A BASIS FOR MULTISTAGE FOREST INVENTORY IN THE BOREAL FOREST REGION

BASE POUR LA REALISATION D'UN INVENTAIRE FORESTIER A PLUSIEURS NIVEAUX DANS LA REGION BOREALE

Kirby, C.L. and P.I. van Eck
Northern Forests Research Centre
Environmental Management Service
Environment Canada

ABSTRACT

Developments in interpretation of Landsat imagery, ultra small and large scale aerial photography and their application in a multistage sampling design are presented. Merchantable softwood area as determined from a computer assisted interpretation of a winter Landsat scene correlates highly with wood volume estimates obtained from aerial photographs and ground samples. This reduces the amount of sampling required in succeeding stages which may be done with various scales of aerial photography and ground sampling. Ultra small-scale, infrared color aerial photography for estimating stand volumes and for the preparation of forest cover and soils maps is evaluated and found to be accurate and efficient It may be used in primary and succeeding stages of the design. Equations for predicting individual tree diameter and volume from measures on large-scale aerial photographs are developed. The test of a multistage sampling design indicates that accurate volume estimates for large areas may be obtained at considerably less cost than would be incurred with conventional methods, especially when measures from Landsat imagery and small and large-scale aerial photographs are utilized.

RESUME

On traite de progrès réalisés dans l'interprétation des images LANDSAT et des photographies aériennes à ultra-petite et à grande échelle, ainsi que de leur application à la réalisation d'un inventaire forestier à plusieurs niveaux. Les volumes de bois marchand d'une région d'arbres feuillus ont été déterminés par interprétation automatisée d'une image LANDSAT obtenue en hiver. Les résultats de ces déterminations présentent une forte corrélation avec les volumes de bois estimés à partir des photographies aériennes et des échantillons recueillis au sol. On réussit ainsi à réduire l'échantillonnage à effectuer dans les niveaux suivants par photographie aérienne à diverses échelles et par prélèvement au sol. La photographie aérienne en infrarouge couleur à ultra-petite échelle s'est révélée précise et efficace pour l'estimation des volumes des peuplements et la préparation de cartes des couverts des sols et des forêts. Elle peut être utilisée pour le niveau primaire du procédé d'échantillonnage ainsi que pour les niveaux suivants. On a établi des équations pour la prévision du diamètre et du volume des arbres individuels à partir des mesures effectuées sur des photographies aériennes à grande échelle. L'essai d'un procédé d'échantillonnage à plusieurs niveaux indique qu'on peut obtenir des estimations précises des volumes sur de vastes superficies, et ce de façon beaucoup plus économique que par les méthodes conventionnelles, particulièrement lorsqu'on a recours aux images LANDSAT et à la photographie aérienne à petite et à grande échelle.

"Presented to the 4th Canadian Symposium on Remote Sensing, Québec City, May 1977".

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by

C.L. Kirby[1] and P.I. van Eck[1]

ABSTRACT

Developments in the interpretation of Landsat imagery, ultra-small and large-scale aerial photography and their application in a multistage sampling design are presented. Because merchantable softwood area determined from a computer assisted interpretation of a winter Landsat scene correlates highly with wood volume estimates obtained from aerial photographs and ground samples, the amount of sampling required in succeeding stages is reduced. Ultra small-scale, infrared color aerial photography is evaluated as a tool for estimating stand volumes and for the preparation of forest cover and soils maps and is found to be accurate and efficient. It may be used in primary and succeeding stages of the design. Equations for predicting individual tree diameter and volume from measures on large-scale aerial photographs are developed. The test of a multistage sampling design indicates that accurate volume estimates for large areas may be obtained especially when measurements from Landsat imagery and small and large-scale aerial photographs are used to provide a dynamic information system.

RESUMÉ

La surface de résineux marchands d'après une interprétation d'une scène d'hiver Landsat avec l'aide d'un ordinateur se révélait en forte corrélation avec les évaluations du cubage du bois, provenant de photographies aériennes et d'échantillons sur le terrain. Dans un "design" à stades multiples, on diminua la quantité d'échantillons requis pour les stades subséquents, ce qui est possible par 'emploi d'échelles variées de photographies aériennes et d'échantillonnage sur le terrain. La photographie aérienne en couleur à l'infra-rouge à ultra petite échelle pour évaluer le cubage des peuplements et préparer des cartes du couvert forestier et des sols est précise et efficace, Elle peut servir lors du stade original et des stades suivants du design. Les auteurs mettent au point des équations qui pourront prédire le diamètre d'un arbre quelconque et son cubage, et ce à partir de mesures prises de photographies aériennes à grande échelle. Un test du design d'échantillonnages à plusieurs stades, mis au point ici, indique que des estimations précises du cubage sur de grandes surfaces sont possibles à un coût beaucoup moindre qu'avec les méthodes classiques, spécialement lorsque les mesures provenant des images du Landsat et de photographies aériennes à petite et grande échelles sont utilisées pour fournir un systèm d'information dynamique.

INTRODUCTION

Recent developments in the interpretation of Landsat (ERTS) imagery and the application of ultra-small and large-scale aerial photography coupled with efficient sampling designs are capable of bringing considerable improvement to Canadian forest inventory methods. As reported by Smith (1976), most provincial and federal operational inventories rely on a two-stage design employing medium-scale photography for preparation of cover type maps and ground sampling to obtain average stand and stock tables. This approach is costly and often prevents, because of the high cost, adequate periodic assessment of forest practice for efficient management.

Multistage designs for forest inventories of large areas can provide timely and economical information for management. The overview from space or high flying jet aircraft provides a means for mapping and efficient sample allocation that reduces the amount of costly larger scaled aerial photography and ground sampling required to achieve a desired precision. A series of successively smaller subsamples selected from the primary stage all contribute to sampling efficiency and to obtaining proressively more detailed information.

In addition, multistage forest inventories provide: broad regional generalization for planning; detailed inventory where and when required; concentration of sampling on high interest areas; statistically valid measures of precision; and measures of changes resulting

[1] Environment Canada, Northern Forest Research Centre, 5320-122 Street, Edmonton, Alberta. T6H 3S5

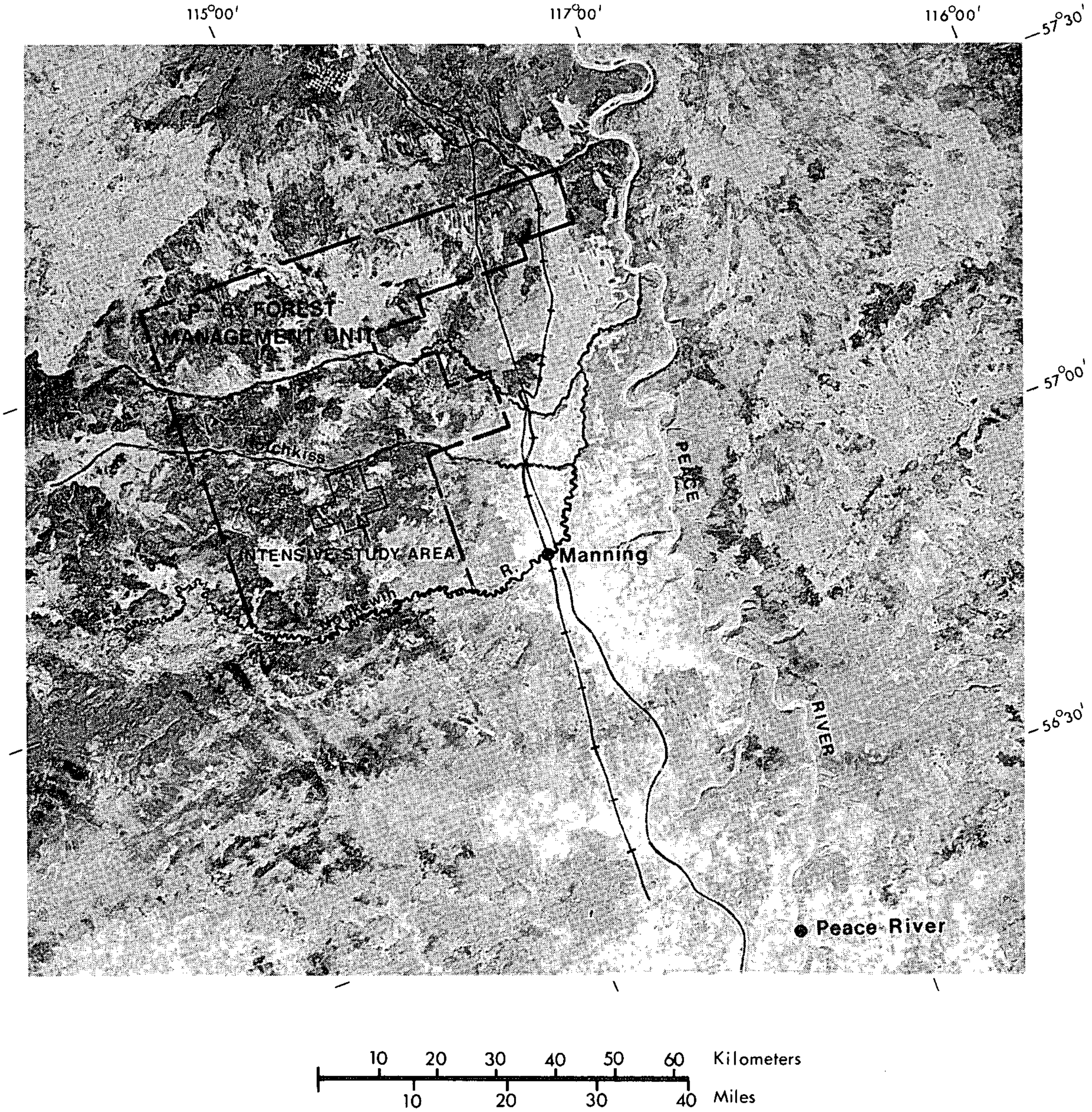


Figure 1. Location of P 6 management unit and intensive study area on Landsat image E-1600-18242 obtained March 15, 1974.

from forest growth, cutting, fire, removal of forest land from production by agriculture and other land uses.

The objectives of this study are to show how measures from Landsat, ultra-small and large-scale aerial photographs may be interpreted and incorporated in a multistage sampling design for forest and habitat inventory of large areas. The design is demonstrated in an application for estimating merchantable softwood timber volume on a 3000 km^2 management unit called P-6.

LOCATION, GROUND TRUTH AND DESCRIPTION OF AREA

The test area is located (Fig. 1) in northern Alberta (centered near 57^oN and 118^oW) in the boreal forest region classified as B19a, lower foothills section (Rowe 1972). It consists of the management unit of P-6, which is approximately 3000 km^2. Within P-6, a 70 km^2 test area was selected for intensive study of forest stand and tree variability and for development of satellite interpretation and photo mensuration techniques. The techniques developed on the intensive study area were then used in a test on the entire P-6 management unit.

Ground truth locations and summary of plot data are presented in Appendix II. In addition, a conventional two-stage forest inventory completed in 1974 from 1:20,000 black-and-white aerial photographs and ground samples, and small (1:114,000) and large- (1:2400) scale aerial photography were used for evaluation and development of techniques.

Typical of the boreal forest region, the area is highly heterogeneous, comprising forest cover types varying with extensive past fire history and with minor changes of soil drainage (Figs. 2 and 3). The topography is flat to slightly rolling. The soil is formed from morainic and glaciolacustrine deposits (Kirby 1976). On the poorly drained areas, extensive sedge and sphagnum-type bogs have developed. The better drained areas have many forest cover types ranging from pure stands of white spruce *Picea glauca* (Moench) Voss to white spruce in association with aspen *Populus tremuloides* Michx. and/or with balsam poplar *Populus balsamifera* L. white birch *Betula papyrifera* Marsh., jack pine *Pinus banksiana* Lamb., lodgepole pine *Pinus contorta* Dougl. var. latifolia Engelm., black spruce *Picea mariana* (Mill.) B.S.P., balsam fir *Abies balsamea* (L.) Mill. and occasionally with tamarack *Larix laricina* (Du Roi) K. Koch.

Figure 2. Extensive stands of white spruce, poplar and mixed cover types.

Figure 3. A spruce understory is present under many of the poplar stands.

LANDSAT INTERPRETATION

Three Landsat images were used to develop interpretation techniques using optical and computer methods. The satellite images studied are:

Number	Imaging Date
E-1600-18242 (Landsat A)	March 15, 1974 (Winter)
E-1295-18353 (Landsat A)	May 15, 1973 (Spring)
E-21064-18174 (Landsat B)	July 5, 1975 (Summer)

Evaluation of all interpretation is based on ground sampling (Appendix II) and small-scale aerial photography. (See Section on Ultra-Small and Large-Scale Photo Applications).

Optical Techniques

The simplest approach for interpreting broad forest cover types and mapping of small cut-overs and new road construction was to obtain a winter Landsat picture in color from the National Air Photo Library in Ottawa (Figures 1 and 4). The interpretation of the March image is possible because the relatively high sun angle in March coupled with snow cover enhanced line detail and differences in forest cover types.

The cover types and line detail interpreted from a photographic enlargement of the winter satellite image (Fig. 4) are: mature soft-wood forest (S), poplar forest (H), black spruce bogs (B), open areas with snow (O), pipelines 30 m wide (P) and logging roads (R). A small-scale (1:114,000) color infrared photograph presented in Figure 4 shows similar generalizations. A comparison of the the ocular Landsat interpretation of the mature softwood forest with the 1974 conventional forest inventory indicated the Landsat inter-pretation to be 78 percent correct on township by township comparison as presented in Table 4. The determination of forest cover types was improved with the use of a color additive viewer and the combination of several seasons to produce a color composite picture (Kirby, 1974). Evaluations of the mapping accuracy of forest clear cut areas indicated that they were within ± 5 percent (Winquist and Jackson 1975, Lee 1975, and Murtha 1975). However, residual strips of timber 200 m wide appeared to be only 100 m wide on Landsat images, because of problems with resolution, and con-siderable error in mapping of small areas would result.

Computer Techniques

Further improvements in forest cover type classification accuracy were made by using the digital magnetic tapes of the satellite images and interpreting these on the General Electric "Image-100" computing system at the Canada Centre for Remote Sensing (CCRS) in Ottawa. The Image-100 and the classification system is described by Goodenough (1975) and Kirby et al. (1975). This system requires training of the computer to recognize various forest cover types by selecting areas where the forest cover is known and determining spectral signatures at these points. These signatures, developed for each image based on measures of reflectance in four spectral bands in the 70 km^2 study area, were used to classify the remainder of the P-6 test site.

All three digital magnetic tapes for three seasons were classified using the Image-100 system. Color coded maps of the classifica-tions were recorded with the electron beam image recorder (EBIR) at a scale of 1:250,000. Examples of the classification produced for the winter and summer seasons studied is shown in Figure 5. Each season provided information on various cover types that could be obtained only at that point in time. The classifica-tions presented in Figs. 5 and 6 are not necessarily optimum, but indicate possible seasons for classification of various cover types.

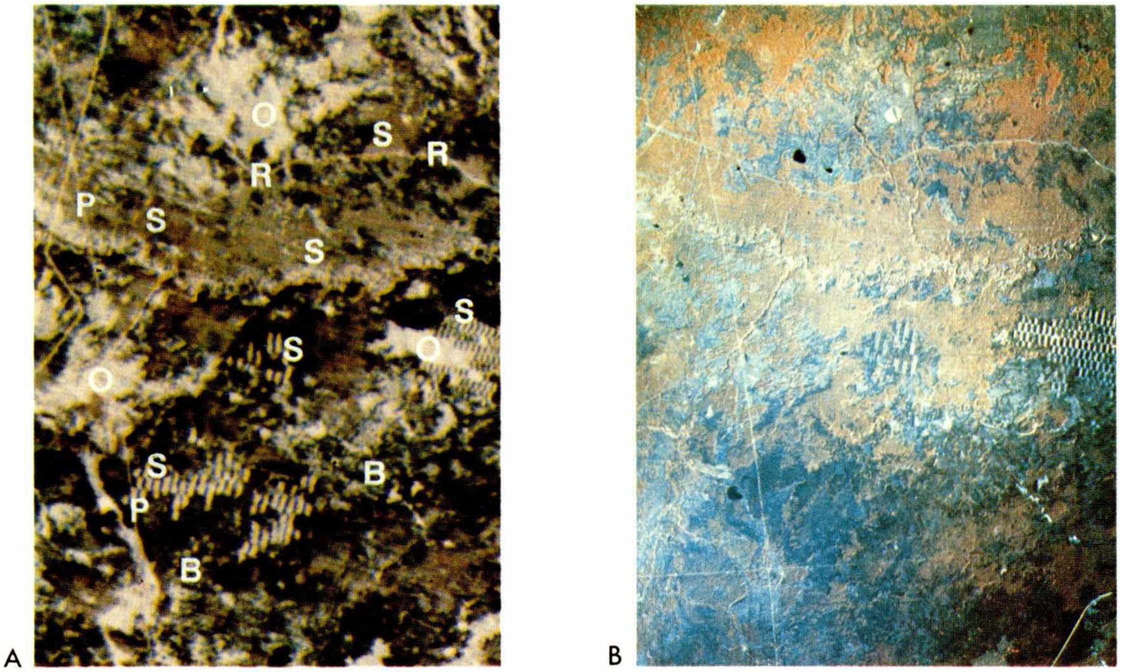
The spring image (E-1295-18353) yielded classi-fications of mature softwood, water, black spruce bog types and grass-shrub cover types that were greater than 80 percent correct. Classification of other cover types was better accomplished with the summer and winter images.

The summer image (E-21064-18174) provided a good classification of all forest cover types except that sedge bogs and poplar forests were confused and were classified as one theme. The classification of mature softwood and mature spruce-poplar forest appeared to be use-ful, but was not evaluated in detail.

The winter image (E-1600-18242) provided three themes that were greater than 80 percent cor-rect. These are open areas with snow; mature softwood and mature spruce-poplar combined; and predominantly poplar forests. In addition, in the winter scene, there is some indication of poplar forests with a spruce understory.

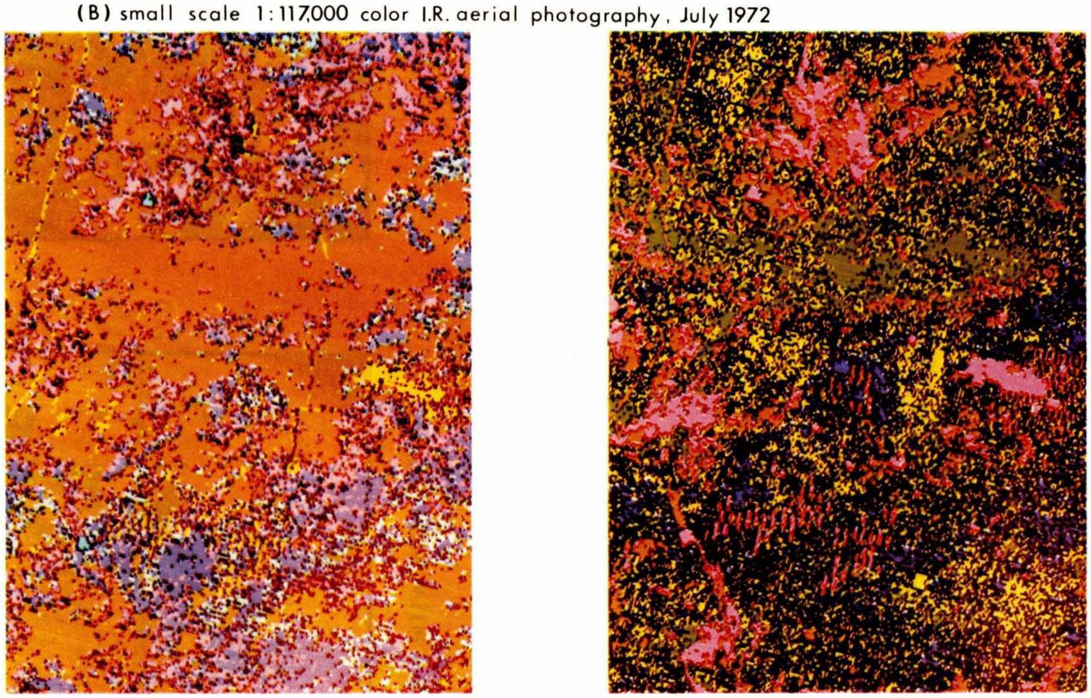
Overlaying the best classifications from various seasons or using the spectral signa-tures from two seasons to classify various forest cover types will probably result in the most accurate classification of forest cover types. One approach is to classify two magnetic tapes of the same area simulta-neously on the Image-100, but obtaining good registration with Landsat A and B images for a classification based on winter and summer imagery proved difficult.

Another approach to using information from various seasons is to produce individual cover types (binary coded theme maps) and have these individual classifications printed on the line printer of the Image-100. Five themes with greater than 80 percent classifi-cation accuracy from the winter and spring classification are shown in Figure 6. The winter scene classification was used to map mature softwood (see Fig. 11), hardwood and open areas with snow; and the spring scene was used to map black spruce bog types and grassland-shrub areas.



S MATURE SOFTWOOD FOREST
H HARDWOOD
B BLACK SPRUCE BOGS
O OPEN AREAS WITH SNOW
P PIPELINES 30 m WIDE
R LOGGING ROAD

Figure 4. A comparison of (A) Landsat ocular interpretation of image E-1600 - 18242, March 15, 1974 and (B) small scale 1:117,000 color I.R. aerial photography, July 1972



SUMMER	
BROWN	POPLAR, SEDGE AND SHRUBLAND
L.BLUE	WATER
PURPLE	MATURE SOFTWOOD FOREST
L.GREY	MATURE SOFTWOOD - POPLAR
PINK	BLACK SPRUCE BOG
YELLOW	GRASSLAND

E-20164-18174, July 5, 1975

WINTER	
PINK	OPEN AREAS WITH SNOW
GREEN	POPLAR
YELLOW	POPLAR WITH SOFTWOOD UNDERSTORY
BLUE	MATURE SOFTWOOD FOREST
BROWN	BLACK SPRUCE BOG

E-1600-18242, March 15, 1974

Figure 5. Electron beam image recording (EBIR) at a scale of 1:250,000 of Image - 100 classification for two seasons

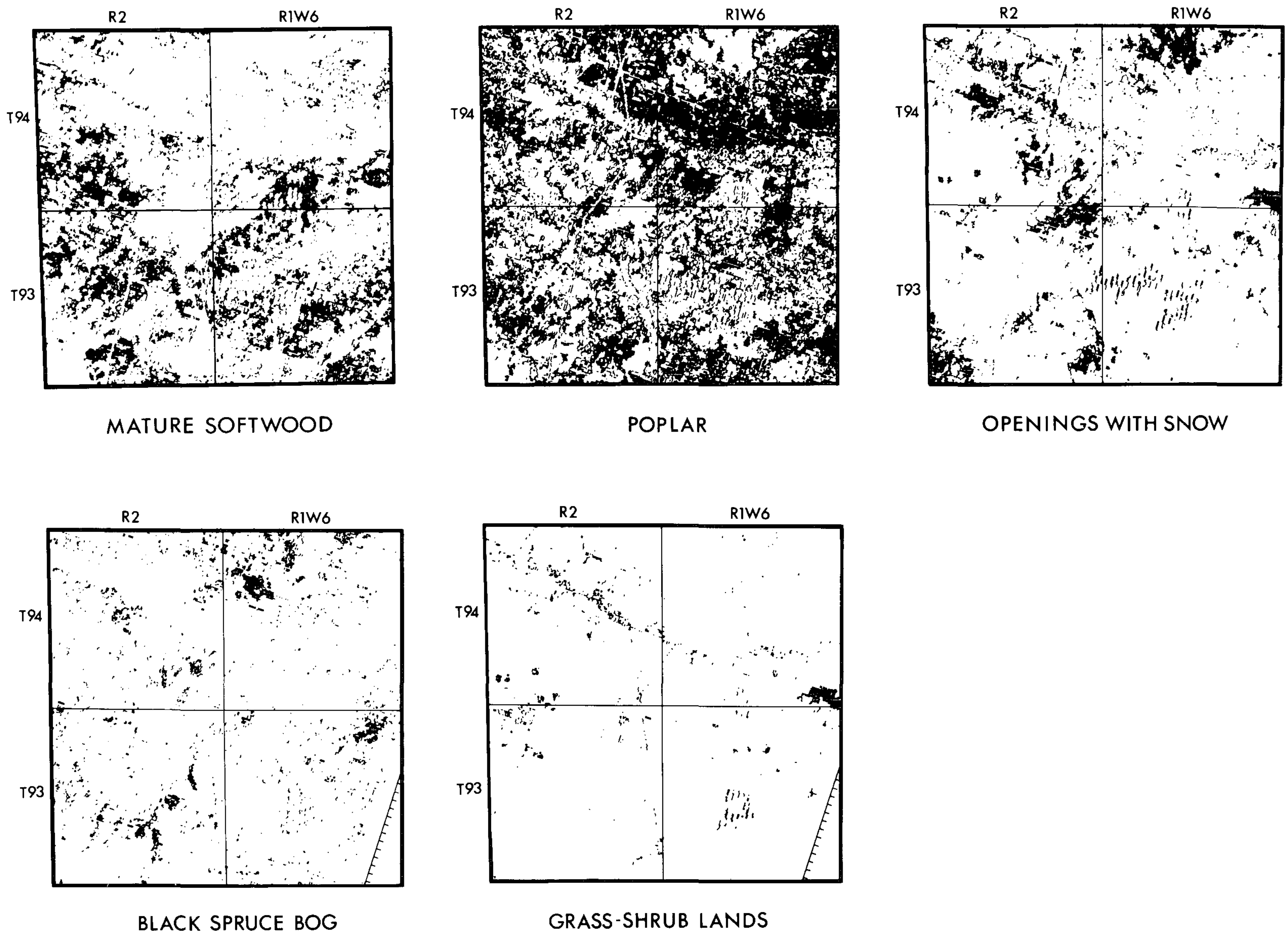


Figure 6. Image-100 binary coded theme maps based on winter and spring images

In the three satellite images classified, some unmerchantable black spruce stands were erroneously classified as merchantable softwood forest. In addition, underestimates of merchantable softwood area occurred when there were many small patches. The underestimate in small scattered stands is attributed to the "pixel" (picture element) size of 57 x 79 m for Landsat. The problem arose from a pixel being half on and half off a theme, resulting in a mixed signature that was not classified. This is important in the mapping of cutting areas where residual strips of forest appear narrower than their actual size. (See Fig. 4).

Cost of ocular methods was approximately $0.03 per km^2. Computer techniques, if all costs of magnetic tapes, computer time and transportation to Ottawa were included would amount to $.3 per km^2 for the 3000 km^2 (P-6) area.

ULTRA-SMALL AND LARGE-SCALE PHOTO APPLICATIONS

This section of the report presents development and evaluation of small-scale photo mapping and photo mensurational techniques for estimating merchantable forest volume. Also presented are large-scale photo sampling techniques for estimating individual tree diameter and volume. All photo interpretation and measures of differential parallax were done (using a Zeiss Jena Interpretoskop) by experienced photo interpreters with the ability to measure differential parallax within ±.02 mm consistently.

Ultra Small-Scale Photo Applications

Small-scale (1:114,000) color IR aerial photography of the P-6 area was obtained by the Canada Centre for Remote Sensing in July, 1972. A jet aircraft flying at 10,000 m above the ground employing an RC-10 camera with a lens focal length of 88.5 mm was used to obtain the photography. Interpretation of forest cover and soils were made on 2X enlargements. Measurements of tree height and stand density were made on contact positive transparencies.

Photo maps at scales of 1:60,000 and 1:30,000 with overlays of forest cover and soils were produced in color and black and white and may be obtained on request from the Northern Forest Research Centre. They illustrate how photo maps of a 400 km^2 area are produced from a single small-scale photograph and provide considerable information for forest management at low cost. They are an improvement over conventional medium-scale photo mosaics (Figs. 4 and 7).

A comparison of the cover type mapping from 1:20,000 black-and-white and 1:114,000 color IR aerial photographs is given in Table 1. For the most part, the interpretation of the two scales of aerial photography by two different interpreters is similar. There was significant difference in the mapping of hardwood and mixed stands as indicated in Table 1. This is attributable to better recognition of white spruce in the mixed stands on the color IR photographs. In addition, small (one ha) patches of tree mortality (caused by beaver activity) were detected on the color IR. There was no significant difference in estimates of crown closure, but the most accurate estimates of crown closure were made on the 1:20,000 black-and-white photographs.

The cost of preparing forest cover maps at a scale of 1:15,000 from 1:114,000 color IR photographs is estimated to be at least one-half of the cost of making forest cover type from conventional 1:15,000 black-and-white aerial photographs.

The main problem with small-scale aerial photography in forest cover type mapping was that more detail could be seen on the aerial photographs than could be delineated. This was overcome by enlarging the photographs twice their linear size, and using contact-scale positive transparencies for checking critical measurement of stand height, species composition and crown closure.

Measurements of average dominant height on the 1:114,000 photography at points near the ground plots with felled trees (see Appendix II) had the following accuracy and precision.

Variable	Interpreter I	Interpreter II
Mean Height from photos (m)	20.6	20.0
Mean height on the ground (m)	21.4	20.9
Standard error of estimate (m) $\sqrt{\frac{d^2}{n-1}}$	2.3	3.0
Number of stands measured	25	33

Similar results on another test area were obtained by Nielson and Wightman (1972) on aerial photographs ar a scale of 1:160,000; their standard errors of estimate were ± 3.1 and ± 3.8 m.

Table 1. A comparison of percentage distribution of forest cover types by height class based on maps prepared from 1:20,000 black and white I.R. photographs and 114,000 color I.R. photographs.

		Cover type percentage distribution on study area			
		Aerial Photos			
Cover type	Height class (m)	1:20,000 Black & White I.R.		1:117,000 Color I.R.	
S	7-12	5.6		7.1	
SH		0.2		1.2	
HS		0.2		0.1	
H		0.4	6.4	0.1	8.5
S	13-18	2.5		2.6	
SH		5.8		0.6	
HS		13.0		34.7*	
H		22.8	44.1	1.3*	39.2
S	19-24	3.3		1.6	
SH		1.0		2.0	
HS		0.2		-	
H		0.1	4.6	-	3.6
S	24+	-		-	
SH		9.2		16.1	
HS		2.8		0.1	
H		-	12.0	-	16.2
Bog		32.4		32.1	
Water		0.5		0.4	
TOTALS		100		100	

* Significant difference between interpretations.

An equation to predict softwood total volume in m^3/ha for forest stands was developed from measures both of height of dominants and of crown cover as a percent of total crown cover on the 1:117,000 photography of the intensive study area. The photo measurements were correlated with measures of volume obtained from the ground plots data (Appendix II). The equation is:

$$Vm^3/ha = 24.5 + .124\ (Hm)\ (S\%) \qquad \text{Equation I}$$

$r^2 = .76$ SE = $\pm$ 24 m^3 or $\pm$ 32% of average volume

Where: Vm^3 = total softwood cubic meters per ha.

Hm = average stand height (m) of dominant and codominant trees measured on small-scale aerial photographs.

S% = percentage of softwood crown cover in the total crown cover.

On one 100 km PSU (primary sampling unit--see section on sampling design) the average height of dominant and codominant trees and the percentage of softwood crown cover in the total crown cover were measured on a stereo pair of the small-scale color IR photos. This was done on a grid of one hundred equally spaced point locations. The measurements were used to estimate merchantable softwood volume. (Eq. I) Standard error of the mean softwood volume estimates in percent for three height classes of softwood cover types are: 24 m (± 2.3%); 19-24 m (± 5.2%); 13-18 m (± 8%). This indicates that ten to twenty estimates in each height class of the merchantable softwood cover types on a PSU would be sufficient to attain a precision ± 10% at the 95% confidence level.

Large-Scale Photo Sampling

Development and testing of equations and methods to obtain detailed information by species of average stand diameters and of number of stems per hectare were done from measures obtained from large-scale aerial photographs. The aerial photographs were taken with a 70 mm Vinten camera equipped with a 305 mm lens, no filter, and medium speed black-and-white film. The lighting of the shadow areas was best without any filter. The photography was done from an elevation of 600 m (Fig. 8) in the fall when the poplar were without leaf.

Individual softwood tree height measurement on the large-scale aerial photographs had a standard error of estimate of 0.5 m when photo measures were compared with ground measurements.

From paired ground and photo measurements of individual trees on the intensive study area within P-6, the following regression equations were obtained. They are based on a model suggested by Aldred and Sayn-Wittgenstein (1972) which may be a slight improvement over those used by Kirby and Johnstone (1970).

The model used is as follows:

$$dbhcm = a + b\,(Hm)\,(\mathrm{Log}_{10}\sqrt{CAm^2})$$

where: dbh cm = diameter breast height in cm.

H m = total height of tree in m.

$\mathrm{Log}_{10}\ CA\ m^2$ = The log of the estimated crown area in m^2. Crown area in this analysis was estimated using a tree crown gauge consisting of a row of circles of different sizes as described by Moessner (1960).

N = number paired ground and photo measurements of individual trees.

The regression equations developed are:

White Spruce: Equation II

$$dbhcm = .57 + .456\,(Hm)\,(\mathrm{Log}_{10}\sqrt{(CAm^2)(27.33)})$$

$$N = 198 : R^2 = .85 : SE_E = \pm\ 4.1\ cm$$

Aspen: Equation III

$$dbhcm = .70 + .479\,(Hm)\,(\mathrm{Log}_{10}\sqrt{(CAm^2)\ (27.33)})$$

$$N = 68 : R^2 = .73 : SE_E = \pm\ 4.3\ cm$$

In a test of equations II and III based on paired ground and photo measurements of nineteen 20 x 100 m plots, the prediction of average stand diameter was good. Eighty-two percent of the variation was accounted for by the photo measurements. The photo estimates of number of stems (r^2 = .72) and volume in m^3/ha (r^2 = .59) are less accurate. This is attributable to displacement of trees because of parallax, and to missed trees on the photo plots. To correct for missed trees and photo interpreter bias regression equations for each survey and interpreter are required for the relationships as shown in Fig. 9.

The optimum allocation of ground and photo plots may be estimated from an equation presented by Cochran (1953) for surveys with double sampling. The optimum allocation is related to the correlation of ground and photo sampling and their relative cost. From our pilot study we estimated that the cost per ground plot was 10 times the cost of a photo plot and that there was about an 80 percent correlation of ground and photo plot measurement when correction for parallax displacement of trees was made.

The equation to calculate the proportion of ground and photo sampling is as follows:

$$\frac{n}{n^1} = \sqrt{\left(\frac{1-r^2}{r^2}\right)\left(\frac{Cn^1}{Cn}\right)}$$

where:

n = ground plot sample size
n^1 = photo plot sample size
r = correlation coefficient of ground and photo plots
Cn = cost per ground plot
Cn^1 = cost per photo plot

Substituting the correlation r of .9 and a relative cost of photo and ground plots of 1:10 in the proceding equation:

$$\frac{n}{n^1} = \sqrt{\frac{(1-(.9)^2)\ (Cn^1)}{(.9)^2\ (10\ Cn^1)}} = \frac{1}{7}$$

The optimum allocation for ground and photo plots with this correlation and relative cost is about one ground plot for every seven photo plots.

Additional equations for predicting individual tree diameter and volume from measures of tree height only are presented in Tables 2 and 3. The equations are based on stem analysis data collected from ground-sample plots (Appendix II). These are local equations and are applicable to the P-6 test area. The high precision of estimates of tree diameter and volume from measures of tree height only indicates that photo measures of crown area may not be required when local equations are available. Even the net volume of poplar is highly correlated with tree height. This is an improvement over correlations obtained with age and approaches the precision obtained with measures of diameter and height. (See Fig. 13, Appendix II and Table 2). The high precision of the equations in Table 2 and 3 and in Fig. 13 is attributable to homogeneous site on the intensive study area and to high quality field measurements.

Figure 7. Photo mosaic prepared from 1:20 000 I.R. black and white photographs.

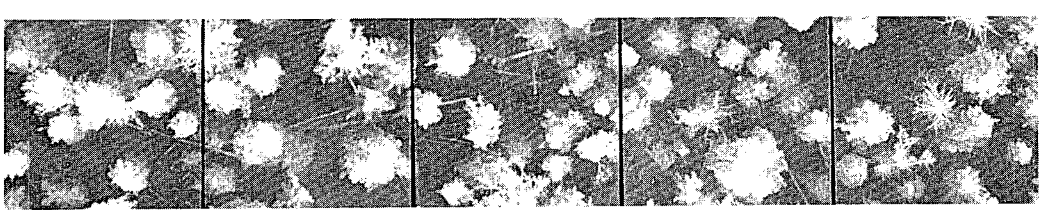


Figure 8. A 20 x 100 m (with 20 x 20 m sub-units) large-scale photo sampling unit enlarged 4X to a scale fraction of 1:633.

Table 2. Equations for estimating tree diameter from measures of tree height in metres.*
[dbh (cm) = a + b (total height in m) + c (total height in metres)^2]

Species	Equation (dbhcm = a + bHm + cHm^2)	r^2	SE_E	No. of trees sampled
White Spruce	$4.64 + .434H + .0146H^2$	.96	1.7	746
Aspen	$4.69 + .326H + .0197H^2$	.96	1.1	713

Table 3. Equations for estimating gross and net total tree volume in m^3 from measures of tree height in metres.*
[Total tree volume in m^3 = a + b (total height in metres) + c (total height in metres)^2]

Species	Equation (Vm^3 = a + bHm + cHm^2)	r^2	SE_E	No. of trees sampled
White Spruce				
Gross Vol. m^3	$-.138 + .00316H + .00101H^2$	.95	± .10	746
Net Vol. m^3	$-.132 + .00291H + .00098H^2$	.94	± .11	746
Aspen				
Gross Vol. m^3	$-.270 + .01515H + .00074H^2$	.93	± .06	713
Net Vol. m^3	$-.167 + .00938H + .00058H^2$	.83	± .08	713

* for trees greater than 12.1 cm in diameter and 10 m in height

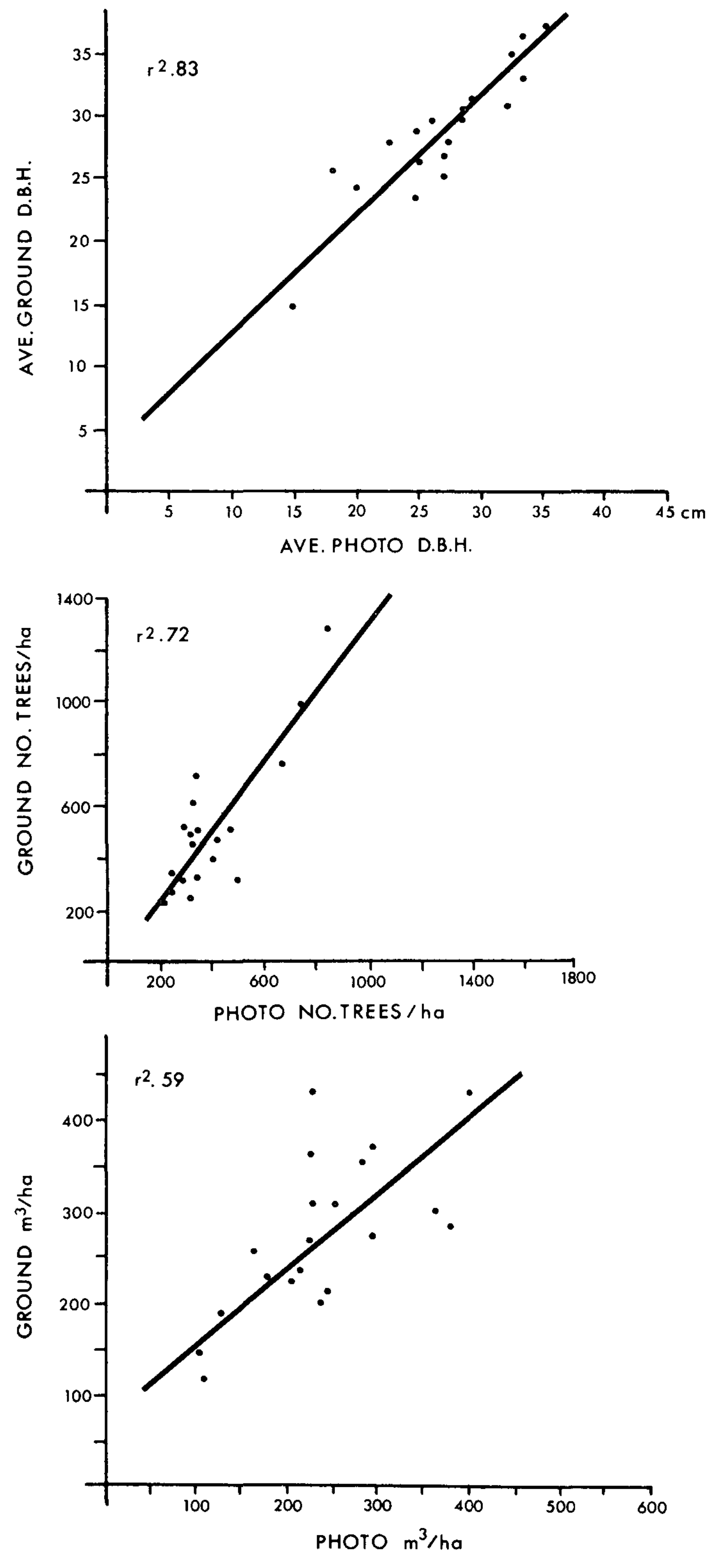


Figure 9. A comparison of ground measurement and photo estimates of average stand diameter, number of trees per hectare, and total m^3 per hectare on paired 20 m x 100 m (1/2 acre) plots for all trees 12.1 cm and greater.

MULTISTAGE SAMPLING

A multistage sampling design that integrates the measures obtained from space images, aerial photographs and ground samples was tested. Basic theory used in the design has been described by Cochran (1953) and Hansen, Hurwitz and Madow (1953). The design has been used infrequently for forest inventories because of the difficulty of obtaining an inexpensive overview. Since the development of spacecraft, Langley (1969) has demonstrated the potential of multistage forest inventories by using information from Apollo 9 photographs. The overview from space improved allocation of sampling units that needed higher resolution aerial photography and ground sampling. The design is suitable for large survey areas with specific objectives, such as estimating timber volume and quality (Langley 1969) (Nichols et al. 1974) or forest damage (Wert 1969). There is no standard procedure. Various combinations of photo interpretation and ground sampling may be applied.

Sampling Design

Presented here is a test of a multistage sampling design to estimate merchantable softwood volume on a 3000 km area (P-6) in the boreal forest region. Figure 10 shows how selected primary sampling units (PSU's) may be subsampled with progressively smaller sampling units in secondary and tertiary stages.

A generalized model for a three-stage design presented by Langley (1976) is:

$$\hat{V} = \frac{1}{m} \sum_{l=1}^{m} \frac{1}{p_i n_i} \sum_{j=1}^{n_i} \frac{1}{p_{ij} t_{ij}} \sum_{k=1}^{t_{ij}} \frac{V_{ijk}}{p_{ijk}}$$

in which v_{ijk} is the measured volume in stage three.

- p_i is the probability of drawing the i^{th} stage unit.
- p_{ij} is the conditional probability of drawing the j^{th} second stage unit given the i^{th} first stage unit.
- p_{ijk} is the conditional probability of drawing the k^{th} third stage unit given the first and second stage units which have been drawn.
- m, n_i, and t_{ij} are the sample sizes in the first, second, and third stages, respectively.

Generalized models for calculating the mean and sample variance follow.

Mean sample population estimate:

$$\hat{V} = \sum_{n=1}^{L} \frac{1}{n_h} \sum_{i=1}^{n_h} \frac{y_{hi}}{p_{hi}}$$

Unbiased estimate of sample variance:

$$\hat{\text{Variance}} = \sum_{n=1}^{L} \frac{1}{n_h (n_n - 1)} \sum_{i=1}^{n_h} \left(\frac{y_{hi}}{p_{hi}} - \hat{V}_h \right)^2$$

Selection of samples may be made using systematic or variable probability. While variable probability sampling is capable of achieving high efficiency with supplementary sampling, it should be used with caution when there is low correlation between estimates made in the first stage and succeeding stages (Langley 1976). However, where multiparameters are to be estimated, systematic sampling procedures may be required (Wensel 1974).

A Test of Multistage Sampling to Estimate the Merchantable Softwood Volume of P-6

For the first stage of the design, the binary coded theme map (Fig. 11) which shows the merchantable softwood in pure and mixed spruce-poplar stands was produced from the magnetic tape of Landsat image number E-1600-18242 on the Image-100 system. The 3000 km^2 area was divided into PSU's of about 10 x 10 km (Fig. 11). The size of the PSU was arbitrarily selected so that we could make comparisons with the conventional two-stage inventory based on 1:20,000 aerial photographs and ground samples. Merchantable softwood forest area in each PSU as determined from the computer output (Fig. 11) is given in column 4 of Table 4. The area and volume of merchantable softwood by PSU indicated by the conventional two-stage inventory are given in columns 2 and 3 of Table 4. The area of merchantable softwood for each PSU based on the Landsat interpretation correlated highly with area (r^2 = .86) and volume (r^2 = .79) estimates of the conventional two-stage inventory.

Sample selection was with replacement and probability proportional to size, where size is defined as the Landsat estimate of area in merchantable softwood. On the six selected primary sampling units (Table 5) estimates of merchantable softwood volume were based on the results of the two stage inventory. These estimates were projected to obtain estimates of merchantable softwood volume for all of P-6 using multistage sampling procedures as presented in Table 5.

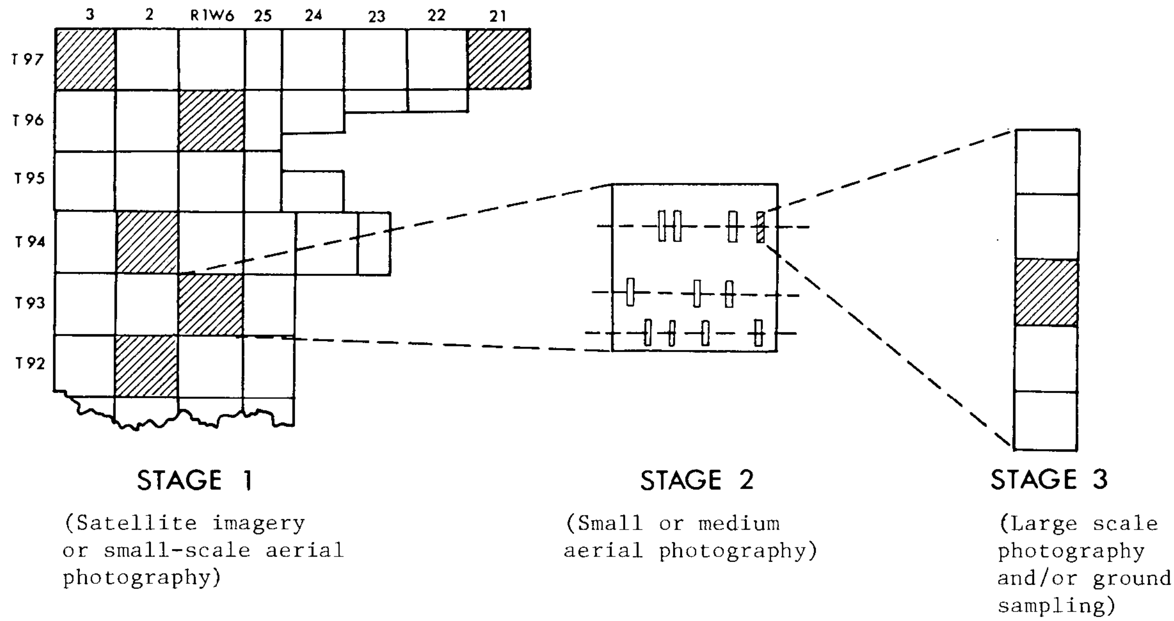


Figure 10. Diagram of sampling design showing the selection of smaller and smaller subsamples at various stages.

The average merchantable softwood volume on P-6 estimated from this sample of size 6 is 11.8 MM m^3 (Table 5) compared to 12.1 MM m^3 estimated by the conventional inventory (Tables 4 and 5). The standard error of the mean is approximately ± 10% at the 67 percent confidence level.

To test the efficiency of variable probability sampling as compared to simple random sampling weighted by PSU size that is commonly used in forest inventories, the variances were calculated based on data for the 38 PSU's (Table 4). This substantial data base indicates that the sample size required to achieve a given precision using variable probability sampling is only one-third of the sample size required when simple random sampling is used. Therefore variable probability sampling based on a Landsat interpretation is demonstrated to be highly efficient for estimating merchantable softwood volume in the boreal forest region.

DISCUSSION

A number of multistage sampling designs is possible. The selection of measures from Landsat, aerial photographs and ground samples to be incorporated into a design will depend on: objectives of the inventory, funds available, time constraints, and relative cost of various alternatives. Immediate gains in reducing forest inventory costs and in supplying current information can be made by using:

1. A multistage design with selection of sampling units based on variable probability established from the interpretation of Landsat images is recommended for large area inventories with specific objectives. In the design presented in this report there is a 66 percent reduction in the variance when variable probability sampling instead of random sampling was used. This greatly reduces the amount of costly photo and ground work required to achieve a desired precision.

2. The synoptic view of Landsat to provide information for broad policy and planning.

3. Small-scale aerial photography (1:50,000 to 1:100,000) for the preparation of forest cover type maps and photo mosaics.

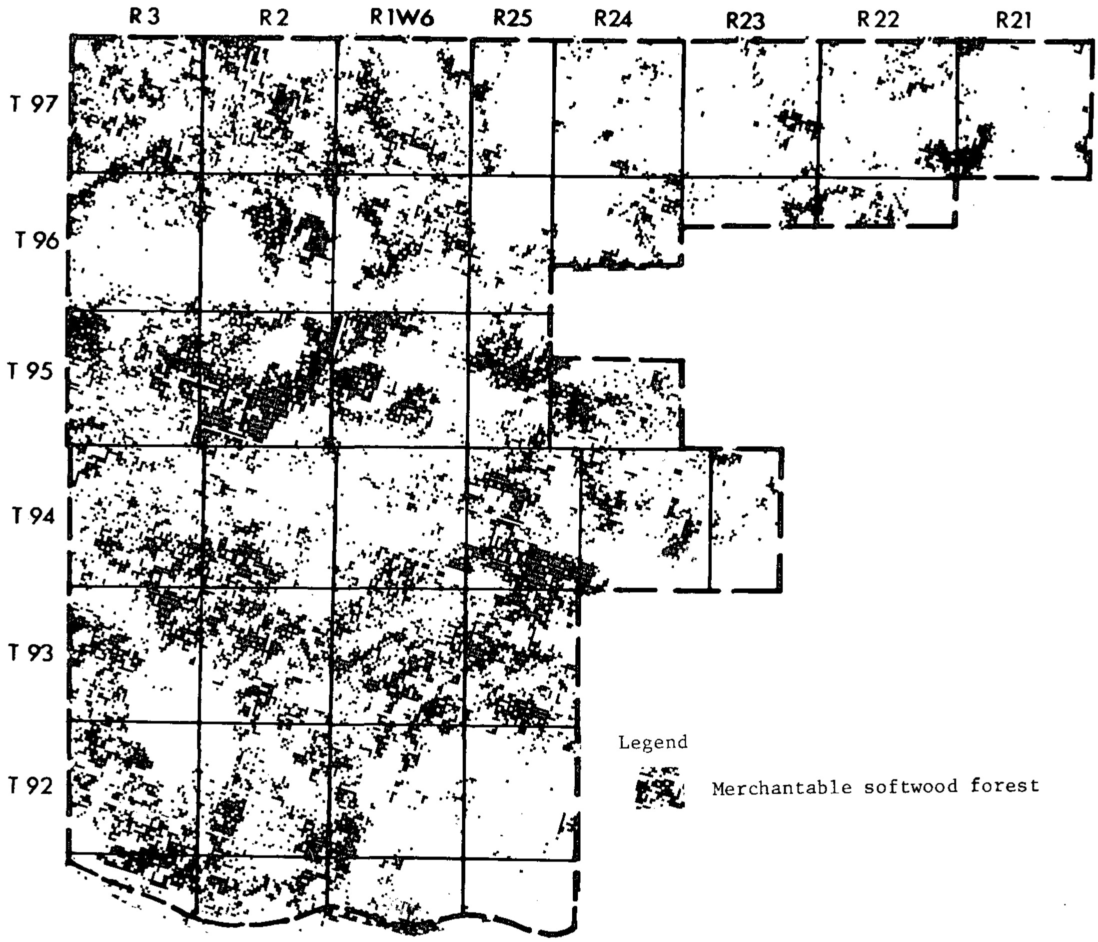


Figure 11. Binary coded theme map at 1/4 resolution showing merchantable softwood stands on P-6 management unit.

4. Large-scale photo sampling to partially replace expensive ground sampling for timber volume estimates and assessment of cut-over lands and habitat types.

5. Landsat imagery for updating of forest cover maps showing areas clear cut, burned and lost to forest production through other uses.

Future research and development at the Northern Forest Research Centre will make multistage inventories even more efficient by incorporating:

1. Landsat images with higher spatial resolution and with thermal sensing. Landsat C to be launched in 1977 will have 4 times the present resolution of Landsat A and B.

2. Improved satellite image interpretation techniques using digital computers and optical methods with multi-season images.

3. An optimum PSU size for a multistage sampling design could possibly bring further reduction in sampling costs.

4. More precise and less costly large-scale photo sampling by virtue of having a radar altimeter to provide accurate scale and a mini computer to speedily compile the photo measurements.

Table 4. Landsat area estimates and Alberta Forest Service statistics on merchantable softwood , area and volume by primary sampling unit (PSU).

PSU Twp-Rge-Mer	Ground truth[1] ** Area (ha)	Ground truth[1] ** Merch. Swd. Volume by township Y_{hi} (M m^3)	Area and volume estimates based on Landsat Image-100 interpretation: Area (xi) (ha)	Cumulative total (Ti) $\sum_{i=1}^{n} xi$ (ha)	Proportion of total area $Pi = \frac{xi}{\sum_{i=1}^{n} xi}$	Merch. Swd. Vol. on total P-6 area $\left(\frac{1}{Pi}\right)\left(Y_{hi}\right) = \left(\frac{1}{Clm6}\right)\left(Clm3\right)$ (MM m^3)
Clms (1)	(2)	(3)	(4)	(5)	(6)	(7)
91- 1-W6	802	113.9	512	512	.007 58	15.0
91- 2-W6	1 837	339.6	1 873	2 385	.027 77	12.2
91- 3-W6	702	135.9	927	3 312	.013 74	9.9
91-25-W5	39	7.1	32	3 344	.000 48	14.8
91- 1-W6	2 339	315.0	2 284	5 628	.033 87	9.3
92- 2-W6*	2 959	636.3	2 587	8 215	.038 34	16.6
92- 3-W6	1 216	176.8	2 434	10 649	.036 08	4.9
92-24-W5	974	174.6	588	11 237	.008 72	20.0
93- 1-W6*	3 473	582.9	3 318	14 555	.049 20	11.8
93- 2-W6	3 025	517.2	2 624	17 179	.038 91	13.3
93- 3-W6	2 348	388.9	2 316	19 495	.034 33	11.3
93-25-W5	4 034	734.7	4 375	23 870	.064 86	11.3
94- 1-W6	765	103.5	1 203	25 073	.017 83	5.8
94- 2-W6*	1 386	215.1	1 723	26 796	.025 54	8.4
94- 3-W6	2 161	329.3	2 130	28 926	.031 59	10.4
94-23-W5	396	78.9	412	29 338	.006 10	12.9
94-24-W5	2 371	630.5	2 680	32 018	.039 73	15.8
94-25-W5	2 403	534.6	3 090	35 108	.045 82	11.7
95- 1-W6	2 717	671.4	2 563	37 671	.038 00	17.7
95- 2-W6	3 304	631.9	4 272	41 943	.063 33	10.0
95- 3-W6	3 219	505.0	2 800	44 743	.041 52	12.2
95-24-W5	2 009	520.5	1 722	46 465	.025 53	20.6
95-25-W5	1 754	411.3	2 077	48 542	.030 79	13.4
96- 1-W6*	2 069	394.0	1 987	50 529	.029 46	13.4
96- 1-W6	1 933	365.1	2 178	52 707	.032 28	11.3
96- 3-W6	1 970	343.7	1 131	53 838	.016 77	20.5
96-22-W5	414	62.2	605	54 443	.008 96	7.2
96-23-W5	673	96.8	390	54 833	.005 78	16.8
96-24-W5	1 760	329.0	1 009	55 842	.014 96	22.0
96-25-W5	558	81.0	452	56 294	.006 69	12.1
97- 1-W6	1 524	244.0	1 343	57 637	.019 92	12.3
97- 2-W6	2 517	349.1	2 277	59 914	.033 76	10.3
97- 3-W6*	4 298	516.3	3 606	63 520	.053 45	9.7
97-21-W5*	855	182.5	1 110	64 630	.016 46	11.1
97-22-W6	813	94.5	1 148	65 778	.017 02	5.6
97-23-W5	906	164.3	730	66 508	.010 83	15.2
97-24-W5	950	127.2	560	67 068	.008 29	15.3
97-25-W5	286	40.8	380	67 448	.005 64	7.2
TOTALS (Σ)	67 759	12 145.4 (12.1 MM)	67 448			
					Mean estimate =	12.6
					Standard dev. =	4.2

[1] Alberta Forest Service statistics based on 1974 two-stage inventory.

* Samples drawn with probability proportional to occurrence using Column 5 and set of random numbers.

** Average stand and stock tables for the various cover types are based on sampling in some of the PSUs. Some error in the ground truth volume is possible because the average stand and stock tables are not applicable to all PSUs.

Table 5. Sample of six PSU's selected from Table 4 to obtain an estimate of P-6 volume.

PSU Twp-Rge-Mer	Area: Ground truth (ha)	Area: I-100 Interpretation (ha)	(P_{hi}) proportion of total area (I-100)	Ground truth estimated (Y_{hi}) merch. swd. vol. (M m^3)	Entire P-6 area predicted (Y_{hi}/P_{hi}) merch. swd. vol. (MM m^3)
92- 2-6	2 959	2 587	.038 34	636.3	16.6
93- 1-6	3 473	3 318	.049 20	582.9	11.8
94- 2-6	1 386	1 723	.025 54	215.1	8.4
96- 1-6	2 069	1 987	.029 46	394.0	13.4
97- 3-6	4 298	3 606	.053 45	516.3	9.7
97-21-5	855	1 110	.016 46	182.5	11.1
Σ	15 040	14 331			71.0
Estimated merch. swd. vol. on P-6					11.8
SEE(Standard error of estimate)					1.2

5. A two-stage large-scale photo sampling system employing two 70 mm cameras to obtain aerial photographs at two scales (i.e., 1:500 and 1:3,250) simultaneously. The largest scale is used to sample at prescribed intervals and the smaller scale is used to obtain a detailed stratification of the sample strip to extend the results of the large-scale photo sampling.

ACKNOWLEDGMENTS

We acknowledge the assistance from the following: The Alberta Forest Service for its cooperation in obtaining the ground truth; The Canada Centre for Remote Sensing for providing small-scale aerial photography and assistance in obtaining the Image-100 interpretations of Landsat images.

APPENDIX I

Metric Conversion Factors

To convert:

inches (in.) to centimetres (cm) multiply by 2.54

feet (ft) to metres (m) multiply by .3048

number per acre (ac) to number per hectare (ha) multiply by 2.471054

square feet (ft^2) per acre (ac) to square metres (m^2) per hectare (ha) multiply by .22957

cubic feet $(ft)^3$ per acre to cubic metres (m^3) per hectare (ha) multiply by .06998

cubic feet (ft^3) to cubic metres (m^3) multiply by .0283168

miles (mi) to kilometres (km) multiply by 1.60934

4.5 (ft) breast height = 1.3 m

To convert cubic foot tree volume equations to cubic metre equations of the form $V = a + bD^2H$ as defined by Myer and Edminster (1974):

1. Multiply the original regression coefficient b by .01440 to obtain the metric coefficient b.

2. Multiply the original intercept a by the cubic-feet to cubic-metres factor (.0283168) to obtain the new intercept a.

After these multiplications have been made, computed volumes are in cubic metres instead of the orginal cubic feet and are applicable to measures of tree diameter in centimetres and total tree height in metres.

APPENDIX II

Ground Truth

Ground plots were established on selected areas that were covered by three flight lines of large-scale aerial photography (Fig. 12). The ground plots were accurately located on maps and on the large-scale photographs for comparisons of ground and photo measurements, and for the determination of scale. The ground and photo plots were 20 x 100 m in area and were divided into five 20 x 20 m subplots. (See Fig. 8). These were tallied by diameter and species for development of tree-and-stand volume estimating techniques (Table 6). In addition, one of the 20 x 20 m plots of each cluster of five was selected randomly for stem analysis to provide information on gross and net tree volumes. On these plots, the trees were felled to obtain measures of height, diameter, age, volume and cull. The trees were sectioned at .3, 1.3, 2.9, 5.5 and in 2.6 m sections thereafter to a 10 cm top. Total cubic-foot volume for each section was calculated by treating the .3 m stump section as a cylinder. For every section thereafter the two end areas were averaged and multipled by the length, and the top was taken to be a cone. Estimates of cull at each section were obtained by making two measurements at right angles and recording the average. Cull for this study was defined as wood that was not firm. Stained wood was not classified as cull.

The stem analysis data were used to develop equations for each species to estimate gross and net volume in m^3 from measures of tree diameter and height (Fig. 13a) and age (Fig. 13b). The volume equations are similar to the equations based on data from all of Alberta and presented in an unpublished report by Kirby (1969).

Conversion to various utilization standards may be accomplished by using techniques presented by Honer (1967).

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Table 6. Summary of ground plot data on intensive study area.

Plot Number	Cover Type	ALL SPECIES: Average Age at 30 cm, Poplar	ALL SPECIES: Average Age at 30 cm, W. Spruce	ALL SPECIES: Ave. Height in m of Dominants and Co-dominants	ALL SPECIES: Average D.B.H. in cm	ALL SPECIES: No. Stems Per ha	ALL SPECIES: Total m^3 Per ha	ALL SOFTWOODS: Average D.B.H. in cm	ALL SOFTWOODS: No. Stems Per ha	ALL SOFTWOODS: Total m^3 Per ha	ALL SOFTWOODS: Site Index Classes[1]
1	C3HS	67		21	16	514	208				
2	C2SH	67	74	17	15	2088	252	14	1206	123	Good
3	B5S		137	27	36	489	481	34	274	271	Good
4	B5S	104	101	26	30	704	478	30	432	304	Good
5	C3HS	60	76	14	15	2503	334	14	1626	167	Fair
6	B4SH	66	81	17	19	1564	357	24	1149	222	Good
7	B4SH	68	74	17	13	3187	256	12	2280	149	Very Good
8	B4SH	103	92	23	21	1156	348	21	712	206	Very Good
9	B5S	66	89	26	25	729	345	26	632	295	Good
10	C3HS	59	77	19	16	1272	199	21	539	50	Good
11	C3HS	56	53	20	17	1366	242	14	99	10	Good
12	C3HS	74	59	17	17	1527	266	17	440	70	Very Good
17	B5S	60	163	23	33	378	341	30	311	278	Fair
18	C3SH		75	16	15	1687	200	26	675	82	Fair
19	B5S	107	180	30	38	247	302	36	205	251	Good
20	C2S		145(Sb)	11	12	1248	77	15	1250	77	
21	B5S		114	31	43	222	354	37	205	338	Very Good
23	B5S	60	173	32	36	378	395	35	311	340	Very Good
24	B5S	55	172	30	33	519	466	34	514	462	Excellent
25	B5S	89	162	29	31	544	424	29	465	353	Very Good
26	C2S(Sb)		57	15	15	1260	155	14	1263	154	Very Good
27	C3HS	56	44	17	15	1786	210	14	410	34	Excellent
28	B3HS	71		23	22	674	219				
29	C4HS	69	66	22	25	773	314	24	81	32	Excellent
30	C3HS	59	63	17	17	1502	257	18	773	115	Very Good
31	B4S	69	76	29	31	593	478	27	445	419	Very Good
32	C3HS	68	74	19	18	1564	309	25	729	199	Good
33	C3HS	54	66	16	14	2038	215	13	1317	100	Good
34	C3HS		81(Sb)	11	11	1680	98	11	1552	84	
35	B3HS	73	74	20	17	1848	343	15	724	102	Very Good
36	B5S		145	25	25	823	406	33	563	336	Good
37	B5S		164	27	35	341	343	36	267	275	Good
38	B5S		173	28	33	539	456	28	447	373	Good
39	B3HS	78	60	19	18	1433	284	17	89	30	Excellent
40	C3HS	60	68	14	13	1774	137	12	1329	87	Fair
41	B4SH	69	66	22	28	494	282	26	205	136	Very Good
42	B4SH	74	49	18	26	296	154	25	222	106	Excellent
43	B4SH	82	79	23	26	613	323	26	514	269	Excellent
45	C3SH	64	39	17	16	1638	259	13	193	16	Good
46	C3HS	64	66	19	18	1235	262	20	304	83	Excellent
47	C3HS	59	66	18	18	1613	311	13	482	81	Very Good
48	C3HS	65	63	20	20	1131	280	31	126	59	Excellent

[1] Classes are based on equations published in "Site index equations for lodgepole pine and white spruce in Alberta" by C.L. Kirby, Information Report NOR-X-142; 40-49 = fair, 50-59 = good, 60-69 = very good, 70-79 = excellent.

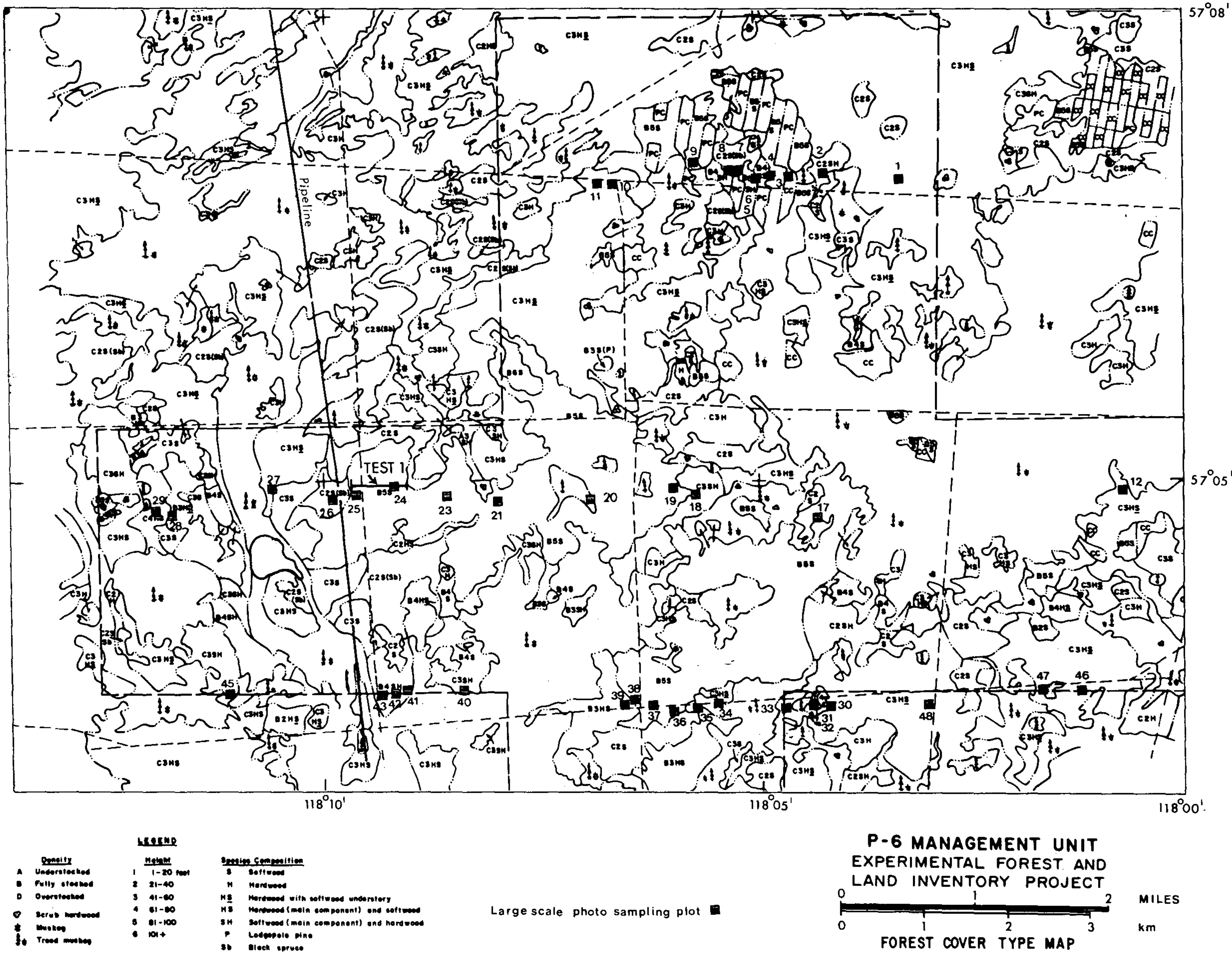

Figure 12. Location of ground sample plots.

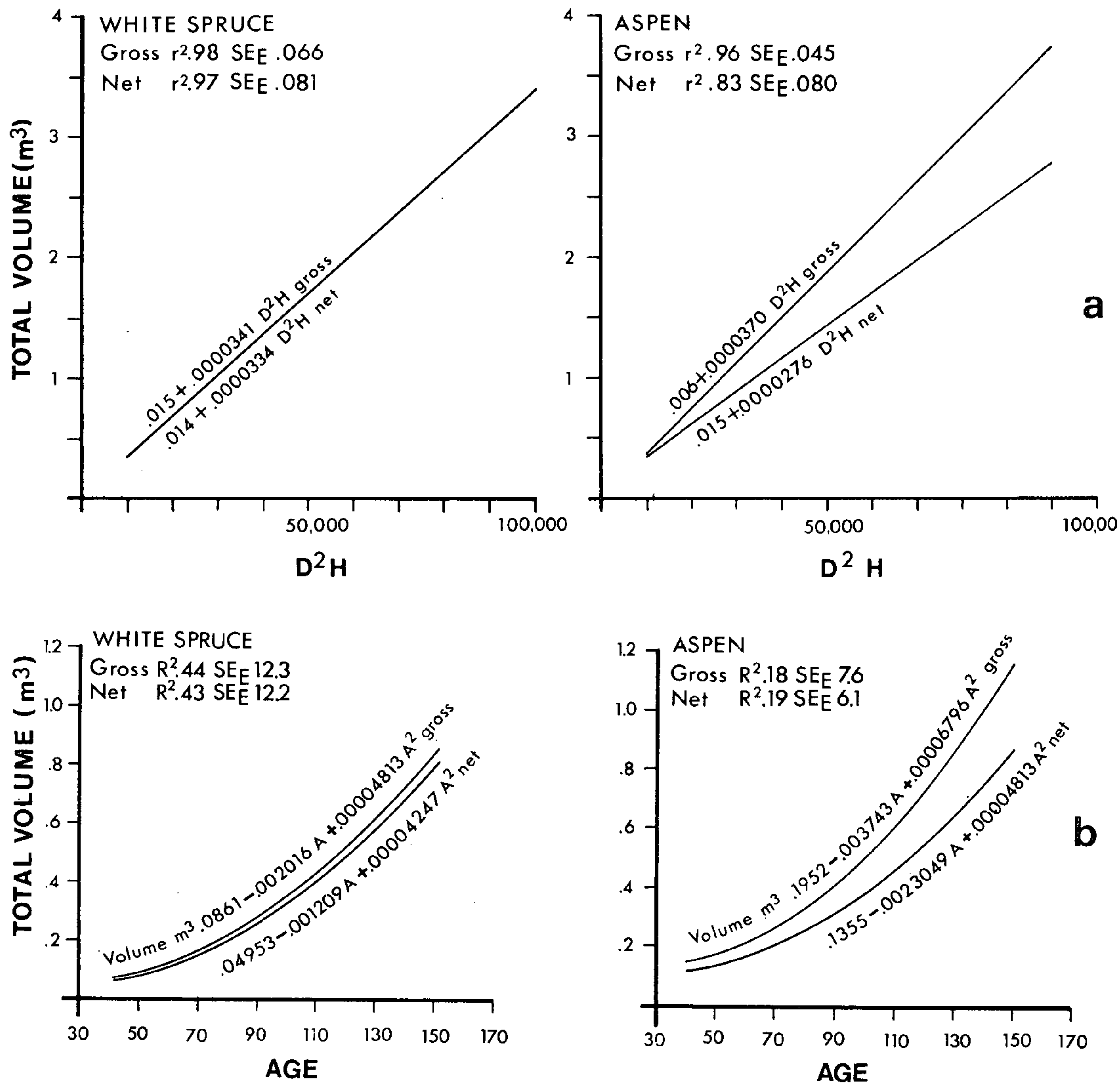

Figure 13. Gross and net total volume (m^3) related to D^2H (a) and age (b).