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Enhancing Ontario's Forest Resource Inventory Using Large Scale Sampling Photographs

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1997

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NODA • EDNO
CANADA
ONTARIO
Northern Ontario Development Agreement
Entente de développement du nord de l'Ontario
Forestry • Foresterie

Funding for this report has been provided through the Northern Ontario Development Agreement's Northern Forestry Program.

Canadian Cataloguing in Publication Data

Dendron Resource Surveys Inc.

Enhancing Ontario's forest resource inventory using
large scale sampling photographs.

(NODA/NFP technical report; TR-45)
Includes an abstract in French.
Includes bibliographical references.
"Funding for this report has been provided through the Northern
Ontario Development Agreement's Northern Forestry Program."
ISBN 0-662-25271-3
DSS cat. no. Fo29-42/45-1997E

1. Forest surveys—Ontario.
2. Aerial photography in forestry—Ontario.
I. Great Lakes Forestry Centre.
II. Title.
III. Series.

SD397.S86D46 1997 333.75'11'09713 C97-980011-0

Catalogue No. Fo29-42/45-1997E
ISBN 0-662-25271-3
ISSN 1195-2334

Copies of this publication are available at no charge from:
Publications Services
Natural Resources Canada
Canadian Forest Service
Great Lakes Forestry Centre
P.O. Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Microfiche copies of this publication may be purchased from:
Micro Media Inc.
Place du Portage
165, Hotel-de-Ville
Hull, Quebec J8X 3X2

The views, conclusions, and recommendations contained herein are those of the authors and should be construed neither as policy nor endorsement by Natural Resources Canada or the Ontario Ministry of Natural Resources. This report was produced in fulfillment of the requirements for NODA/NFP Project No. 4021 "Enhancing Ontario's forest resource inventory using large-scale sampling photographs".

Dendron Resource Surveys Inc. 1997. Enhancing Ontario's forest resource inventory using large scale sampling photographs. Nat. Resour. Can., Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON. NODA/NFP Tech. Rep. TR-45. 18 p. + appendices.

ABSTRACT

The purpose of this project was to investigate how large scale sampling photography can be used to enhance the Ontario Ministry of Natural Resources' current Forest Resource Inventory methodology, particularly for forest management planning, regulation, and control purposes. The Timmins Forest, 162 923 ha in size, was used as the study area.

Large-scale photography complements the Forest Resources Inventory program by providing more comprehensive stand data, such as the proportion of species in a stand, number of stems, basal area, and volume per hectare. Stand data can be broken down by species and diameter. The cost of data collection is usually less than $100 per plot.

The enhancements concentrate on three primary roles: namely, (i) how large scale sampling photography parallels the Forest Resource Inventory data collection procedures and can produce some complementary results; (ii) how large scale sampling photography can support current Forest Resource Inventory data collection tasks; and (iii) how large-scale photography can provide supplementary information that Forest Resource Inventory data cannot.

The project also assessed the effectiveness of the inventory data produced by each of the three contributions in an operational context. Effectiveness was evaluated in terms of the accuracy of the information, cost, and limitations.

RÉSUMÉ

Ce projet vise à étudier comment la photographie par échantillonnage à grande échelle pourrait améliorer la méthode que le ministère des Richesses naturelles de l'Ontario utilise pour dresser l'Inventaire des ressources forestières, particulièrement à des fins de planification, de réglementation et de contrôle de l'aménagement forestier. La forêt de Timmins, d'une superficie de 162 923 ha, a constitué la zone d'étude.

La photographie par échantillonnage à grande échelle vient compléter l'Inventaire des ressources forestières, car elle dégage des données plus exhaustives sur les peuplements, comme la proportion des essences, le

nombre de tiges, la surface terrière et le volume par ha, lesquelles peuvent être ventilées selon les essences et les diamètres. Leur collecte coûte généralement moins de 100 $ par parcelle.

L'étude veut répondre à trois grandes questions sur la photographie par échantillonnage à grande échelle : (i) Équivaut-elle à la collecte des données pour l'Inventaire des ressources forestières et produit-elle certains résultats complémentaires? (ii) Concourt-elle à la collecte actuelle des données pour l'Inventaire des ressources forestières? (iii) Fournit-elle une information que les données de l'Inventaire des ressources forestières ne révéleraient pas?

En outre, le projet a évalué l'efficacité des données d'inventaire issues des trois contributions dans le contexte opérationnel. Cette efficacité a été mesurée en fonction de l'exactitude de l'information, des coûts et des contraintes.

TABLE OF CONTENTS

ENHANCING ONTARIO'S FOREST RESOURCE INVENTORY USING LARGE SCALE SAMPLING PHOTOGRAPHS

INTRODUCTION

All ten Canadian provinces and the northern territories use a forest inventory method based on the production of stand maps from aerial photo interpretation, a database that describes these stands, and a source of data that summarizes the amount (volume) and distribution of available forest resources. The quantities, usually expressed in stems per hectare, basal area, gross total and merchantable volume, and sometimes biomass, may be further subdivided by species and diameter class. Until recently the data focused primarily on information needed to plan, schedule, and regulate fiber production.

Most Canadian jurisdictions rely on a blend of temporary and permanent sample plots; the former to support their inventory projections, and the latter to assess stand growth, development, and yield. The exception is the Ontario Ministry of Natural Resources' (OMNR) Forest Resource Inventory (FRI), which, although it emphasizes forest stand mapping, does not compile stand timber volumes from sample plots except for locally focused operational cruises. Instead, the volume is based not on empirical data but on existing published yield tables or equations that provide a generalized and idealized expression of a stand's potential productivity. Reliance on yield data avoids the high cost of establishing and measuring a large number of field sample plots.

All the inventory methodologies have adequately served the needs of timber management. However, because management planning must now adjust to broader issues, and to stricter regulation of harvest levels within guidelines that are based on principles of sustainability of the forest ecosystem and on integrated resource management (IRM), much more is being demanded of the forest inventory. Current inventory methodology cannot always meet the emerging information needs for IRM planning and control. Inevitably this will lead to a broadened perspective that will include such areas as forest ecological classifications, soil productivity, water quality, maintenance of biodiversity, suitability of wildlife habitat, status of forest protection, and traditional uses of the forest.

In response to these needs, attention has turned to ways of enhancing forest inventories with data that is better suited to the requirements of the '90s, and to the potential role of new technologies, such as the use of satellite data, digital elevation models, specialized general-coverage aerial photography, large scale sampling photography (LSP), global positioning systems (GPS), and geographic information systems (GIS). GIS, apart from greatly improving the methods of analyzing, presenting, and updating inventories, provides a platform for merging data on a common geographic base for analysis and presentation purposes. Considerable progress in applying these technologies to the forest inventory has been made in recent years.

This project investigated the role that large scale sampling photographs can play in enhancing, supporting, and supplementing Ontario's Forest Resource Inventory. The role of LSP was intimately related to many of the other technologies mentioned, especially GIS.

OBJECTIVES

The purpose of this project was to use the Timmins Forest, in northeastern Ontario, as a study site to demonstrate how large-scale photography can enhance the current FRI methodology, particularly for forest management planning, regulation, and control purposes.

The enhancements concentrated on three primary roles: namely, (i) how LSP parallels the FRI data collection procedures and can produce some complementary results; (ii) how LSP can support current FRI data collection tasks; and (iii) how LSP may provide supplementary information that the FRI cannot. The project was expected to assess the effectiveness of the inventory data produced in an operational context. To do so, the data ultimately had to be tested as part of a decision support system for forest management planning purposes.

APPROACH

The LSP methodology was originally designed to replace or supplement the costly process of collecting sample plot data in the field. The data, which can be effectively collected by means of LSP, include both stand averages and individual tree dimensions. The stand data most commonly collected are: species composition; height; crown cover density; average tree diameter; basal area; several expressions of gross, merchantable, and net volume; and sometimes biomass. These data largely parallel or complement that found in the FRI in much the same way as would an intensive field sampling or an operational cruise. The LSP methodology can also be used to determine plot shape and size and to assess individual tree species, height, crown width, length, and area and position coordinates of the tree on the plot. The diameter at breast height (DBH) and volume are estimated from other photo-measured variables. Tree position data can be used to express the degree of tree competition and growing space, and mapped to illustrate or analyze spatial relationships among the trees or tree clusters in the stand.

The LSP has not been established as a reliable means of estimating age or tree growth rates, or for assessing cull and defect. However, damage caused by some defoliating insects can be detected and assessed. Generally, a small quantity of field data is required to supplement such data, to check the accuracy of the LSP data, and to develop models for estimating some tree dimensions that cannot be measured directly, viz., diameter and volume.

How may LSP be used to enhance FRI? From past experience, it appears that it may contribute in three primary ways. First, LSP can be used as a more realistic source of tree and stand data for assessing stem counts, basal area, and various expressions of volume that would normally be taken from yield models or based on field surveys. The LSP data, for example, can provide a breakdown of such information by species and diameter class—empirical information that is valuable for operational decisions and necessary to drive many of the simulation models used for scheduling forestry operations, planning, and control. The effectiveness ultimately must be assessed in terms of accuracy or reliability, practicality, and cost-effectiveness.

Secondly, LSP may be able to support current FRI procedures. For example, FRI 1:20 000 photo interpretation requires that the interpreter assemble existing data, coordinate field sampling to cover problem areas, or make field visits for verification purposes. As indicated above, LSP can be used as a source for most of the data needed for the FRI interpretation.

Finally, LSP may offer data that the FRI is unable to supply. For example, the FRI stand data provides information on stand averages, but not on the spatial distribution of attributes within the stands. LSP, on the other hand, provides the distribution of tree cover and spaces, which may be of vital importance to the habitat of some wildlife species, and can be characterized, analyzed, mapped, and displayed for planning purposes. Under some conditions, LSP also offers the opportunity to survey dead standing and fallen trees, which may provide important wildlife habitat and contribute to dead organic material for micro-organisms, all of which contributes to ecological integrity and the maintenance of biodiversity.

The ability, accuracy, and cost-effectiveness of LSP in enhancing FRI were tested and analyzed in this project. An operational case study was conducted to demonstrate the overall effectiveness of the technology. To maintain a tight focus on operational use, the tests and case study were assessed on an active forest management unit where the data were needed by the operator for planning, scheduling, and control purposes. Successful use should indicate in a general way where the technology could best complement FRI, either for company operations or for provincial purposes.

In the course of this project a number of specific tasks and roles were investigated. These investigations provided details of the methodology, as well as results, and are being published as separate Northern Ontario Development Agreement (NODA) technical notes.

LARGE SCALE PHOTO METHODOLOGY

Study Area

The study area chosen for this project was the Timmins Forest, the location and general outline of which are shown in Figure 1. This is a forest management unit operated under licence by the QUNO Corporation. It was ideal for this work because of its size and stature in serving a viable industrial operation, and because forest inventory and related resource data were needed for management planning and simulations, wood supply projections, and the scheduling of forestry operations.

According to the FRI survey, the total area of productive forest land is 162 923 ha. The breakdown of that area by species and site class is shown in Table 1.

Sampling Design

FRI maps of the study area were available in digital format for the project. The target area was covered by 38 sheets, filling the inset shown in Figure 1. A complete set of FRI stand attribute data was also available.

The species groups and age classes were used to identify sampling strata. The strata have two purposes: the first is to provide summaries that relate closely to operational needs, and the second is to improve sampling efficiency. In the latter case, aggregation of stands into groups based on similar characteristics tends to reduce the variability of key variables, such as basal area and volume. When variability within the strata is reduced, the accuracy of estimates for a given number of sample plots will be higher. Thus, stratification improves sampling efficiency.

The strata in Table 2 were defined by QUNO for the three highest site classes (X, 1, and 2 according to FRI criteria) on the basis of species groups and age classes.

A given stratum contained aggregations of stands from many map sheets. These strata formed the foundation of the stratified random sampling design for the large scale photo method.

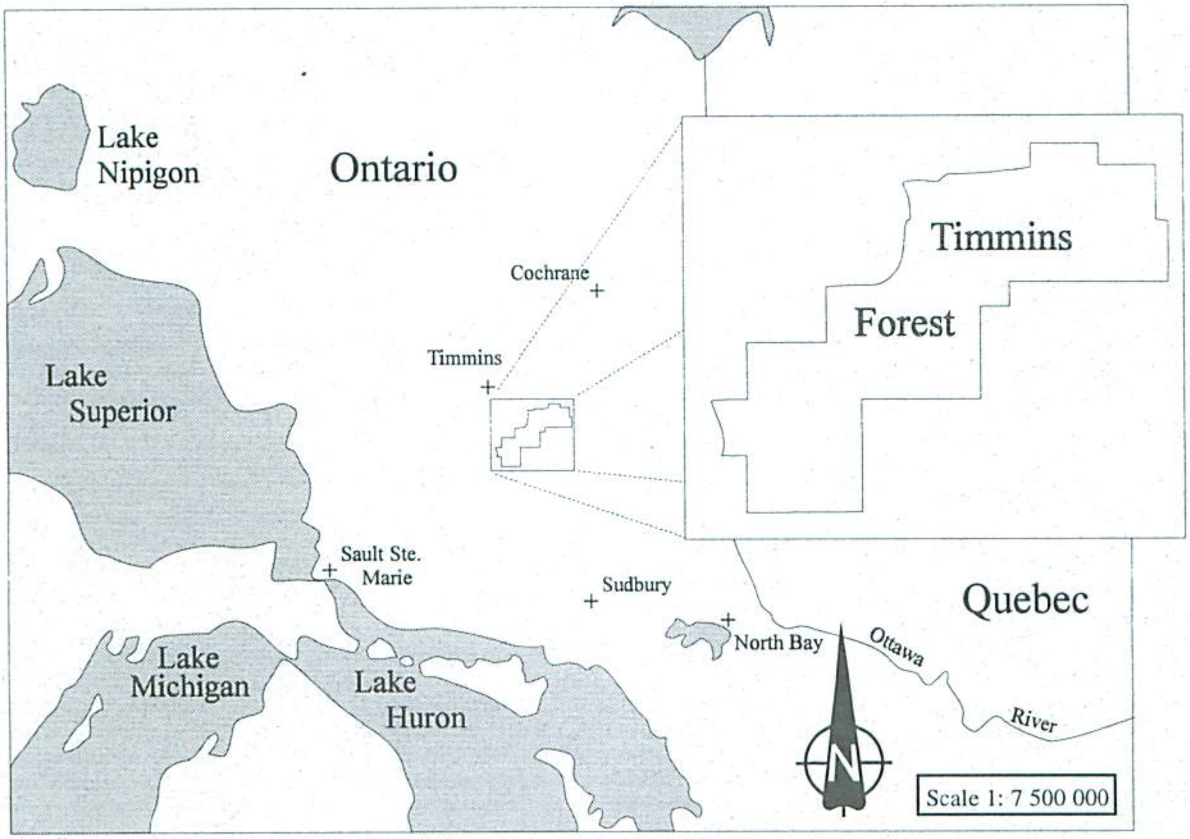

Figure 1. Location and outline of the Timmins Forest adopted as the study area for the project.

Table 1. Productive forest land base area (ha) of the Timmins Forest.

Species	Site class					
	X	1	2	3	4	Total
Spruce	698	22 081	45 851	2 939	277	71 846
Balsam fir	644	22 766	6 007	54	107	29 578
Pine	223	10 587	8 697	794	34	20 335
Other conifers	-	7	1 428	840	65	2 340
Poplar	16	1 192	17 960	4 881	567	24 616
White birch	60	2 973	9 998	1 002	35	14 068
Other hardwoods	-	27	113	-	-	140
Total	1 641	59 633	90 054	10 510	1 085	162 923

Each stratum to be sampled was treated as an independent population on which estimates of key characteristics (e.g., number of trees per hectare, basal area per hectare, total and merchantable volume per hectare, etc.) were obtained to a prescribed level of accuracy.

Figure 2 illustrates a reduction of one of the map sheets, showing the distribution of stands comprising Stratum S11.

All stands that matched a stratum description were aggregated and highlighted on all the maps covering the target area. In a conceptual sense, the stratum was completely covered by a series of strips the width of the LSP coverage (about 70 m at a photo scale of 1:1 200), either in the computer or manually. The length of each strip within the stratum was obtained and the strips numbered and listed. Candidate strips for photo coverage were selected from the list, with probability proportional to length. This

Table 2. The forest strata specified for this project, based on species group and age class.

Stratum	Species group	Age class (years)	Stratum	Species group	Age class (years)
S5	Spruce	41–60	A5	Poplar	41–60
S7		61–80	A7		61–80
S9		81–100	A9		81–100
S11		101–120	A11		101–120
S13		121+			
P5	Jack pine	41–60	B9	Birch	81–100
P7		61–80	B11		101–120
P9		81–100	B13		121+

ensured that every photo falling along the lines had an equal probability of being selected. Lines shorter than a ten-photo series were rejected because the burst of the photographs taken was too short to be photographed efficiently, and because they usually concentrated along the edge of a stand and appeared to overrepresent borderline transition conditions. The strips continued to be chosen until the total length of selected strips attained a prescribed length. This prescription was determined by the budget for the project and the allocation or balance of photo coverage among all the strata. Some strata may be assigned more importance than others (perhaps because of commercial value, which influences the allocation). The maximum length of LSP coverage for a particular stratum was determined by the allocation.

The selected strips were then mapped by the GIS system, a hard copy of which was used to make up the flight map for the project. Figure 3 illustrates a portion of such a flight map based on the S11 stratum in Figure 2.

To complete the random sampling process, every large scale photo pair along the selected strips was assigned an equal probability of being selected after the LSP was obtained. Plots were selected at random until an initial minimum number was obtained. If necessary, additional samples can be chosen by a sequential sampling process until the required accuracy is achieved.

Acquisition of Large-scale Photographs

The selected strips were photographed during a photo mission using a light, fixed-wing aircraft and the LSP airborne system shown in Figure 4. The system is comprised of two 70-mm cameras, a laser range finder, and a pitch and roll sensor. At the time of this project, the controller/data acquisition system was upgraded to a PC 386 to accommodate an interfaced GPS. The PC regulates and logs the firing of the cameras, captures the data from the sensors, and records the data on diskette and tape. The

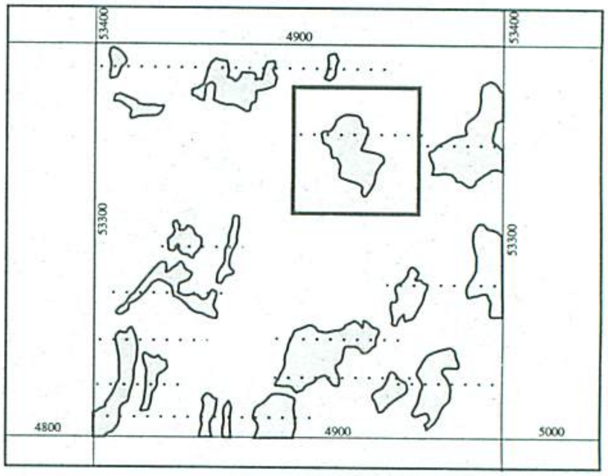

Figure 2. Map showing the distribution of Stratum S11 across one of the 1:20 000 FRI maps of the project area, and the random selection of strips for large-scale photography. The highlighted polygon is enlarged in Figure 3.

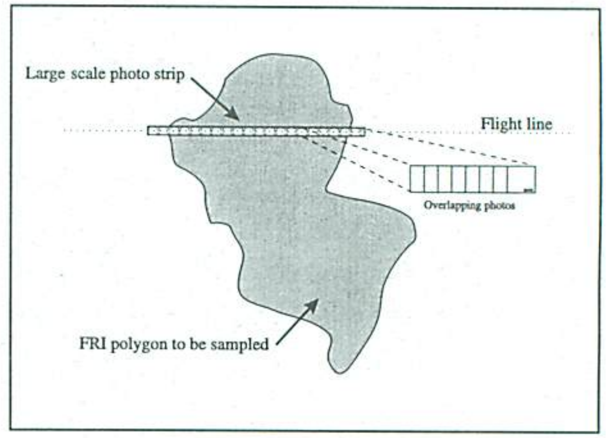

Figure 3. Illustration of a portion of a flight map used to plan and guide the LSP acquisition.

GPS was used both to guide the LSP flight navigation during the mission and to provide the geographic location of every photo. The trial attempted to determine if the new technology improved the LSP navigation during the flight mission and, more particularly, the efficiency of the post-flight LSP track recovery, which is usually completed manually. The manual process involved the transfer of the LSP center points to an intermediate-scale tracking camera photo using common image features, then to a general-coverage photo of the same area, and finally to the corresponding map by a photo-to-map transfer. The GPS modification and accuracy evaluation are described in the next section.

The flight specifications used for this project were:

Camera 1: Vinten 70 mm with 300 mm lens for LSP coverage
Camera 2: Vinten 70 mm with 80 mm lens for tracking
Scale determination: pulsed laser range finder
Camera attitude: gyro-based pitch and roll sensor
Navigation and positioning: GPS
Controller/data acquisition system: PC 386 modified for an aircraft environment
Nominal flying height: 350 m
Nominal LSP scale: 1:1 200
Film type: Ilford FP5 panchromatic black and white
Forward overlap: 55 to 70 percent

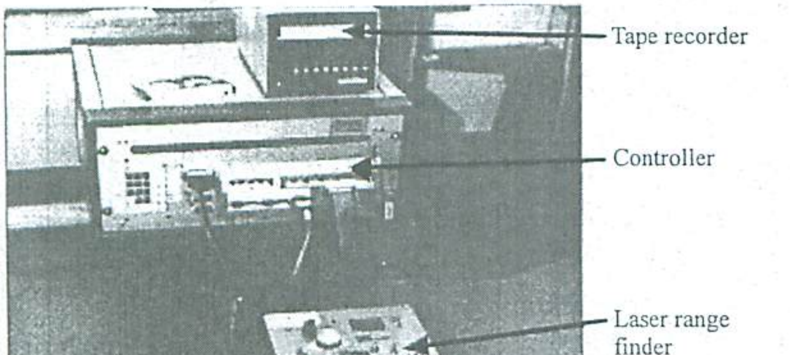

Figure 4. Large-scale photo acquisition system.

Evaluation of the Role of the Global Positioning System

Global positioning systems have evolved rapidly in the last few years, and are finding applications in many areas and on many kinds of platforms. GPSs operate by receiving time-coded data simultaneously from several navigation satellites. They then process the data through computations that are analogous to triangulation and which determine the longitude, latitude, and elevation of the system along with time and other data at each capture interval. GPSs are used on the ground in a stationary mode, on foot, on various terrestrial and aquatic vehicles, and in aircraft. Evaluation of a low-cost GPS by Brown (1993) describes the performance that can be expected from inexpensive systems. New processing techniques, which take advantage of redundancies and input from more satellites, are advancing steadily. Systems are becoming more accurate, smaller, and cheaper. GPS systems installed on a card that can be inserted directly into a PC or notebook portable have recently been introduced.

An airborne system called GPSNAV, designed by Sander Geophysics Ltd. of Ottawa, was used for this project. GPSNAV was based on a Trimble 4000DL, eight-channel GPS receiver. The system was interfaced to Dendron's airborne PC-386 controller via an RS232 link. GPSNAV provided the navigational data used by the pilot to fly the aircraft on a predetermined flight path; the RS232 interface supplied the longitude, latitude, elevation, and time data to the PC, where it was tied to the individual photo exposures and then recorded.

The recorded longitude and latitude were converted to UTM coordinates using the NAD27 convention so as to be compatible with the available base maps. The UTM coordinates were imported into the GIS, and individual photo positions were plotted on the maps. Figure 5 illustrates a plot of points from an LSP line and compares their position with the manual track recovery method. Except for a leg of about 60 photos in the test, where the conventional track recovery was based on an incorrect tie point, the plots of photo locations by the GPS and manual method deviated by less than 30 m. This was a more accurate result than expected, likely because the SA was inactive during the flight. The GPS-based track recovery, as illustrated in Figure 5, identified a significant error in the manual method. The navigational data used to guide the pilot were also found to be very effective.

Track recovery by the manual method, with the approximately 28 000 photos used in this project, cost about \$10,000. On the other hand, the GPS rental was \$1,250 and, once the software and interfacing were in place, additional processing and plotting costs were minor.

Photo Plot Measurement

For each stratum, a sample of LSP pairs was selected at random from the list of eligible plots. The list usually has about four or five times as many potential plots as would actually be measured. This allows for better coverage and

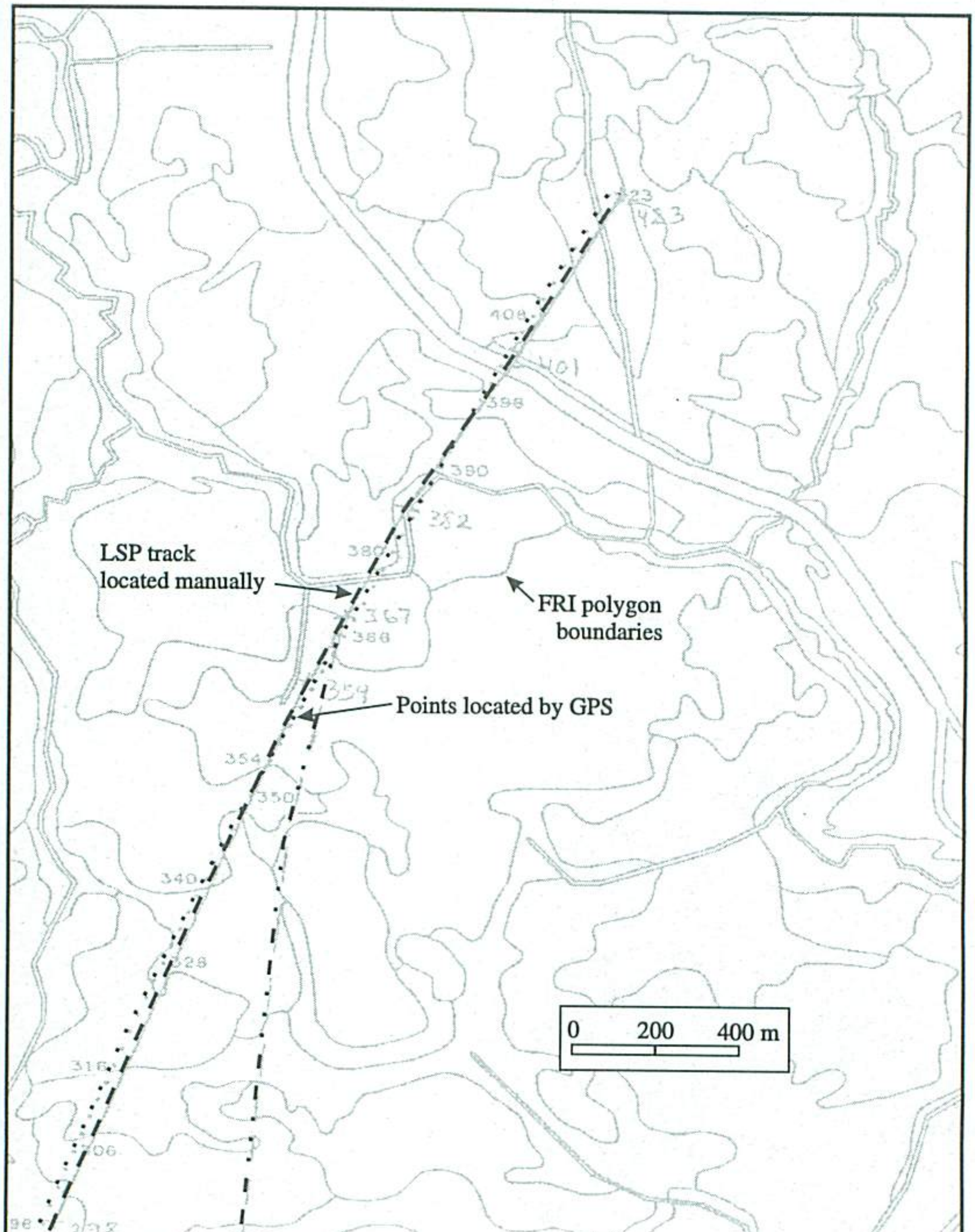

Figure 5. Section of a stand map, comparing manual LSP track recovery with GPS positioning.

representation of the strata and, if required, the latitude to intensify sampling. On the stereo pair of photos, a rectangular plot approximately twice as long as wide, and about 170 m^2 in size, was established in the center of a line connecting the principal points of the photo pair (Fig. 6).

All trees taller than a specified height value (7 m in this study) were numbered on the photos. A photo interpreter coded the species of all living trees and identified each standing or downed dead tree. The fallen material included broken tops, fallen snags, or recently fallen or broken live trees.

Reference data pertaining to the plot (plot identifier, map name or number, stand number, flight line, and UTM coordinates) and photo model data (flying height, and the pitch and roll of the stereo pair) were set up in an LSP database. The photo base and the area of the sample plot were added later, when the photogrammetric model was constructed and the plot dimensions measured.

The database also included tree data that were relationally linked to the plot data. The database structure included the number and species code of each tree; the X,Y position of the tree on the plot; tree height and crown area; and, for fallen dead material, a place to store the length and diameter of the pieces.

To obtain the plot and tree measurements, a stereo pair of photos was mounted on the digitized photogrammetric plotter. The photo model data were used at this time, and the photogrammetric model was created through an analytical process using digitized photo points, flying height, and pitch and roll data to scale and level the model. The model was then capable of generating X,Y, and Z (elevation) data of any point in the stereo pair. The origin was set at the bottom left corner of the plot (Fig. 6). All coordinates and linear measurements were recorded to the nearest decimeter, except the diameter of dead material, which was recorded to the nearest centimeter. The plot measurements included the plot corners, used to check whether or not a tree was in the plot and to determine the exact plot area, and sample ground level points used to create a terrain elevation model over the plot surface. Each numbered tree was digitized at the top. The X,Y position was recorded, the in/out status checked, and the height calculated as the difference between the elevation at the tree top and the elevation of the terrain surface at the same X,Y location. For trees with a significant lean, both the position of the top and base were digitized and the length calculated. The crown area was measured as the area of a polygon formed by a digitized stream of X,Y coordinates around the crown perimeter.

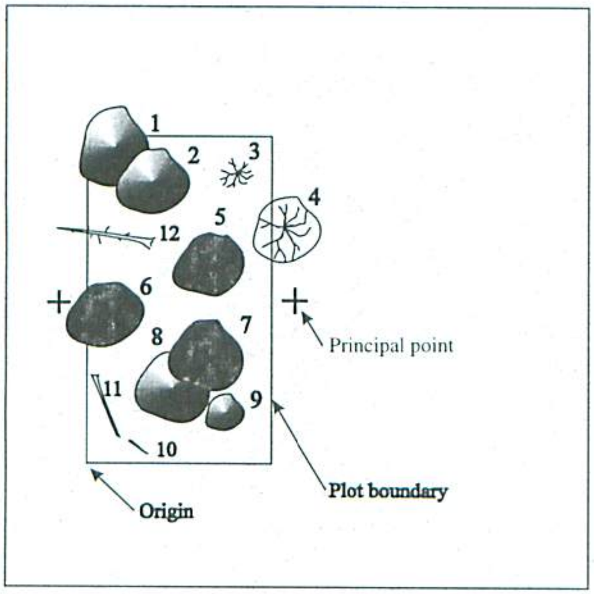

Figure 6. Diagram of a stereo pair of LSP showing the plot layout, tree crowns of standing trees, and some fallen residues.

Dead standing trees were measured only for height; crown area was omitted because, in most cases, the crown was missing or could not be clearly seen. The species of the dead tree was assumed to be the same as its nearest neighbor. A tree with a broken top was treated as a dead tree, except that the position of the top was estimated (from neighbors), digitized, and the elevation of the breakpoint digitized. To account for the missing top, the information was used at the compilation stage to adjust the volume estimates.

The fallen dead trees, or portions thereof, were measured within the plot only. Any portion lying beyond the plot boundary was disregarded. The diameter of the piece was measured midway between the ends of the portion within the plot. The X,Y location of the midpoint was also captured.

Trees were processed one at a time until all numbered trees were measured. If, during the course of the measurement work, eligible trees were found without numbers, they were measured and appended to the database. Errors in species identification or entry can be edited interactively during the measurement phase. Likewise, absurd measurements were detected and flagged for re-measurement. Any living or dead material can be reinterpreted and measured if errors are suspected.

Field Evaluation

The field exercise had two purposes: to check the accuracy of the LSP work, and to collect data that could not be measured directly on the photos. In the latter case, stem characteristics such as diameter at breast height (DBH), were estimated from closely related tree dimensions that could be measured. The development of models that exploit these relationships required taking measurements of the same trees on the photo and on the ground. This is referred to as paired sampling.

In both cases, a subsampling process was used to ensure that a reasonably representative sample of trees was obtained in the field. Random subsampling was used to select the LSP plots, but was constrained by access considerations. Plots were located in the field in three stages: namely, find the location of the plot on general coverage photos of the area (FRI 1:20 000); transfer the plot to the tracking photos to facilitate precisely locating the plot in the field; and proceed to the LSP plot where the individual trees could be located and identified. Although not tested, GPS may offer some help in locating field plots.

The accuracy assessment included a check on borderline and omitted trees, the accuracy of species identification, and a check on the height of a few trees. Crown area was not checked because it cannot be determined well in the field. The procedures and the results of the paired comparison are described in Dendron Resource Surveys Inc. (1996a).

In this project, the accuracy assessment revealed no surprises or anomalies. The assessment described in a report by Nielsen et al. (1979) and Dendron Resource Surveys Inc. (1996a) indicate clearly the level of accuracy that can be achieved on LSP.

During field work, the DBH of trees selected for the model development that will be described next were measured and recorded. The size–class distribution of sample trees was analyzed to ensure that the full range of tree sizes was well represented for each species requiring an equation.

Development of Diameter Equations

Considerable effort has been devoted to testing different model versions and to finding the most effective LSP tree variables for estimating DBH. Reports by Aldred and Sayn-Wittgenstein (1972), Nielsen et al. (1979), and Hall et al. (1984), summarize this work.

The model generally considered to work the best is an exponential type. It assumes that when height and crown area tend to zero, so also should DBH. The exponents determine the linearity or shape of curved relationships. The model builds on the easily recognized direct relationship between DBH, tree height, and crown size, individually, and the less obvious combined effect of height and crown size on the relationship. The use of combined variables is based on the notion that the DBH/height relationship will change in stands of varying density. Dense stands will generally have smaller crowns for a given DBH/height ratio; open stands will tend to have larger crowns. Therefore, the combined equation helps to take into account stand stocking or density differences and incorporates them into the model.

Crown area has generally been found to be the most effective measure of crown size, primarily because it can be measured most consistently on the photos. Other variables that express stocking, density, or growing space (such as expressed by Thiessen polygons) were tested and, although effective in some cases, they were not consistent. The combined model takes on the following general form:

$$\text{DBH} = \mathbf{a} \times (\text{Height})^{\mathbf{b}} \times (\text{Crown Area})^{\mathbf{c}}$$

where **a, b,** and **c** are equation coefficients for a particular species or species group.

The development of the combined model and the resulting models for this project are described in detail in Dendron Resource Surveys Inc. (1996b). Equations developed for this project are listed in Table 3.

The N, R, and SE values in Table 3 refer to the number of observations (trees), correlation coefficient, and standard error of the equations, respectively. The last two values can be used as a measure of goodness of fit of the equation. The SE is usually interpreted to mean that the equation will approximately estimate DBH within ± SE two-thirds of the time, or within 2 SE 95 percent of the time. In this project, the white birch (*Betula papyrifera* Marsh) and aspen (*Populus* spp.) SEs were somewhat larger than usual. This is likely explained by the higher variability introduced by the overmature stands, broken tops, damaged or distorted trees, and dense patches of regrowth.

Inventory Compilation

Compilation involved the selection of measured plots by stratum and the processing of plot and tree data to produce the key per hectare inventory statistics and stand and stock tables. The key statistics included tree count, basal area, total volume, and merchantable volume per hectare; breakdowns by live and dead material, species or species group, and diameter class; and related stand data such as average tree height, crown cover density, and components of biomass. The key statistics also included the sample size and accuracy estimates for the stratum. The stand and stock tables present detailed breakdowns by species and diameter classes, and provide a clear picture of stand structure. Some examples of key statistics and stand and stock tables are shown in Appendix A.

The per hectare statistics were multiplied by the stratum area and constituent stand polygon areas to provide estimates of the inventory totals and their expected accuracy.

Table 3. DBH on LSP-derived height and crown area coefficients and statistics for the model: DBH = **a** x $(\text{Height})^{\mathbf{b}}$ x $(\text{Crown Area})^{\mathbf{c}}$.

Species	Regression coefficients			N*	R**	SE***
	a	b	c			
Spruces	1.168	0.850	0.250	549	0.92	2.06
Jack pine	1.580	0.700	0.230	117	0.84	2.77
Balsam fir	1.880	0.650	0.230	47	0.86	1.83
Larch[1]	1.490	0.705	0.350	17	0.84	3.82
Cedar[2]	1.287	0.880	0.280	21	0.86	2.72
Balsam poplar[3]	1.683	0.640	0.297	33	0.93	2.57
Aspen	0.638	0.850	0.395	88	0.95	3.52
White birch	2.346	0.440	0.390	124	0.90	3.97

*N = Number of observations.

**R = Correlation coefficient.

***SE = Standard error in cm.

[1] *Larix Laricinia* (DuRoi) K. Koch.

[2] *Thuja occidentalis* L.

[3] *Populus balsamifera* L.

Inventory Results

Key statistics for the strata defined in Table 2 are presented in Table 4. These data provide an overall picture of the amount of timber available and its distribution by species groups and age classes, as well as associated accuracy levels. The age–class distribution provides general information on the long term timber supply. To fill out the picture, the stand and stock tables, illustrated in Appendix A, show the distribution of stem counts, basal area, and merchantable volume by species and diameter classes. Use of the data in simulation models, such as PC NORMAN or FORMAN, provide much more detailed supply projections and illustrate the flow of timber by species and products that can be expected from the forest. The use of such models is further illustrated in a later section of this report.

In this project, LSP was also used to assess the quantity of dead standing trees and fallen materials. The procedures used to assess dead materials are described elsewhere.[1]

Also in this project, the use of LSP to assess the growth rate of individual trees was investigated for the first time. During the paired sample field work, 5- and 10-year radial growth rate data were obtained. Photo measurements such as tree height; crown area, length, and volume; and expressions of competition or the growing space occupied by trees were analyzed for their ability to estimate growth rates. The methodology is described in Appendix B. However, the growth models were relatively weak predictors of growth rates.

COMPARISON OF LSP AND FRI INVENTORY METHODOLOGIES

A comparison was made between estimates of the net merchantable volume compiled from the LSP data and a counterpart based on the OMNR's PC NORMAN File Creation System (PC NORMAN FCS). The latter is a Dbase software program that checks FRI attribute data, aggregates stands into forest classes, and sets up data and yield curves for one of the following forest simulation models: NORMAN, FORMANCP, or FORMAN 2.1. The system is documented in a manual prepared for the OMNR by Lindquist (1994).

The comparison made on the Timmins Forest used the forest and age classes shown in Tables 2 and 4. All the stands comprising these classes were processed through PC NORMAN and summarized as per hectare estimates of net merchantable volume.

The LSP sample plot data set, consisting of 2 730 samples, was compiled by the same species groups and age classes given in Tables 2 and 4. The compilation used the LSP tree observations of species, height, and crown area on the sample plots. The species-based DBH equations developed for this project (Table 3) were used to estimate

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[1] Dendron Resource Surveys Inc. Survey of dead wood using large scale sampling photos. Nat. Resour. Can., Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON. NODA Note No. 27. (In press)

DBH from the height and crown area measured on the photo. The resulting DBH and height estimates were processed through gross total and merchantable volume equations developed by Honer et al. (1983). The same volume equations, merchantability standards (stump height, minimum DBH, and minimum top diameter), and cull factors as used in PC NORMAN were used to produce the net merchantable volume entries. The results of the comparison are presented in Table 5.

The overall estimates differed by less than 1 percent, indicating virtually no systematic errors or biases. However, the totals by species group differed somewhat from the FORMAN estimates. These differences were analyzed and found to originate from the DBH-on-photo height and crown area equations used in the LSP method, and the height-on-DBH equations used in the PC NORMAN method.

The effect of the equations was analyzed using the paired-sample trees data set (*see* Dendron Resource Surveys Inc. 1996a), which included field measurements of both DBH and height, by species. The analysis allowed tree heights generated from the FRI equations to be matched against the actual tree heights, and the DBHs from the LSP equations (Table 3) to be compared with the field-measured DBH. The source of the differences between models used by both the LSP and PC NORMAN methods was identified and the equations were adjusted using the common field data set. The respective data sets were reprocessed through the respective compilations systems for a revised comparison. The results of the comparison are shown in Table 6.

The remaining differences between the LSP and the PC NORMAN estimates were within 6.5 percent of one another, well within sampling and other residual differences, such as might be introduced by the yield models and natural variation within stands.

These results highlight the importance of developing equations after selecting data that are well matched and representative of the population to which they will eventually be applied. This principle holds both for the DBH equations based on LSP measurements, and the PC NORMAN practice of using equations to fill in tree height entries when they are not measured in the field.

ROLE OF LARGE-SCALE PHOTOS IN THE MANAGEMENT PLANNING PROCESS

As outlined in the introduction, LSP can enhance FRI in three main ways: namely, contribute to the quality and accuracy of some data, and to cost-effectiveness; support current FRI tasks; and supplement forest information that FRI is unable to provide. The preceding investigation focused on the first role; the supporting and supplementary roles have been addressed previously or in related NODA-funded projects. All three contributions are summarized below in preparation for implementing them into the resource management planning process.

Table 4. Key inventory statistics for primary Timmins Forest strata as defined in Table 2.

Species group	Age	Number of plots	Stems /ha	Basal area (m^2/ha)	Total volume (m^3/ha)	Merchantable volume (m^3/ha)	SE* (%)
Spruce	50	130	1023	14.7	89.5	41.4	11.6
	70	203	951	16.7	110.6	57.6	9.8
	90	201	908	19.6	142.8	88.6	7.5
	110	200	844	18.6	135.2	88.6	6.3
	130	197	855	18.3	128.3	82.9	7.7
Pine	50	203	1182	25.5	194.3	121.8	5.3
	70	197	1087	31.7	267.6	199.7	3.6
	90	122	1129	30.7	248.4	187.0	5.5
Aspen	50	207	914	23.4	185.4	90.6	5.5
	70	204	861	33.1	307.3	183.9	4.0
	90	186	546	21.2	185.4	131.0	6.7
	110	168	590	21.1	185.5	128.8	7.0
Birch	70	12	1006	24.3	177.6	83.6	9.4
	90	209	598	18.8	143.2	86.2	6.0
	110	201	482	18.7	143.3	88.6	5.5
	130	88	851	19.7	140.4	88.4	8.9

*SE = Standard error.

Table 5. Comparison of net merchantable volume per hectare obtained by LSP and PC NORMAN for the main species and age classes.

Forest stratum		LPS		PC Norman	Difference
Species group	Age class	N*	NMV**/ha (m^3)	NMV/ha (m^3)	(%)
Spruce	50	130	41	12	
	70	203	57	55	
	90	201	87	119	
	110	200	87	95	
	130	197	80	69	
	Overall	931	72	70	+ 3.4
Jack pine	50	203	129	59	
	70	197	209	157	
	90	122	193	180	
Poplar	Overall	523	174	132	+ 32.0
	50	207.	85	118	
	70	204	166	164	
	90	186	109	162	
	110	168	93	-	
	Overall	766	129	148	- 18.9
Birch	70	12	84	94	
	90	209	84	97	
	110	201	82	102	
	130	88	80	-	
	Overall	510	83	98	- 15.5
All working groups		2730	105	106	- 0.9

* N = Number of observations.

** NMV = Net merchantable volume.

Table 6. Comparison between LSP and PC NORMAN of estimates of net merchantable volume after adjustment for DBH and height equations.

Working group	Differences between LSP and PC NORMAN before adjustment (%)	Effect of differences between LSP and PC NORMAN equations (%)	Net percent differences in NMV remaining (%)
Spruce	3.4	-3.8	-0.4
Jack pine	32.0	-25.9	6.1
Poplar	-18.9	12.5	-6.4
White birch	-15.5	10.2	-5.3

The LSP methodology complements the FRI by providing some information that may not be as accurate or complete as needed, in much the same way as does an intensive field survey or an operational cruise. The data include estimates of species composition, average stand height, basal area, and crown cover density. During the FRI photo interpretation, for example, stocking levels are judged from relationships among crown cover density, stand age, and basal area. The last two stand characteristics normally rely on existing or sampled field data. The LSP method can provide reliable estimates of both crown cover density and basal area, and strengthen the stocking assessments. Also, the LSP data can provide estimates of the stem count frequencies and basal area, as well as expressions of gross, merchantable, and net merchantable volumes based on actual data rather than on yield models and stocking adjustments. Furthermore, the LSP data can provide valuable information on the structure of the stands—the distribution of stem counts, basal area, and volume by species and DBH classes—as illustrated in Appendix A. In the FRI context, most of this information must be obtained from operational cruises.

The accuracy of LSP data is comparable to operational cruise information except for age, site class, and growth data. These are not reliable from the LSP. The cost of LSP versus operational cruises is more difficult to assess because of differences in the sampling units. The cost per hectare of a strip cruise, for example, is somewhat equivalent to LSP sampling, but the LSP plots can be distributed more widely and with greater randomization for little extra cost. The population will therefore be better sampled, thus reducing the sample size and the cost for an equivalent level of accuracy.

LSP data have been used effectively as operational tools, providing stand information to support the FRI photo interpretation process. The supporting information includes species composition data, estimates of average stand height, crown cover density, and basal area stocking. The supporting data usually has to be collected in the field or drawn from existing field observations or plots, when available. This role is principally an opportunistic use of LSP data, assuming that the photos have already been obtained according to a random sampling design. Some additional LSP, however, may be acquired during the same photo mission to target particular stands or areas where interpretation is a problem, or to acquire LSP for related applications.

The LSP methodology is also able to provide data that the FRI cannot. The survey of dead standing and fallen trees or parts thereof was tested in this project and useful results were produced, particularly concerning dead standing trees.[2] Although not especially important for conventional timber inventories, inventories of the amount and distribution of dead wood are of value for biodiversity considerations and the assessment of wildlife habitat.

In other NODA projects, the LSP methodology has been shown to provide valuable information on crown cover density, the identification of conifer cover, and the mapping of spatial relationships among trees in a stand. The crown cover density and spatial distribution information is lacking in the FRI data set, but is urgently needed to assess wildlife habitat suitability. The role and benefits of this information have been described elsewhere.[3]

INCORPORATION OF RESULTS IN DECISION SUPPORT SYSTEMS: A CASE STUDY

Forest Management Simulation Trial

The purpose of the trial was to test FORMAN 2.1 using enhanced LSP inventory data, and to compare the results of simulations with a standard FRI application. FORMAN 2.1 is a forest management simulation model developed in 1987 by the New Brunswick Department of Natural Resources and Energy. It was adapted from an earlier version of FORMAN that was programmed in 1982.

FORMAN 2.1 is based on a sequential inventory projection algorithm designed to aid forest managers in the evaluation of alternative forest management strategies. The standard application of FORMAN follows the steps, forest class aggregations, and yield curve configuration described by Hayhurst (1993). The steps usually include: setting management objectives, defining constraints to management, defining management prescriptions, characterizing the initial condition of the forest (inventory), quantifying forest development (yield), developing management strategies, creating the simulation process, and evaluating results. For the purpose of this trial the configuration focused mainly on the inventory and yield curves.

The model was run using FRI data from the Timmins Forest and PC NORMAN rules and yield curves. The LSP simulation was run using the data and curves developed from LSP data. Some adjustments were made to the yield curves based on the paired comparison described in the preceding section, which identified differences in the PC Norman height-on-DBH equations and the DBH-on-photo height and crown area equations.

The input data for FORMAN consisted of the population of eligible forest stands, aggregated into forest units on the basis of the working group species and age class. FRI Site Classes X, 1, 2, and 3 were included in the trial; Site Class 4 was excluded. The following four forest units

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[2] Ibid.

[3] Dendron Resource Surveys Inc. Integration of new technologies for deer yard assessment. Nat. Resour. Can., Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON. NODA/NFP Tech. Rep. TR-42. (In press)

were used: spruce (*Picea* spp.), pine (*Pinus* spp.), poplar (*Populus* spp.), and white birch. Ten-year age classes were established.

The FORMAN projection algorithm calculated the yield of each aggregated forest unit over time. To do this, a single average stand structure, in terms of species composition and stocking, was assumed for each forest unit. Average stocking and species composition, weighted by stand area, were calculated from FRI data.

Because the average stand yield for each forest unit was required, appropriate yield curves had to be provided. Further, since the average stand was comprised of several species, a multiple species yield curve was required for each forest unit. These were derived by calculating, at different ages, the net merchantable volume per hectare (NMV/ha) for each species in the average stand. For the computer run, the most appropriate single species yield curves were selected for the Timmins area. A site class cross-reference table identified the single species yield curve to be applied to each component of the multispecies group.

Yields for each average stand species, for each age class, were summed to derive the multiple-species curves. Separate sets of yield curves were developed for the test runs: one based on FRI data and the second based on the compiled LSP results.

Two volume-based operability limits were required by FORMAN. Operable First (OF) was the level of NMV/ha a forest unit had to achieve in a simulation before it became harvestable. Volume Last (VL) was the minimum NMV/ha required for a forest unit to remain harvestable.

The harvested forest classes were reassigned to an age of zero on the curve sets from which they originated. No silvicultural treatments or regeneration delay periods were included in the model. Unharvested forest classes that matured to an inoperable age were not regenerated, and were left inoperable for the remainder of the simulation.

A simple analysis was configured, all harvest areas were reassigned the same curve sets, no silvicultural activities were modeled, and no harvest costs were tracked. For all forest units the primary curve represented the softwood component and the secondary curve represented the hardwood component. The following specific rules were assigned to the modeling configuration:

- harvest oldest stands first;
- maximize an even-flow harvest over a 100-year period; and
- disallow inoperable stands to succeed back into the productive forest base.

Under the preceding configuration, the model was run using the standard FRI data and yield curves and re-run using the LSP data and curves. Tables 7 and 8 compare the results of the FRI and LSP runs.

In general, the FRI run was able to sustain an even flow of 70 000 m^3 per year of fiber, and LSP a somewhat higher volume at about 95 000 m^3 per year, in each 5-year period (Table 7).

Although both the FRI and LSP start with a similar inventory and species composition, the LSP shows an increased yield, mainly arising from the later development of a spruce understory in the jack pine (*Pinus banksiana* Lamb.), poplar, and birch working groups. Over time, the understory contributes significantly to the yield. The FRI data evidently does not address the understory conditions well, generally because yield tables are designed to represent even-aged stands which, by definition, do not have understories. Some stands, particularly the tolerant hardwoods and where spruce or balsam fir (*Abies balsamea* [L.] Mill.) are present, tend to be uneven aged and not well represented by yield models. The poor match between the yield models and the prevailing stand structure is one of the reasons why having actual data on stand structure (species composition and size class distribution) is important when implementing forest management planning simulation models based on the growth and development of stands over time.

Management Implications

Forest management simulators such as NORMAN, FORMANCP, and FORMAN 2.1 serve the needs of forest management and operational planning by projecting the effects of various management strategies, operational practices (harvesting, reforestation, and silvicultural prescriptions), and protection programs over time. Current timber management simulators provide information on the long-term sustainable timber supply and procedure schedules, based on proposed scenarios that are developed by planners. The schedules indicate when, where (often which stands or groups of stands), and what interventions should take place.

The management planning projections may extend for a rotation period or more; the operational planning horizon is typically 5–20 years, usually within the framework of the long-term plan. The simulators begin with the current status of the resource as expressed by the forest inventory, assumptions about the growth and development of stands, the risk of depletions from damaging agents (fire, infestations, disease, wind damage, etc.), changes in the size of the productive land base, and the level of harvest. Stand development encompasses the net effect of tree growth, ingrowth, mortality, and successional changes over time.

Table 7a. FRI data report on the forest using the FORMAN 2.1 simulation model.

	Residual forest				Statistics for the period				
Time	Operable volume (m^3)		Volume cut (m^3)		Area (ha)			Mortality (m^3)	
(years)	Primary	Secondary	Primary	Secondary	Cut	Plant	Space	Potential	Realized
5	3 622 579	0	350 000	0	5 295	0	0	95 135	47 026
10	3 596 676	0	350 000	0	5 327	0	0	45 997	30 016
15	3 345 622	0	350 000	0	7 294	0	0	155 897	45 891
20	3 373 822	0	350 000	0	4 901	0	0	45 002	30 299
25	3 070 609	0	350 000	0	7 460	0	0	238 556	47 639
30	2 934 826	0	350 000	0	4 654	0	0	37 682	23 149
35	2 614 573	0	350 000	0	10 323	0	0	351 451	49 340
40	2 344 042	0	350 000	0	3 476	0	0	45 056	31 233
45	2 019 394	0	350 000	0	6 592	0	0	144 897	42 362
50	1 746 363	0	350 000	0	6 018	0	0	35 786	17 732
55	1 463 581	0	350 000	0	6 027	0	0	77 776	16 610
60	1 347 652	0	350 000	0	5 311	0	0	16 610	677
65	1 270 361	0	350 000	0	4 658	0	0	0	50 813
70	1 272 617	0	350 000	0	3 842	0	0	0	0
75	1 303 691	0	350 000	0	4 128	0	0	4 265	0
80	1 106 438	0	350 000	0	6 702	0	0	0	0
85	1 111 530	0	350 000	0	5 775	0	0	0	0
90	881 103	0	350 000	0	7 267	0	0	0	0
95	728 650	0	350 000	0	4 816	0	0	0	0
100	639 480	0	350 000	0	6 588	0	0	0	0

Table 7b. LSP data report on the forest using the FORMAN 2.1 simulation model.

	Residual forest				Statistics for the period				
Time	Operable volume (m^3)		Volume cut (m^3)		Area (ha)			Mortality (m^3)	
(years)	Primary	Secondary	Primary	Secondary	Cut	Plant	Space	Potential	Realized
5	4 692 278	0	475 000	0	5 974	0	0	99 968	57 341
10	4 564 608	0	475 000	0	7 378	0	0	77 313	28 191
15	4 206 196	0	475 000	0	5 677	0	0	165 644	79 091
20	3 986 764	0	475 000	0	6 966	0	0	71 963	48 677
25	3 564 387	0	475 000	0	4 342	0	0	182 128	82 619
30	3 204 932	0	475 000	0	8 521	0	0	75 881	40 937
35	2 736 593	0	475 000	0	8 872	0	0	81 647	71 018
40	2 340 790	0	475 000	0	7 303	0	0	55 554	31 479
45	1 883 942	0	475 000	0	6 285	0	0	132 537	41 301
50	1 700 968	0	475 000	0	8 152	0	0	36 545	7 644
55	1 554 320	0	475 000	0	7 281	0	0	126 361	6 648
60	1 422 519	0	475 000	0	4 763	0	0	6 648	0
65	1 414 498	0	475 000	0	6 454	0	0	4 524	0
70	1 173 216	0	475 000	0	10 199	0	0	0	0
75	973 162	0	475 000	0	10 089	0	0	0	0
80	789 820	0	475 000	0	9 163	0	0	0	0
85	795 683	0	475 000	0	7 552	0	0	0	0
90	577 291	0	475 000	0	12 925	0	0	0	0
95	481 337	0	475 000	0	7 196	0	0	0	0
100	140 104	0	475 000	0	11 290	0	0	0	0

Table 8. Age class structure (ha) produced using the FORMAN 2.1 simulation method.

a. FRI data

Time	Age class (ha)									
(years)	0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180	180–200
5	22	6 994	7 764	20 127	19 725	14 669	1 4826	4 380	236	210
10	5 317	6 994	7 764	20 127	19 725	9 738	14 763	4 380	23	122
15	10 622	963	10 345	8 743	27 704	13 817	10 678	2 638	3 298	145
20	17 916	963	10 345	8 743	27 704	9 694	10 678	2 638	127	145
25	17 522	5 317	6 994	7 764	20 127	17 931	825	11 119	1 209	23
30	19 655	10 644	6 994	7 764	20 127	10 471	825	11 119	1 209	23
35	17 015	17 916	963	10 345	8 743	21 065	0	10 388	2 246	127
40	22 437	22 817	963	10 345	8 743	10 742	0	10 388	2 246	127
45	18 453	24 982	5 317	6 994	7 764	9 792	3 382	825	11 119	180
50	20 391	24 309	10 644	6 994	7 764	5 870	3 382	825	8 449	180
55	16 086	27 338	17 916	963	10 345	6 527	3 382	0	5 404	720
60	18 637	25 913	22 817	963	10 345	3 873	3 382	0	2 031	720
65	17 356	25 045	24 982	5 317	6 994	6 093	0	143	825	1 873
70	15 996	26 409	24 309	10 644	6 994	1 578	0	0	825	1 873
75	13 811	22 113	27 338	17 916	963	3 789	0	0	0	2 031
80	12 628	23 948	25 913	22 817	624	0	0	0	0	2 031
85	14 672	22 014	25 045	19 766	4 433	0	0	0	0	2 031
90	16 605	19 838	26 409	22 663	415	0	0	0	0	825
95	19 744	17 939	22 113	21 866	4 268	0	0	0	0	0
100	17 858	19 330	23 948	23 393	1 401	0	0	0	0	0

b. LSP data.

Time	Age class (ha)									
(years)	0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180	180–200
5	22	6 994	7 764	20 127	19 725	14 669	14 826	4 380	236	210
10	5 996	6 994	7 764	20 127	19 332	9 597	14 429	4 380	212	122
15	13 352	963	10 345	8 743	27 704	13 424	10 503	1 259	2 515	145
20	19 029	963	10 345	8 743	25 762	10 532	9 660	1 259	2 515	145
25	20 021	5 996	6 994	7 764	20 127	15 989	2 305	8 403	1 209	23
30	16 985	13 374	6 994	7 764	16 956	15 468	1 655	8 403	1 209	23
35	19 829	19 029	963	10 345	8 743	17 894	3 422	8 226	230	127
40	21 735	25 995	963	10 345	7 607	11 813	1 767	8 226	230	127
45	24 696	24 363	5 996	6 994	7 764	8 656	4 513	0	5 646	180
50	22 460	25 506	13 374	6 994	6 462	5 065	3 121	0	5 646	180
55	21 740	28 701	19 029	963	9 684	5 225	2 746	0	363	230
60	21 718	29 038	25 995	963	8 573	1 801	0	0	363	230
65	20 196	30 981	24 363	5 996	3 535	3 017	0	0	0	540
70	18 498	30 612	25 506	13 065	407	0	0	0	0	540
75	21 416	29 021	28 701	8 950	0	0	0	0	0	363
80	26 742	26 481	29 038	5 827	0	0	0	0	0	363
85	29 451	26 650	26 636	5 351	0	0	0	0	0	0
90	26 804	28 697	30 612	1 975	0	0	0	0	0	0
95	29 640	31 505	22 801	4 142	0	0	0	0	0	0
100	27 673	35 905	22 855	1 655	0	0	0	0	0	0

Within this framework, different management strategies, practices, and scheduling scenarios can be proposed and tested to assess the long-term impact on the resource base and the flow of benefits from it. Among the expected benefits would be a long-term sustainable timber supply, but in integrated resource management planning the simulations must extend to other demands, values, or interests, such as those pertaining to wildlife habitat; recreational use; protection of traditional uses; and concerns about maintaining biodiversity, ecological integrity, and soil and water quality. Other than imposing constraints on aspects such as harvest levels, size of cut blocks, protection zones, and operational practices, current simulators have not addressed the needs of fully integrated resource management planning. Some of the GIS, spatially oriented stand models, such as GIS FORMAN (Jordan[4]) and HSG (Dendron Resource Surveys Inc. 1994) are making important advances toward integrated planning.

As with any model, the simulators are a fabrication and usually a great oversimplification of the complex factors that affect the growth and development of a forest. Many assumptions, explicit or implicit, have to be made for simulators to work. Thus they are subject to errors that are usually minor in the short term but, beyond 20 years, may deviate radically from what actually occurs. The manager should be aware of their limitations and rely on available expertise, experience, and insight to continuously question the validity of the projections. Careful monitoring of the projections must be relied upon to reveal where the simulators begin to break down or to drift away from reality.

In the current case study, the projections concentrated on establishing the building block that primarily characterizes the resource base—the inventory. Although the FRI satisfactorily provides the data needed for fiber management planning, the methodology is unable to meet all the needs of integrated resource management planning. As demonstrated, LSP helps to fill some of the gaps—better data on stand structure; data on dead standing and fallen trees; and spatial data characterizing growing space, tree competition, cover density, and the distribution of open spaces. Much of the enhanced data pertains to the assessment of habitat suitability and biodiversity, as these relate to ecological integrity and stability. All of these considerations are basic to integrated resource management planning.

A simulator is unable to compensate for weak inventory data. Extending the simulators from timber supply projections to the broader and much more complex issues raised by integrated resource management planning places much heavier demands on the inventory data. As well as providing the starting state for the simulator, the inventory must also establish the baseline from which the effect of changes, strategies, and operational practices or the lack thereof can be monitored and compared to what the simulators predicted. Thus, the inventory will provide the baseline for early detection of the drift or breakdown of the simulation. The quality of the inventory is vital to the successful use of forest management planning simulators.

CONCLUSIONS

This project concentrated on the role that large scale sampling photos can play in enhancing Ontario's FRI for forest management planning purposes.

The LSP methodology was found to complement the FRI program by providing more comprehensive stand data—data that the FRI can obtain only from expensive operational cruises. The addition includes: accurate data on the proportions of species in a stand; data on per hectare stem counts, basal area, and gross total, merchantable, and net volumes; and the breakdown of such data by species and size classes (DBH).

Depending on sample size and access difficulty, LSP is able to provide the bulk of such data at a reduced cost—generally less than $100 per plot for LSP versus operational cruises or field plot surveys that cost $150 or more. For example, sample plots in remote parts of the territories can cost as much as $1,000 per plot when helicopters are used to deploy field crews. Comparison with operational cruise methods is more difficult because of differences in the shape and size of the sampling unit (plots versus strips or clusters), and with how variability in the population is sampled. LSP can generally sample to equivalent accuracy for less cost because it offers the opportunity for broader and more randomized sampling. However, some data, such as stand age and site class, are not captured because they can only be determined reliably on the ground.

LSP is limited in its ability to provide reliable information on age, growth, and site class, but this can be supplied using a limited field sample. The use of LSP tree variables to estimate tree growth was further examined in this project and found wanting, likely because many of the stands tested were overmature, and growth rates were declining and unresponsive to the available growing space. Thus, the ability of LSP to assess growth must still be proved.

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[4] Jordan, G. Forest modeling and management planning. Copies of a slide presentation to the Prince Albert Model Forest Association Inc., workshop on forest modeling. 24 August 1994, Prince Albert, Saskatchewan.

The accuracy of the species identification, tree counts, and height measurements of live trees by the LSP method was confirmed to be of high order. The accuracy results are reported in detail in Dendron Resource Surveys Inc. (1996a). The estimation of DBH and the several expressions of volume are reliable, provided the data used to develop the estimation models are representative of the forest stands in the inventory to which they are applied (Dendron Resource Surveys Inc. 1996b).

The LSP provides data that supports the current FRI photo interpretation procedures used to describe the stands. However, this role of LSP, which works best when it can target particular stands where interpretation is a problem, must be reconciled with the random sampling approach used in the plot sampling application. The best way to do this is to use the randomly selected LSP where it meets the interpreters needs, and then add some additional LSP to the photo mission to target specific problem areas. The LSP data provides the interpreter with information on species composition, average stand height, basal area, crown cover density, and estimates of stocking. The benefits of the supporting role of LSP have been confirmed in a separate project on a company license.

The LSP offers data on the spatial position and distribution of trees, tree clusters, and spaces among them, which FRI is unable to offer. Such spatial data, expressions of tree density, crowding, or tree competition are vital to characterizing the suitability of stands for the habitat of many wildlife species. The role of LSP, satellite data, and FRI data together has been the subject of two other NODA projects[5] (Dendron Resource Surveys Inc. 1995). The use of GIS as a common geographic base for combining such information is featured elsewhere.[6] In this project, GIS also greatly facilitated the application of the LSP methodology and provided the platform for combining the results with the FRI data.

The FRI and LSP were compared in terms of the inventory results produced and on how well the resulting data served the forest management planning simulations. The inventory results that were based on FRI and LSP data were similar, and confirmed one another. The LSP, as noted above, provided more detailed data on stand structure (distribution of quantities by species and size classes). The stand structure data better addresses the emerging need to incorporate stand growth models and simulators in the management planning process. In the case study, the improved characterization of stand structure by LSP, in terms of species composition and tree size class, provided the better understory development data needed to drive the simulators. Although the understory data made little difference to the initial inventory, it became significant later as the stand development was projected ahead in time. In essence, it substantially increased the sustainable level of harvest. Thus the stand structure data, captured from plot sampling either in the field or from LSP, are important in the development of long-term plans and in testing them through simulation techniques.

The simulators must also prepare for newly emerging issues that call for data and tools to address integrated management planning requirements. Wildlife habitat suitability, for example, will have to be included in the modeling process. Simulators that incorporate habitat suitability models will make new demands for data, some of which LSP has already been effective in providing. Thus, LSP can effectively enhance the FRI by filling data gaps, by supporting current FRI procedures, and by providing key tree data more accurately and efficiently than do current inventories.

ACKNOWLEDGMENTS

Funding for this project was provided under the auspices of the Northern Ontario Development Agreement/Northern Forestry Program.

Significant contributions to the project were made by QUNO Corporation staff. As the primary user of the inventory results for forest resource management planning purposes, QUNO helped to establish the context and scope of the project, and to redirect or refine the project objectives.

The Ontario Ministry of Natural Resources, with Neil Maurer as scientific authority, guided the technical direction of the project, assisted in overcoming technical problems, and suggested ideas and contacts for broadening the project to include integrated management planning and, especially, wildlife habitat suitability issues. Bob Watt and Jim Duncan of the OMNR's Northeast Science and Technology Unit assisted with wildlife habitat considerations and elucidation of the information needed to support wildlife management decisions.

Frank Addante, Norm Iles, and other Forest Resource Inventory staff within the OMNR provided important guidance, technical advice, and support.

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[5] Ibid.

[6] Ibid.

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APPENDIX A. Example of inventory results using the large scale photo method.

QUNO Corporation

KEY INVENTORY STATISTICS

Stratum: s9

Sample size: 201

08-21-1996

	Mean	Standard error (66 percent)	
Live trees		Absolute	Percent
Stems per hectare	907.8	45.0	5.0
Basal area per hectare (m^2)	19.6	0.9	4.7
Total volume per hectare (m^3)	142.8	8.3	5.8
Merch volume per hectare (m^3)	88.4	6.7	7.5
Average stand height (m)	13.9	0.3	1.8
Average crown cover (percent)	49.0	1.8	3.6

QUNO Corporation Stand Data

Stratum: s9

Stems per hectare

08-21-1996

Mean (living trees)	907.8	Minimum DBH (cm)	15.0
Standard error (66 percent)	45.0	Top diameter (cm)	10.0
Sample size	201	Stump height (cm)	30.0

DBH (cm)	Species categories									
	Softwoods				Hardwoods					
	Spruce	Pine	Fir	Other	Poplar	Birch	Other	Live	Snags	Fallen
8	93.8	0.3	0.6	3.0	1.4	8.9	0.0	108.1	0.0	0.0
10	105.5	1.8	4.7	8.6	1.2	12.5	0.0	134.3	0.0	0.0
12	108.0	2.7	3.2	7.5	2.1	12.9	0.0	136.4	0.0	0.0
14	87.7	4.9	2.4	6.2	4.1	15.5	0.0	120.9	0.0	0.0
16	82.1	5.7	3.4	7.8	3.9	11.2	0.0	114.1	0.0	0.0
18	62.3	5.4	1.2	5.1	3.0	9.3	0.0	86.3	0.0	0.0
20	41.6	6.4	2.2	7.5	2.4	6.2	0.0	66.3	0.0	0.0
22	29.7	3.8	0.3	4.0	3.6	4.5	0.0	45.9	0.0	0.0
24	19.3	3.9	0.0	2.8	4.1	5.1	0.0	35.2	0.0	0.0
26	8.0	3.6	0.0	2.8	1.2	3.5	0.0	18.9	0.0	0.0
28	8.5	2.0	0.3	2.1	1.2	1.2	0.0	15.2	0.0	0.0
30	3.6	1.2	0.0	1.2	2.0	1.8	0.0	9.8	0.0	0.0
32	1.7	1.1	0.0	0.3	1.2	1.5	0.0	5.8	0.0	0.0
34	0.6	0.3	0.0	0.0	0.3	0.3	0.0	1.5	0.0	0.0
36	0.3	0.0	0.0	0.3	1.4	0.3	0.0	2.3	0.0	0.0
38	0.3	0.3	0.0	0.3	0.6	0.3	0.0	1.8	0.0	0.0
40	0.9	0.0	0.0	0.0	0.3	0.3	0.0	1.4	0.0	0.0
42	0.6	0.0	0.0	0.3	0.3	0.0	0.0	1.2	0.0	0.0
44	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0
46	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0
48	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0
50	0.3	0.0	0.0	0.0	0.9	0.0	0.0	1.2	0.0	0.0
Total	655.6	43.4	18.3	59.7	35.5	95.1	0.0	907.8	0.0	0.0

QUNO Corporation Stand Data

08-21-1996

Stratum: s9

Basal area per hectare (m^2)

Mean (living trees)	19.6	Minimum DBH (cm)	15.0
Standard error (66 percent)	0.9	Top diameter (cm)	10.0
Sample size	201	Stump height (cm)	30.0

DBH (cm)	Species categories									
	Softwoods				Hardwoods					
	Spruce	Pine	Fir	Other	Poplar	Birch	Other	Live	Snags	Fallen
8	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0
10	0.9	0.0	0.0	0.1	0.0	0.1	0.0	1.1	0.0	0.0
12	1.2	0.0	0.0	0.1	0.0	0.2	0.0	1.6	0.0	0.0
14	1.4	0.1	0.0	0.1	0.1	0.2	0.0	1.9	0.0	0.0
16	1.7	0.1	0.1	0.2	0.1	0.2	0.0	2.3	0.0	0.0
18	1.6	0.1	0.0	0.1	0.1	0.2	0.0	2.2	0.0	0.0
20	1.3	0.2	0.1	0.2	0.1	0.2	0.0	2.1	0.0	0.0
22	1.1	0.1	0.0	0.2	0.1	0.2	0.0	1.8	0.0	0.0
24	0.9	0.2	0.0	0.1	0.2	0.2	0.0	1.6	0.0	0.0
26	0.4	0.2	0.0	0.1	0.1	0.2	0.0	1.0	0.0	0.0
28	0.5	0.1	0.0	0.1	0.1	0.1	0.0	0.9	0.0	0.0
30	0.3	0.1	0.0	0.1	0.1	0.1	0.0	0.7	0.0	0.0
32	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.5	0.0	0.0
34	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
36	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0
38	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0
40	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
42	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
48	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
50	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0
Total	12.4	1.5	0.3	1.6	1.7	2.2	0.0	19.6	0.0	0.0

QUNO Corporation Stand Data

Stratum: s9

08-21-1996

Total volume per hectare (m^3)

Mean (living trees)	142.8	Minimum DBH (cm)	15.0
Standard error (66 percent)	8.3	Top diameter (cm)	10.0
Sample size	201	Stump height (cm)	30.0

DBH	Species categories									
(cm)	Softwoods				Hardwoods					
	Spruce	Pine	Fir	Other	Poplar	Birch	Other	Live	Snags	Fallen
8	2.0	0.0	0.0	0.1	0.0	0.2	0.0	2.4	0.0	0.0
10	4.0	0.1	0.2	0.3	0.1	0.5	0.0	5.1	0.0	0.0
12	6.7	0.2	0.2	0.4	0.1	0.8	0.0	8.4	0.0	0.0
14	8.3	0.5	0.2	0.5	0.4	1.5	0.0	11.4	0.0	0.0
16	10.8	0.8	0.5	0.9	0.7	1.4	0.0	15.1	0.0	0.0
18	11.0	1.1	0.2	0.8	0.7	1.6	0.0	15.4	0.0	0.0
20	9.7	1.6	0.5	1.5	0.7	1.3	0.0	15.3	0.0	0.0
22	8.8	1.2	0.1	1.1	1.4	1.3	0.0	13.8	0.0	0.0
24	7.2	1.6	0.0	1.0	1.9	1.7	0.0	13.3	0.0	0.0
26	3.6	1.8	0.0	1.1	0.6	1.3	0.0	8.4	0.0	0.0
28	4.5	1.2	0.2	1.0	0.8	0.5	0.0	8.1	0.0	0.0
30	2.3	0.8	0.0	0.7	1.4	0.8	0.0	6.1	0.0	0.0
32	1.2	0.9	0.0	0.2	1.0	0.9	0.0	4.3	0.0	0.0
34	0.5	0.3	0.0	0.0	0.3	0.2	0.0	1.3	0.0	0.0
36	0.3	0.0	0.0	0.3	1.7	0.2	0.0	2.5	0.0	0.0
38	0.3	0.3	0.0	0.4	0.7	0.3	0.0	2.0	0.0	0.0
40	1.1	0.0	0.0	0.0	0.4	0.3	0.0	1.9	0.0	0.0
42	0.9	0.0	0.0	0.4	0.5	0.0	0.0	1.8	0.0	0.0
44	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.6	0.0	0.0
46	1.1	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0
48	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0
50	0.5	0.0	0.0	0.0	3.2	0.0	0.0	3.8	0.0	0.0
Total	85.7	12.4	2.1	10.7	17.1	14.7	0.0	142.8	0.0	0.0

QUNO Corporation Stand Data

Stratum: s9

08-21-1996

Merch volume per hectare (m^3)

Mean (living trees)	88.4	Minimum DBH (cm)	15.0
Standard error (66 percent)	6.7	Top diameter (cm)	10.0
Sample size	201	Stump height (cm)	30.0

DBH (cm)	Species categories									
	Softwoods				Hardwoods					
	Spruce	Pine	Fir	Other	Poplar	Birch	Other	Live	Snags	Fallen
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0
16	8.2	0.6	0.4	0.7	0.0	0.0	0.0	9.9	0.0	0.0
18	9.0	0.9	0.2	0.7	0.0	0.0	0.0	10.7	0.0	0.0
20	8.3	1.4	0.5	1.3	0.0	0.0	0.0	11.5	0.0	0.0
22	7.7	1.1	0.1	1.0	0.0	0.0	0.0	9.8	0.0	0.0
24	6.4	1.5	0.0	0.9	0.2	0.0	0.0	9.0	0.0	0.0
26	3.2	1.7	0.0	1.1	0.4	0.7	0.0	7.0	0.0	0.0
28	4.1	1.1	0.1	0.9	0.5	0.3	0.0	7.1	0.0	0.0
30	2.2	0.8	0.0	0.7	1.0	0.5	0.0	5.2	0.0	0.0
32	1.1	0.9	0.0	0.2	0.8	0.6	0.0	3.6	0.0	0.0
34	0.5	0.3	0.0	0.0	0.3	0.1	0.0	1.2	0.0	0.0
36	0.3	0.0	0.0	0.3	1.4	0.2	0.0	2.2	0.0	0.0
38	0.3	0.3	0.0	0.3	0.6	0.2	0.0	1.8	0.0	0.0
40	1.1	0.0	0.0	0.0	0.4	0.2	0.0	1.7	0.0	0.0
42	0.8	0.0	0.0	0.4	0.4	0.0	0.0	1.7	0.0	0.0
44	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.0
46	1.1	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0
48	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0
50	0.5	0.0	0.0	0.0	3.0	0.0	0.0	3.5	0.0	0.0
Total	55.8	10.4	1.2	8.4	9.5	2.9	0.0	88.4	0.0	0.0

APPENDIX B. Tree growth estimation from large scale sampling photos.

INTRODUCTION

As part of the NODA/NFP large-scale photo (LSP) inventory project, field work was carried out to assess and measure a sample of individual trees on the photos. The field work was used to check the accuracy of the photo assessments and to supplement data, such as diameter at breast height and age, that cannot be measured directly on the photos. The possibility of estimating tree growth from photo-measured variables was investigated and the results are reported here.

METHODOLOGY

The field measurements included increment core samples of jack pine trees, which were used to assess growth rates during the last 20 years. The measurements provided a unique opportunity to investigate whether useful relationships prevail among measures of tree growth and tree variables measured on the LSP.

The widths of annual growth rings were measured and recorded using Dendron Resource Survey Inc.'s customized dendrochronology system, which measures widths to the nearest 0.01 mm and stores the data for analysis. The analysis normally explores ring-width chronologies in relation to change factors such as climate, air pollution, insect attacks, medium or long-term changes to the environment, relative tree dominance, and crowding and to factors creating competition for nutrients, water, and light. Figure B1 illustrates a typical ring width chronology i.e., the growth rates are high in the early years and decline as the tree ages.

In this brief investigation, the average width over the last 5, 10, 15, or 20 years or subintervals, was related to relative tree position on the sample plot, tree height, crown size (crown area, length, perimeter, or volume), and growing space. The last was defined by Thiessen polygons, as illustrated in Figure B2. Thiessen polygons are governed by the coordinate position of a tree in relation to its nearest neighbors and a set of rules that was used, for example, to see if more available growing space would result in high growth rates.

Linear regression was used to investigate the strength of the relationships and the possible value of LSP tree measurements in predicting growth rates. Six LSP plots in a jack pine stand with approximately 100 tree observations were used to carry out a preliminary evaluation. The following variables were tested:

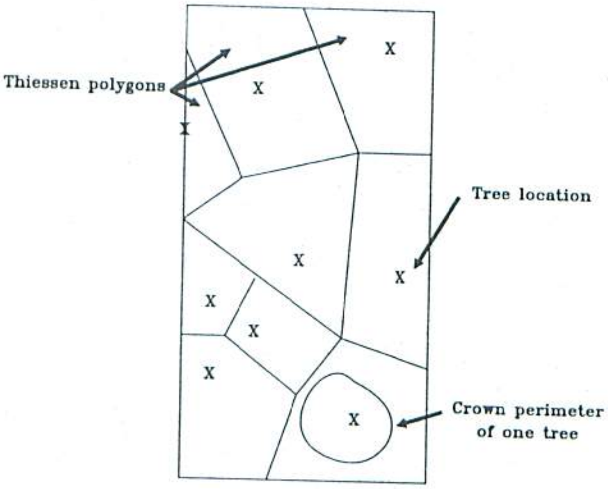

Figure B2. Diagram showing how Thiessen polygons can be used to allocate growing space to trees.

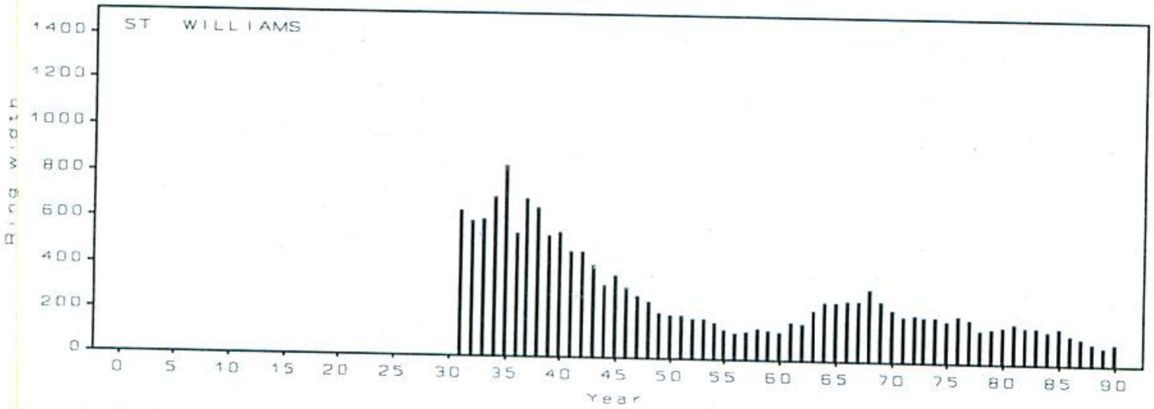

Figure B1. Increment core series of a Northeastern Ontario jack pine tree. Ring width measurements are in units of 0.01 mm.

Dependent variables: mean growth in the last 1 to 5 years and mean growth from Year 16 to Year 20.

Independent variables: total height, crown area, crown length, crown perimeter, polygon area, crown area x crown length, crown perimeter x crown length, and polygon area/crown area.

RESULTS AND CONCLUSIONS

The results of the analysis revealed perceptible trends but relatively weak correlations and poor predictive power. Expressed in terms of R-square, the multiple correlation coefficient squared, all models were less than 0.30, which can be interpreted as meaning that only 30 percent or less of the variation in growth rates can be accounted for by the model. The predictive power is weak for the jack pine stand tested. Crown length, crown area, and their product (related to crown volume) were the strongest variables.

The low predictive power of the models tested may have several explanations. Other variables, such as climatic variations or disturbances, which were not included in the test, may have confounded or masked the influences tested. The growth rates in the intervals tested may not have been related to the present stand conditions or other intervals. Factors other than the size and spatial variables that underlie growth, such as root competition or water and nutrient limitations, may be the dominant constraint. The relatively high density of the pine stand may also have suppressed growth response in general, and thereby narrowed the range of growth rates. The effect of suppression is evident in the last 20 years of "closed" stand chronology (*see* Fig. A1). It is likely that more open stands or other species, such as spruce or poplar, may react differently. These have yet to be tested and should be before concluding that tree spacing measurements, which are captured so well on LSP, have no value in assessing tree growth rates.

Under other conditions, spatial relationships are known to influence growth rates, sometimes quite powerfully, as illustrated in Figure B3. The chronology in Figure B3 is based on stem analysis of a red pine (*Pinus resinosa* Ait.) stand that was thinned twice—once in the early 1960s and again in 1980. The primary rationale behind silvicultural practices such as spacing and thinning is to take advantage of accelerated growth after release. Under such conditions, LSP should provide an effective and practical means of assessing tree and crown spacing relationships and the effect of crown competition on growth. Further testing of stands that are not fully stocked or "closed" is recommended.

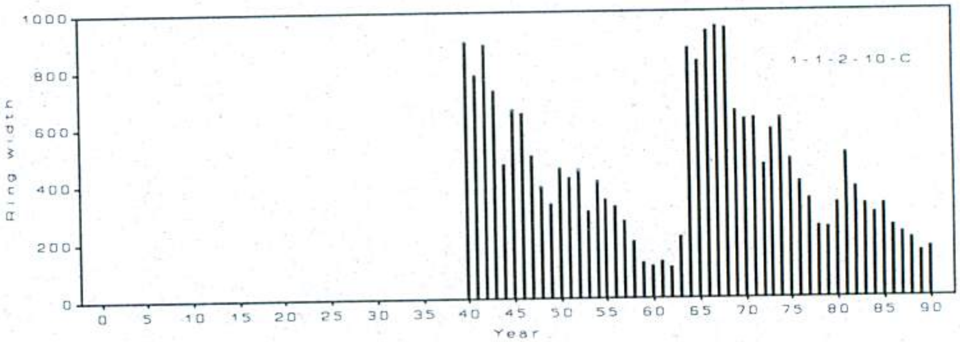

Figure B3. Growth response to thinning and pruning of a red pine stand in 1960–62 and thinning in 1980.