Taylor, Frank W. Corley, Christian J. Brodbeck
Biosystems Engineering Department, Auburn University, USA
E-mail: mcdontp@auburn.edu

Abstract

Herbaceous weed control and planting of southern pines share a common attribute in that they are both implemented using primarily hand labor in the southern US. Contractors providing these services have had problems documenting the amount and quality of work performed by individual laborers, and in providing auditable data to landowners of the extent of services provided. Electronic systems were developed to resolve these problems. The 'SmartPak' system recorded location while a worker sprayed herbicide and the 'SmartDibble' documented location when a tree was planted. Both systems had problems, but were also shown to provide value to the contractor using them.

Keywords: Herbicide, hand planting, electronic monitoring

Introduction

Temporary seasonal workers are commonly used in forest management in the US South, primarily in two specific tasks: regeneration planting, and herbaceous weed control. There are many reasons for this reliance on human labor, but the primary driver has been that costs tend to be lower. Mechanical alternatives are not available that provide as consistently good results across the broad range of conditions found in the region. In addition, a pool of non-resident labor is available and willing to work for wages lower than most native-born citizens, and at an acceptable level of productivity and quality.

There are questions, however, surrounding the employment of this temporary labor force, and the work they produce, that have caused some controversy. Large landowners, and the silvicultural contractors they employ, are seeking ways of improving the quality and accountability of work produced using seasonal laborers. This report will outline the authors' efforts to create information systems for documenting the output of manual labor in herbaceous weed control and hand planting.

Backpack Herbaceous Weed Control

Woodland Specialists, a silvicultural services contractor located in Chapman, AL, developed, in association with Auburn University Biosystems Engineering Department, a backpack spray system to reduce concerns with employee safety and quality assurance for clients. Design changes resulted in a new type of spray rig that addressed health concerns and added monitoring electronics to record spray system performance. Their objectives in creating the new system were:

1. Create a safer, healthier work place for their employees to reduce turnover and increase awareness of job performance standards, and
2. Develop a data collection system to document worker activity and chemical spray coverage over an entire tract.

The system they produced has been dubbed the 'SmartPak' and has been deployed in the field for one full season.

Worker safety concerns arose because of the nature of the work being performed. Herbicides are used extensively in forest stand management in the US, especially in the South, where an estimated 93 percent of silvicultural herbicides were sold (Shepard and others 2004). Their use in silvicultural stand management can be broken down into three primary objectives: site preparation, herbaceous control, and release (woody competition control). Site preparation and release treatments are typically broadcast applied using mechanized aerial or ground-based systems. Herbaceous weed control is usually applied a short time after planting to provide a window of time within which the seedlings can become established without competition. Applications are usually sprayed in bands directly over the seedlings, saving chemical and providing equal benefit to broadcast application. Because no official statistics are kept on herbicide use in forestry, estimates of the acreage treated for herbaceous control are sometimes conflicting. Dubois and others (2003) reported estimates of usage from the four largest herbicide distributors in the South, who based their numbers on sales volume and presumed application rates. About 950,000 ha of pine plantation were treated with some form of herbicide in 2002, with nearly 25 percent representing herbaceous competition control. Shepard and others (2004) also reported herbicide use estimates. Based on survey data collected from member institutions of the National Council for Air and Stream Improvement (NCASI), primarily forest products companies, herbaceous competition control was found to represent 43 percent of the area treated in the South, the largest single use. The companies included in the NCASI report might have practiced a more intensive form of silviculture than the groups in the former survey, perhaps explaining the difference in values.

Regardless of the exact amount of herbaceous competition control being practiced, its use seems to be currently in favor, and one common means of implementing this type of prescription is through banded spraying using backpacks. Miller (1998) reported that, during the mid 1990's, only about one percent of herbicides used in the South for silvicultural purposes were applied using backpacks. That figure has certainly increased over the ensuing years. Dubois and others (2003) found in their survey that backpack application was used on about 16 percent of total pine plantation acres treated in 2002. The increase can be attributed to reduced chemical use compared to broadcast applications, lowering costs, plus a decrease in acreage mechanically site prepared, reducing the area on which spray machinery can subsequently operate cost effectively.

Chemical application by hand can be a risky business, for both the person carrying the backpack and that person's employer. For the worker, the risks are primarily associated with inadvertent contact with the chemicals being applied. In the past, backpack applicators consisted of a tank and a wand with which the worker sprayed the chemical. Spray pressure was typically maintained using a hand-powered pump, a significant physical burden. From a safety standpoint, this system forced the operator to walk through vegetation that had just been sprayed.

Shepard and others (2004) reported that 90 percent of herbaceous weed control chemicals used in the South were classified as imazapyr, metsulfuron methyl, or hexazinone. Toxicity of such chemicals is normally expressed in terms of an LD_{50}, the amount of the substance per kg of bodyweight that is toxic to 50 percent of subjects to which it is administered. Campbell and Long (1995) reported LD_{50}s for imazapyr and metsulfuron methyl as 5000 mg / kg, and for hexazinone 1690 mg / kg. By contrast, the LD_{50} for caffeine is about 200 mg / kg. The amount of imazapyr ingested to be toxic to an average sized human, therefore, would be on the order of 375 g, an amount equivalent to the total active ingredient normally used in treating 0.4 ha of forest.

Although herbicides used in herbaceous weed control are relatively non-toxic, significant exposure of workers is possible because of the nature of the typical backpack sprayer and how it is used. Long-term exposure effects are not known, and neither is the effect of inert ingredients used in commercial forms of the herbicides. Most herbicide manufacturers do not reveal exactly what additives their products contain, but enough is known to further discourage exposure of workers.

Besides having to control exposure of workers to herbicides, application contractors must provide their clients with evidence of the quality of the services rendered. Ideally, a contractor should be able to provide an auditable record of the amount of chemical applied at what locations. These data are useful for billing clients and in resolving disputes over efficacy of the treatment.

Modified Spray System Design

Spray system changes implemented by Woodland Specialists included mounting the tank on an ergonomic backpack frame to increase worker comfort, and conversion of the hand-powered spray system to use an electric pump, reducing physical demands placed on the worker. Spray nozzles were mounted in a fixed, rearward-facing direction so the worker was not constantly moving through chemically treated vegetation. These modifications reduced the level of exertion required while spraying and freed the worker's hands to help maintain balance when moving through thick vegetation and slash.

A spray monitoring system was used to record the state of the spray pump and location of the worker over time. The system itself consisted of an AMD 188 microcontroller that used a digital I/O port to track the state of the spray pump switch. The microcontroller sensed the pump being switched on and began recording position output from a global positioning system (GPS) attached through a serial port. Data were recorded at 1-s intervals on a compact flash card. Garmin model 18 and 16 GPS units have been used, and both have proved successful. The microcontroller extracted relevant data from a group of NMEA 0183 strings (RMA, GGA, VGA) output from the GPS unit.

Included in the monitoring system was an LCD screen through which the microcontroller could provide information to the operator. Output included updates on the state of switches and the GPS (satellite and WAAS availability), plus an error field that reported problems with data storage and other high-level system functions. The microcontroller also kept track of travel speed of the worker and gave constant updates via the LCD screen. The operator would typically be given a target speed at which to walk in order to apply the herbicide at the prescribed rate.

Figure 1 shows the spray systems in use. Note also the use of chemical resistant suits by the workers. Figure 2 shows details of the data recording and GPS systems, including the LCD screen.

Figure 1. Workers using SmartPaks to apply herbicide for banded herbaceous weed control.

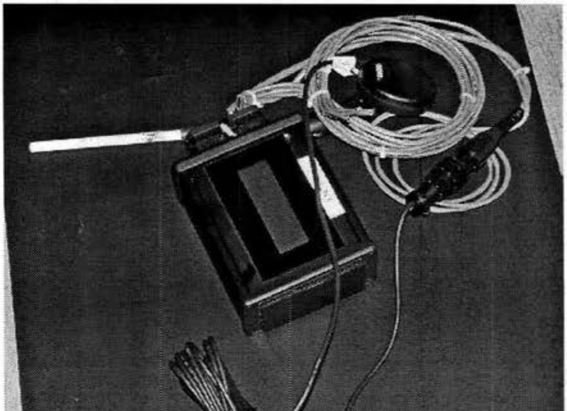

Figure 2. SmartPak electronics. The enclosure housed all electronics, including the memory card, which was accessed through the cover attached with Velcro on the side opposite the cable plug.

Field Experience Using the System

Woodland Specialists employed the SmartPak system in herbaceous competition control contracts on over 6000 acres during the 2005 spray season. About 20 total units were in use over that period, most on backpack units, but a few were used on mechanized spray equipment to track their application coverage. In general, the systems were deemed a success and plans are to use them again in the coming spray season.

Worker satisfaction with the SmartPaks was generally good, with the exception of a perception that, perhaps, productivity was not as high as desired. Wages were calculated on a linear distance application basis, so workers were very sensitive to any changes that affected their ability to cover ground. Although some spray system modifications enhanced productivity (the electric pump, hands-free operation), spray tank size had to be reduced in order to accommodate batteries, pumps, and other components. Most hand-powered spray units have a 19-liter tank. That volume was reduced by about 20 percent on the SmartPak, requiring additional trips to refill. The electronic components added 850 grams to the SmartPak, the battery about 3.5 kg more, but wet weight of the units (hand-powered and SmartPak) was roughly equivalent.

Operation of the SmartPaks required the workers to pay close attention to the feedback provided by the microcontroller, especially regarding battery status. They were motivated to do so, however, because of the link between the successful operation of the system and their pay. Workers typically monitored their speed while spraying, but they also looked for signs that the battery was beginning to lose its charge. When battery capacity was low, switching the pump on would drop the system voltage below a threshold required to run the electronics. In that case, the microcontroller would often power cycle and reinitialize the system. The initialization process would trigger the beginning of a completely new data record, which complicated an already too involved data management process.

There was some concern on the part of field technicians that the feedback given workers on speed did not have enough resolution. The speed data were extracted from the GPS information and were only available to the nearest 1/10th mph. The technicians, and presumably workers, felt this level of accuracy might not have been sufficient to ensure uniform spray coverage.

As one might expect, the SmartPak units deployed in the 2005 season proved not quite as durable as hand-powered units. Field technicians working with the spray crews felt the 2005 units would work reliably for about 3 to 4 months in the field. Spray season might last 6 months in that region of the country. Some of the failures observed had to do with the backpack carrier systems, which were essentially hiking pack frames that could not sustain the abuse suffered in field work over long periods of time. Units used later in the season were strengthened. Vibration and impacts during transport to and from the field was thought to decrease reliability of some of the electronics, but contamination from water or dirt was not a problem. Some of the components to be used in units for the coming spray season will be modified to increase the service life of the systems.

Workers were required to charge enough batteries every evening for the next day's work. The packs required at least two batteries per day in normal operation. Workers were not always happy with the responsibility of dealing with batteries, but seemed to accept it.

In the field, the SmartPaks worked about as well as could be expected for a prototype system. One area of operation that proved to be somewhat burdensome, however, was handling the constant stream of data being generated. This task required an estimated 30 to 40 hours per week for each of two technicians supervising seven spray crews. Over the course of the season, about 6 gigabytes of information were downloaded from the spray units, summarized, and transferred into a geographic information system (GIS). There was consensus among technicians that this process could be improved greatly.

The SmartPak controllers created a new output text file every time they were powered up. As work progressed, position information was logged into the file stored on a removable memory card in hour-minute-decimal second format. In the evening, files created for each worker were compiled then processed to convert the positions to decimal degree form. These data were exported into a dbf-type file for import into the GIS. Daily summaries of work activity were created for each laborer.

SmartPak Conclusions

After one season of extensive field testing, the management of Woodland Specialists felt the enhanced spray systems were worth the extra effort required to keep them operating. They cited the auditable documentation of work performed as the single greatest benefit of the systems. The data derived from the Smartpaks were used in settling accounts with landowners concerning number of acres treated and in resolving disputes over spray efficacy. Being able to show exactly where chemical had been applied proved a significant business advantage for the company. A map, such as that in figure 3, established a basis from which disputes could be resolved. The maps also provided a means of distinguishing Woodland Specialists from their competition and contributed to an atmosphere of trust with clients. When disputes arose over the level of herbaceous control in a particular tract, the company was able to show that they had in fact applied the chemical at the prescribed rate and that the prescription, or the chemical itself, must have failed.

Although other expected benefits, such as reduced chemical use through accurate application, were not as readily apparent, the SmartPak proved to be a useful tool in managing and educating workers. Maps of over sprayed and missed areas gave field technicians an unequivocal means of expressing concerns about poor performance to workers that most often did not speak English. Figure 4 shows detail of the data from figure 3. Areas of over- and under-spray, as well as the identity of the person responsible for the errors, are easily seen.

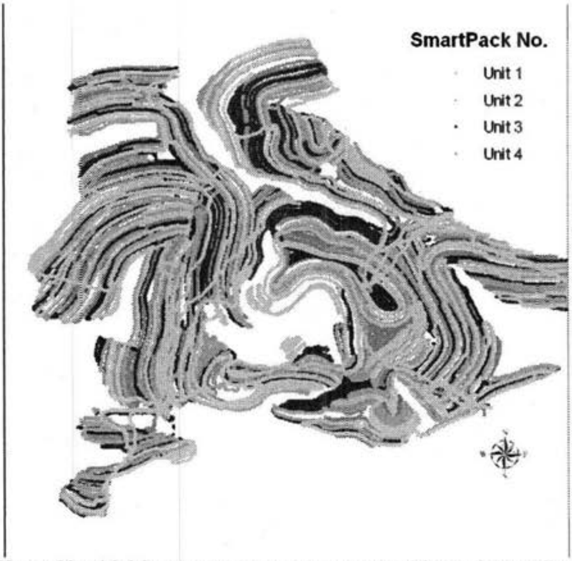

Figure 3. Map of herbicide spray coverage generated from data collected using the SmartPak. Color of the bands corresponds to which worker walked the given area.

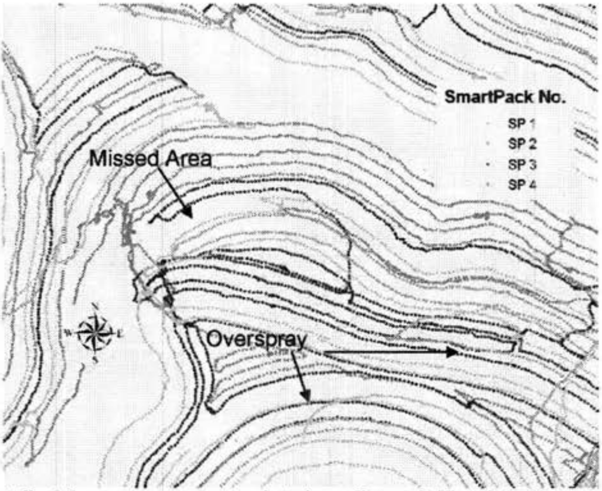

Figure 4. Detail of the spray coverage data from figure 3. The data illustrate gaps in spray herbicide application, and areas sprayed multiple times.

Hand Planting

Every year, US law allows issuance of 66,000 H2B guest worker visas to help companies involved in businesses other than agriculture hire workers they cannot recruit locally. In recent years, the majority (over 20 percent) of the visas issued have been for forest management activities (McDaniel and Casanova 2005). The program has been successful and Congress is considering upping the cap on visas to 200,000.

Regeneration planting of southern pines has been the largest single use to which H2B visas have been applied. McDaniel and Casanova (2005) reported that only about 8 percent of tree-planters working in the southern US were citizens, and about 84 percent were working with H2B visas. The remainder was on other types of visas, or undocumented.

A series of reports in the Sacramento Bee newspaper published in 2005 alleged serious mistreatment of workers hired for forestry work under H2B visas (Knudson and Amezua 2005). The articles reported many types of abuses, most involving taking advantage of the workers' dependency on the employer to maintain their status in the country. This publicity has focused a great deal of attention on the tree planting industry in the US. Some of the most critical has involved payment of planters. It has been alleged that workers were defrauded by unscrupulous employers that manipulated production figures, and the Southern Poverty Law Center of Montgomery, AL has filed a legal complaint on behalf of guest workers against the three largest contract planters in the country (Linn 2005) seeking redress.

These legal troubles have created to a tense atmosphere among companies involved in regeneration services. As in the case of herbaceous weed control, those companies that do their best to treat workers fairly and in compliance with laws feel they should be rewarded for the extra costs that effort entails. Unless they can fully document that compliance, however, their claims of unfair competition from other, less scrupulous, employers have no basis.

Woodland Specialists has, again working with Auburn University Biosystems Engineering, begun to investigate the use of electronic monitoring systems to document worker activity, this time involving tree planting. The concept, as in herbaceous weed control, was to create the technology to map all activity carried out by workers on a site, For planting, this meant showing placement of all trees across an entire stand. Such technology would form the basis of a fair piece-rate pay incentive program for workers, create an auditable record of work done for a landowner, and be a tool available to implement the concepts of 'precision forestry'. Given data on every tree in a stand, including its location, managers can focus attention and resources to the level of the individual tree, rather than the population. Managing for average conditions on a site will produce average results over time, but, as the technology becomes available, optimizing the growth potential of every individual should maximize the output of the entire stand.

The objectives of the work have been to

1. Create a wearable device that accurately records the location and time of a tree-planting event, and to
2. Use that device to map tree locations in hand planting operations.

A proof-of-concept version of such a device has been tested and prototype versions of a 'SmartDibble' are being assembled for use in the current planting season.

The SmartDibble

Trees are hand planted using one of two implements, a dibble or hoedad. Both are designed to create a hole in which the seedling is placed, the difference is in the motion required by the worker to use them. The hoedad uses an over-the-head swinging motion, much like an axe, while the dibble is an impact-type device, punched in a downward motion into the ground. While hoedads are used quite extensively in the southern US, dibbles are recognized as being superior from a quality of planting standpoint and were the focus of this research.

The tree planting event 'sensor' developed for the project took advantage of the fact that every tree required a rather abrupt motion on the part of the worker to create a hole in the ground. An accelerometer was used to detect impacts of the dibble with the ground, and a microcontroller, when an impact was observed, recorded the event along with a time stamp and a position from a GPS.

The proof-of-concept system built used an Atmel Atmega-128 processor with integrated 10-bit analog-to-digital converter to monitor the output of a National Semiconductor ADXL150 accelerometer. When acceleration exceeded a threshold value, position was read from a Garmin model 18 GPS, interfaced through a Bluetooth connection. There was also an LED controlled through a microcontroller digital output port that provided a rudimentary type of operator feedback. Figure 5 shows the dibble system, with the GPS antenna affixed on the top of a hardhat and the monitoring electronics in the box attached to the dibble handle.

The system was tested under controlled conditions and figure 6 shows the results of one such test. An operator walked through a field and, at a prescribed distance interval, simulated a tree-planting event. Instead of a tree, the operator left a pin flag in the hole. The location of the pin flags was established using a real-time kinematic (RTK) GPS system and compared to the location reported by the dibble. In general, fixes of tree position were close to what could be considered a 'true' position from the RTK system. Differences could be reliably attributed to the relative inaccuracy of the GPS worn by the operator in these tests.

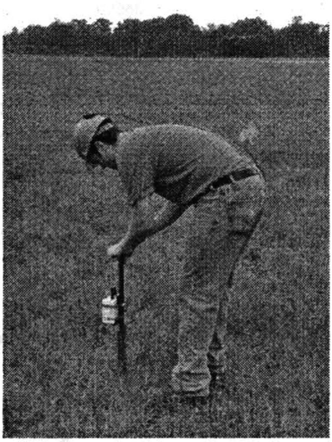

Figure 5. A prototype SmartDibble, a tool to collect information on tree location while planting. The system electronics are housed in the small box attached to the dibble handle. The electronics monitor received position information output from a GPS attached to the helmet the operator is wearing. The link between the controller and the GPS is established using a Bluetooth connection.

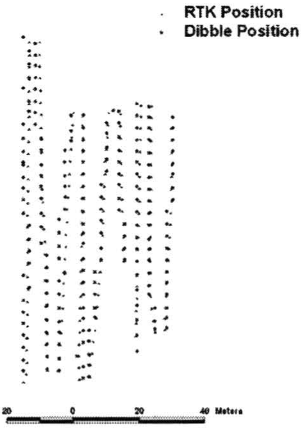

Figure 6. Map of planting locations established using two positioning systems: the SmartDibble, and an RTK GPS system.

Evidence has suggested that this, or a similar, system could be used in the field. A new prototype system has been developed for application in actual planting, but results have not been obtained as of yet. Plans are to test it over the first few months of 2006. The new SmartDibble incorporated several improvements over the previous version in electronics hardware, primarily in using a wireless connection between the accelerometer and the computer. The proof-of-concept system used a wireless link with the GPS to eliminate a physical connection between the operator and the dibble, but this meant there was quite a bit of additional hardware carried on the dibble itself, including the sensor, microcontroller, and batteries to power the entire system. In the newest version, only the sensor is carried on the dibble, while GPS, controller, and data storage hardware are carried on the person.

The hardware side of the SmartDibble has shown great promise, but, as in the SmartPak, data management will likely present the greatest obstacle in practice. One problem that has not been solved at this time is the issue of multiple impacts associated with a single tree-planting event. The hardware detects when an impact greater than a specific value occurs, but cannot discriminate if two or more impacts happen in the same location. It is most often the case when planting that multiple impacts are required to create the hole for the seedling, and that another impact is normally associated with closing the hole. Data from the SmartDibbles will therefore have to be filtered to arrive at a final list of legitimate seedling locations.

Conclusions

Manual operations are used widely in forest management in the southern US and likely will be in the future. Many concerns have been raised about the quality of work performed by hand and the systems presented in this report were developed to document the rate and spatial attributes of two forms of manual labor. The SmartPak system documented application of herbicides for herbaceous weed control, providing maps of where and when chemical was sprayed, as well as who performed the work. Although collecting the data was problematic, it has proved its value to contractors in documenting for landowners work performed and in resolving efficacy disputes. Although it has not been applied in practice as of yet, similar benefits should accrue from use of the SmartDibble system.

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ROBUST OPTIMIZATION OF FOREST TRANSPORTATION NETWORKS: A CASE STUDY

Glen Murphy and Henk Stander
Forest Engineering Department, Oregon State University, USA
E-mail: glen.murphy@oregonstate.edu

Abstract

Transportation of log products from forest to mills is becoming the largest single component (20% to 50%) of seedling to mill-door, wood supply costs for many suppliers around the world. Consequently, there is considerable interest globally in work procedures, equipment configurations and decision support systems that lead to reductions in overall forest transport costs. Decision support tools for optimizing forest transportation networks have been successfully used for more than four decades. These tools are generally based on the assumption that data inputs are known with certainty.

There is often a lot of uncertainty associated with forestry data, however. For example, in relation to forest transportation problems there is uncertainty associated with stand volumes, product yields, variable transportation costs, road and bridge construction costs, timing of harvest, market prices, etc.

Robust optimization procedures are now being developed to tackle problems in many industries. These procedures have a goal of finding "a near-optimal solution that is not overly sensitive to any specific realization of the uncertainty". The literature on robust optimization is still evolving and provides a variety of measures for assessing "near-optimal" and "not overly sensitive" solutions.

In this paper we report the effects of five robustness measures on route allocation and infrastructure investment decisions for a small New Zealand forest transportation network. Over 400 sales were scheduled to be harvested over an eleven year period. Each sale represented one of four log product types. Because of the forest's location on a peninsular and nearness to a railway line, modes of transport from the forest landings to the mills included truck, rail, and barge, as well as combinations of these. The harvest schedule, that is year of harvest, was known with certainty for each sale. Log product yields and costs, both fixed and variable, were uncertain.

Our research demonstrated firstly that "the optimal solution" was largely dependent on the assumed input values and secondly that substantial differences in route allocation and investment decisions would result. Thirdly, it demonstrated that "the robust solution" selected would depend on the robustness measure used - not all five measures indicated the same solution was the most robust.