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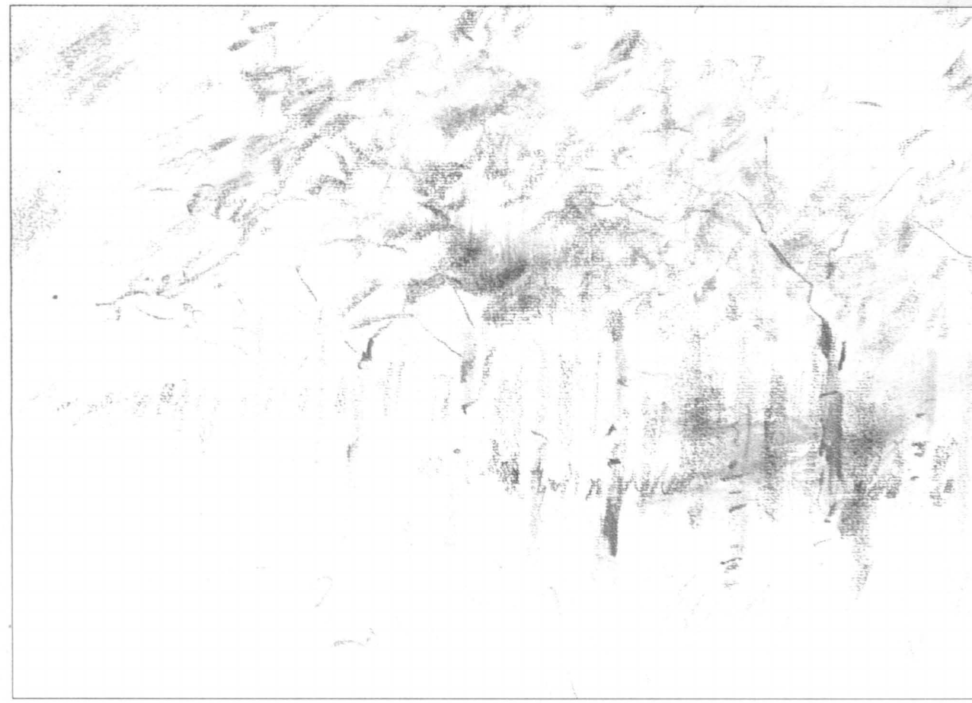

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Estimation of Cutting Volume with Three Inventory Methods for Harvest Planning in Canadian Boreal Forests

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Johanne M.G. Morasse

Estimation of Cutting Volume with Three Inventory Methods for Harvest Planning in Canadian Boreal Forests

The Finnish Society of Forest Science — The Finnish Forest Research Institute

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Two methods of pre-harvest inventory were designed and tested on three cutting sites containing a total of 197 500 m^3 of wood. These sites were located on flat-ground boreal forests located in northwestern Quebec. Both methods studied involved scaling of trees harvested to clear the road path one year (or more) prior to harvest of adjacent cut-blocks.

The first method (*ROAD*) considers the total road right-of-way volume divided by the total road area cleared. The resulting volume per hectare is then multiplied by the total cut-block area scheduled for harvest during the following year to obtain the total estimated cutting volume. The second method (*STRATIFIED*) also involves scaling of trees cleared from the road. However, in *STRATIFIED*, log scaling data are stratified by forest stand location. A volume per hectare is calculated for each stretch of road that crosses a single forest stand. This volume per hectare is then multiplied by the remaining area of the same forest stand scheduled for harvest one year later. The sum of all resulting estimated volumes per stand gives the total estimated cutting-volume for all cut-blocks adjacent to the studied road. A third method (*MNR*) was also used to estimate cut-volumes of the sites studied. This method represents the actual existing technique for estimating cutting volume in the province of Quebec. It involves summing the cut volume for all forest stands. The cut volume is estimated by multiplying the area of each stand by its estimated volume per hectare obtained from standard stock tables provided by the governement.

The resulting total estimated volume per cut-block for all three methods was then compared with the actual measured cut-block volume (*MEASURED*). This analysis revealed a significant difference between *MEASURED* and *MNR* methods with the *MNR* volume estimate being 30% higher than *MEASURED*. However, no significant difference from *MEASURED* was observed for volume estimates for the *ROAD* and *STRATIFIED* methods which respectively had estimated cutting volumes 19 % and 5 % lower than *MEASURED*. Thus the *ROAD* and *STRATIFIED* methods are good ways to estimate cut-block volumes after road right-of-way harvest for conditions similar to those examined in this study.

Keywords harvesting inventory, methods, GPS, Canada.
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Contents

Preface

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Helsinki, March 1998

Johanne M.G. Morasse

1 Introduction

Quebec inventoried forest land is nearly 122.8 millions of hectares, which represents 82 % of the total land in this Canadian province. However, only 73.4 millions of hectares of this forest is described as productive and accessible (Massicotte and Carpentier 1993). This represents 20 % of the Canadian productive forest area and around 2 % of the world's productive forests. The provincial government owns and manages 92 % of the forest land (St-Laurent 1990). The remaining 8 % is shared among 120 000 private wood lot owners, mainly concentrated along the shores of the St-Laurence River (Rapport sur l'état ... 1991) as shown in Fig. 1.

Since 1987, a forest policy based on multiple-use sustained yield management has been enforced on Quebec public forests (Manuel d'aménagement forestier 1989). Those public forests are divided into ten administrative regions, which are subdivided into 42 management units. Close to two hundred forest areas called Common Forest Area (CFA) subdivide the management units allocated to processing mills under a Forest Management and Supply Licence (FMSL). Forest inventory of Quebec land is conducted by the provincial government authorities with approximately one hundred thousand (100 000) permanent and temporary plots established every decade (Normes de stratification ... 1993). These sample plots are compiled to produce stock tables which provide wood volume estimate for each forest stand, and these tables are applicable to each specific territo-

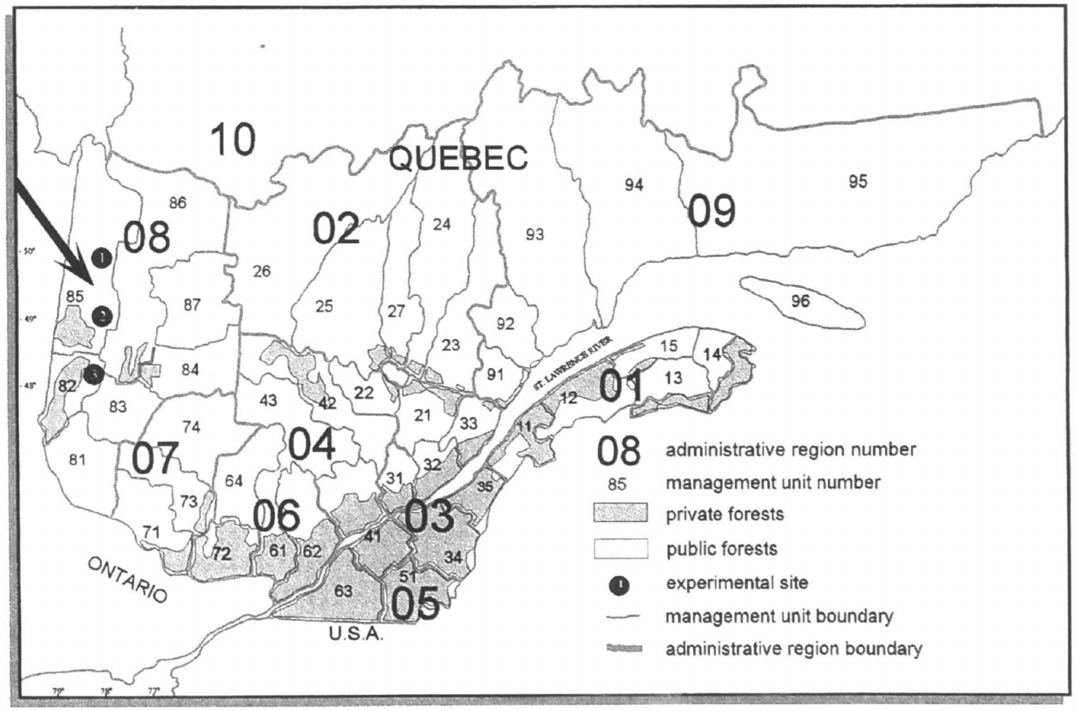

Fig. 1. Experimental site location on a province of Quebec forest administrative regions and management units map with private and public ownership.

ry (or sampling unit) where the inventory was conducted.

Until now, forest inventory methods were designed to obtain general information for long-term management purposes applicable on vast territories such as determining the annual sustainable yield of a management unit or a CFA. For these reasons, the stock tables produced by the Quebec Ministry of Natural Resources (MNR) are referred to as *forest management stock tables* since they are designed for long term management of large territories. Small scale application of these tables (such as single stand volume estimate) often leads to significant deviation from reality (Jamnick and Walters 1993). With the present trend for lower wood storage and "just-in-time" delivery to the mill, greater reliability of cut-block volume estimates is needed. Undertaking more intensive sampling within forest areas included in short-term harvesting plans would certainly provide greater accuracy of volume estimates. The costly nature of these local intensive inventories are now motivating forest companies to investigate new of forest inventory methods that might provide accurate volume estimates within reasonable costs.

One of the most important elements for planning harvest operations is the merchantable wood volume within each cut-block. The scheduling of forest workers and their equipment are directly related to the amount of wood produced over time in a cut-block. Thus, reliable wood volume estimation per cut-block is essential for planning forest logging with respect to the needs of wood processing mills holding wood supply contracts (FMSL) with the government. Overestimation of these volumes will likely be translated into a premature stop of logging operations, which could lead to a shortage of wood at the mill. Conversely, underestimation of the cut-block volume could generate a wood surplus at the mill and make it difficult to plan efficient field operations.

Presently, the most common source of information used for short-term harvest planning is the *MNR* management stock tables. The problem is that the sampling intensity used to compile these tables at an acceptable volume precision level of 95 % is designed for application over entire sampling units (Normes de stratification ... 1993). Using these stock tables over much smaller areas than those for which they were designed , such as the cut-block, violates the statistical range of application. Greater precision for cut-block volume estimation would require additional forest inventory data concentrated in the area planned to be harvested. Husch et al. (1982) use the terminology *complete inventory* for measurements taken over the entire forest, and *sample inventory* when measurements are taken for a sample of the forest. In this manuscript, these two terms will be replaced by *forest management inventory* and *forest harvesting inventory* since they better translate the purpose of each cruising.

In countries such as Finland, where forest land tenure is mostly private with a well developed logging road network, it is often economical for wood lot owners to undertake harvesting inventories with intensive ground measurements within each identifiable homogeneous forest stratum (Päivinen 1994) to obtain greater reliability of timber production information. This harvesting inventory method would be difficult to apply within countries where forest land tenure is mostly public with little or no permanent road access to harvest areas. For this reason, in countries such as Russia, where public forests are spread over very large territories, low forest labor wages, and forest mensuration tools not easily available, the harvesting inventory is usually performed with as little instrumentation as a pen and a note book. It usually consists of a visual estimation of average stem diameter, stand average height and the average number of stems per hectare. These data are then associated with stock tables having similar forest stand descriptions (Valjaev 1993). This high labor-intensive harvesting inventory method would become extremely costly for countries such as Canada, which have vast public forests, where harvest sites are usually not easily accessible, and where high forest worker wages are supported. In most cases, there are no permanent roads giving access to areas planned for harvest. Thus, inventory crews would either need to access the site through long ground distances without motorised vehicles or via air transportation, which is very expensive. Generally, trees located on the planned road right-of-way for an area are cut no longer than one year prior to logging operations of adjacent cut-blocks. The right-of-way becomes accessible by road vehicle only after roads are covered with a filling material placement, such as gravel, which generally occurs shortly before logging. This accessibility constraint has so far forced most forest industries to use available management stock tables for short term harvest planning, even if the precision of such local volume estimation is insufficient to provide data for accurate harvest scheduling (Beaulieu and Lowell 1994). Furthermore, a study (Coulombe and Lowell 1995) conducted within Quebec boreal forests had demonstrated that a higher sampling intensity (one plot per 17 ha) versus (one plot per 500 ha, Ung 1991) commonly used by the *MNR* had provided modest gains in precision compared to the high cost involved.

Recently, two low cost harvesting inventories were proposed for Quebec forests by Beaulieu (1994) and Coulombe (1996). The first of these two authors used spatial autocorrelation to establish a grouping of forest strata while the second author used relationships between ecophysiographic factors and ground measurements. Unfortunately, both of these GIS-assisted inventory methods failed to provide satisfactory results. Other low cost harvesting inventory methods are sometimes used to verify if cut-block volume estimation based on management stock tables corresponds to standing tree volumes. Measurements of trees cut along the road right-of-way is sometimes used to obtain volume estimates of adjacent cut-blocks scheduled to be cut later. This rule-of-thumb was mainly used in the past, where road right-of-ways were logged a few seasons prior to harvest operations of adjacent cut-blocks. This method effectively uses the road as a long, continuous sample plot. The use of such a road-plot is most useful where roads cross forests that are relatively homogeneous, with little volume variation from one forest stand to another. If it were possible to stratify these road-plots where stand limits cross the road, it would be possible to obtain an approximate estimation of wood volume within each forest stand in the cut-block. Thus, instead of using a single forest type road volume estimation over all adjacent cut-blocks, it would be possible to estimate the volume of each forest stand in a cut-block crossed by the road, simply by using the measured volume per hectare within each segment of road for all different forest stands.

In theory, this stratified road-sampling method has the potential to provide a more precise way of estimating cut-block volume than non-stratified road-sampling, especially if stand boundaries are located and mapped with geomatic tools such as GPS (global positionning system) and GIS (geographic information system). This estimation could be compared with cut-block volume estimates from management stock tables. What remains is to design and evaluate a stand-stratified road sampling method that could be integrated into normal forest harvesting operations in a practical fashion. The development and presentation of such a method is the subjet of this research.

2 Background

The main difficulty in applying management survey stock tables to small local areas can be explained in part by the nature of the forest surveying method used to compile these tables. The forest inventory plan of this stratified random sampling method with conditional distribution of samples (Richard 1971) comprises four main steps in Quebec. First, aerial photographs of the inventoried land are taken at a scale of 1:15 000 (sometimes 1:10 000). These aerial photographs are used for photointerpretation of different forest types. Photointerpreters delineate forest type polygons and rectify them on to a 1:20 000 base map which also includes hydrography, topography, roads, transportation lines and administrative boundaries. Secondly, forest sampling is performed with tree measurements collected within sample plots conditionally distributed accross the inventoried land. Thirdly, forest inventory data are then used for mapping sample plots on forest maps. Finally, sample plot data compilation is undertaken to produce stock tables for the various cover types within sampling units. Each of these four steps will be discussed in more detail in the following sections.

2.1 Forest Type Photointerpretation

Each management unit in Quebec is divided into forest sampling units of sizes ranging from 1000 km^2 to 3000 km^2. These sampling units are delineated by photointerpreters into polygons, not smaller than 4 hectares, with five main groups of forest stand characteristics. The first two characteristics indicate the dominant and co-dominant tree species. The main commercial tree species encountered within the studied site (see Section 4.1) have the following map symbols:

Pg (*P*in *g*ris) for jack pine (*Pinus banksiana* Lamb.);
En or (*E*pinette *n*oire) for black spruce (*Picea mariana* (Mill.) B.S.P.);
Sb or (*S*apin *b*aumier) for balsam fir (*Abies balsamea* (L.) Mill.);
Pt (*P*euplier faux-*t*remble) for trembling aspen (*Populus tremuloides* Michx.); and
Bb (*B*ouleau *b*lanc) for white birch (*Betula paperifera* Marsh),

The dominant and co-dominant trees occupy respectively, more than 50 %, and at least 25 % of the forest stand cover. The third and fourth characteristics represent the crown cover of the forest stand expressed in terms of percentage of the area occupied by the forest cover and the average tree height of dominant and co-dominant tree species. Forest stand crown cover and height classes are shown in Table 1. The last group represents the age class of the forest stand. *MNR-QUEBEC* classification for even-aged forests is given in Table 2.

For example, the cartographic stratum of *Pg En B2 70* represents a forest stand with more than 50 % jack pine (*Pg*) and at least 25 % black spruce (*En*) with a crown cover between 60 % and 80 % (*B*) and an average dominant tree height between 17 m and 22 m (*2*) with an age between 61 and 80 years old (*70*). Each sampling unit may have up to 2000 different forest stand appellations (or stand types). Ecological stand characteristics have recently been added to the standard forest stand appellation to answer the needs for forest information other than wood volume for harvest purposes. These ecological caracteristics have not been included in this study since they were not available for the experimental site at the time data collection was performed and their presence would not alter in any large manner the work conducted nor the results of that work.

Table 1. *MNR-QUEBEC* classification for forest crown cover and average tree height.

Cover	Height >22.0 m 1	17.0 to 21.9 m 2	12.0 to 16.9 m 3	7.0 to 11.9 m 4	4.0 to 6.9 m 5	< 4.0 m 6
A >80 %	A1	A2	A3	A4	A5	6
B 60 to 79 %	B1	B2	B3	B4	B5	6
C 25 to 59 %	C1	C2	C3	C4	C5	6
D < 25 %	D1	D2	D3	D4	D5	6

Table 2. *MNR-QUEBEC* age classification for even-aged forests.

Age class (yrs)	Age limits (yrs)
10	0 to 20
30	21 to 40
50	41 to 60
70	61 to 80
90	81 to 100
120	101 and more

2.2 Forest Sampling

In general, each sampling unit in Quebec will have approximately 300 to 600 circular sample plots of one twenty-fifth of an hectare located on it, depending on the size of the inventoried land and the homogeneity of the forest. Field data collected within sample plots include DBH (Diameter at Breast Height) measurements and species identification of each tree, height and age measurement of three trees, and site quality observations. Field crews must establish their sample plots along a linear transect using a predetermined azimuth. The sampling method has a conditional distribution since inventory transects do not start from a random point. Each must begin from an easily identified location on an aerial photograph. Usually, a team of two people can establish from six to seven sample plots during a working day. Forest data are collected with electronic notebooks (data loggers) and transfered to a main computer at the end of the day or at the end of the week.

2.3 Mapping Sample Plots

Standard forest maps in Quebec are produced at a scale of 1:20 000 with numbers of each forest stand and the names of cartographic strata marked along with the location of each sample plot and its number. A line going through the sample plots is also drawn on the forest map to indicate the azimuth of the transect used by the inventory crew.

Until now, the sample plots were located in the forest with metric ribbon (or hip-chain) and compass. Since most plots are located far from official geographical bench marks, inventory crews start their transects from an identifiable point on an aerial photograph such as a road intersection or the junction between a lake and a river. This approximate transect location method may generate a significant deviation from true coordinates when plots are positioned on the forest map due to the use of a hip-chain for distances and a hand-compass for direction.

For example, sample plot measurements may have occurred within a spruce stand and be erroneously positioned on the forest map in a nearby pine cartographic stratum. This faultily positioned spruce plot will be named and classified as if it came from a pine stand and its measurement will be used with other similar grouped pine stands to compile stock tables for this specific grouped stratum. Although sample plots should be located at a minimum of 50 meters distance from a stand limit based on *MNR* standards, this type of error most likely occurs where sample plots are located close to forest stand boundaries and/or when one is farthest from the starting point of a transect. The fuzzy nature of these photo-interpreted cartographic forest stratum boundaries (Edwards and Lowell 1996) suggests that either one avoid sampling near stand boundaries or that one use more precise surveying instruments to locate sample plots. Each sample plot stand type recorded in the forest can also be compared against the photo-interpreted description of the forest stand into which it is located on the forest map. Hence, verifications should be undertaken for sample plot stand types that deviate significantly from forest stand photo-interpreted descriptions.

Greater accuracy in sample plot location may now also be obtained with the use of the global positioning system (Domingue 1994). Sample plot

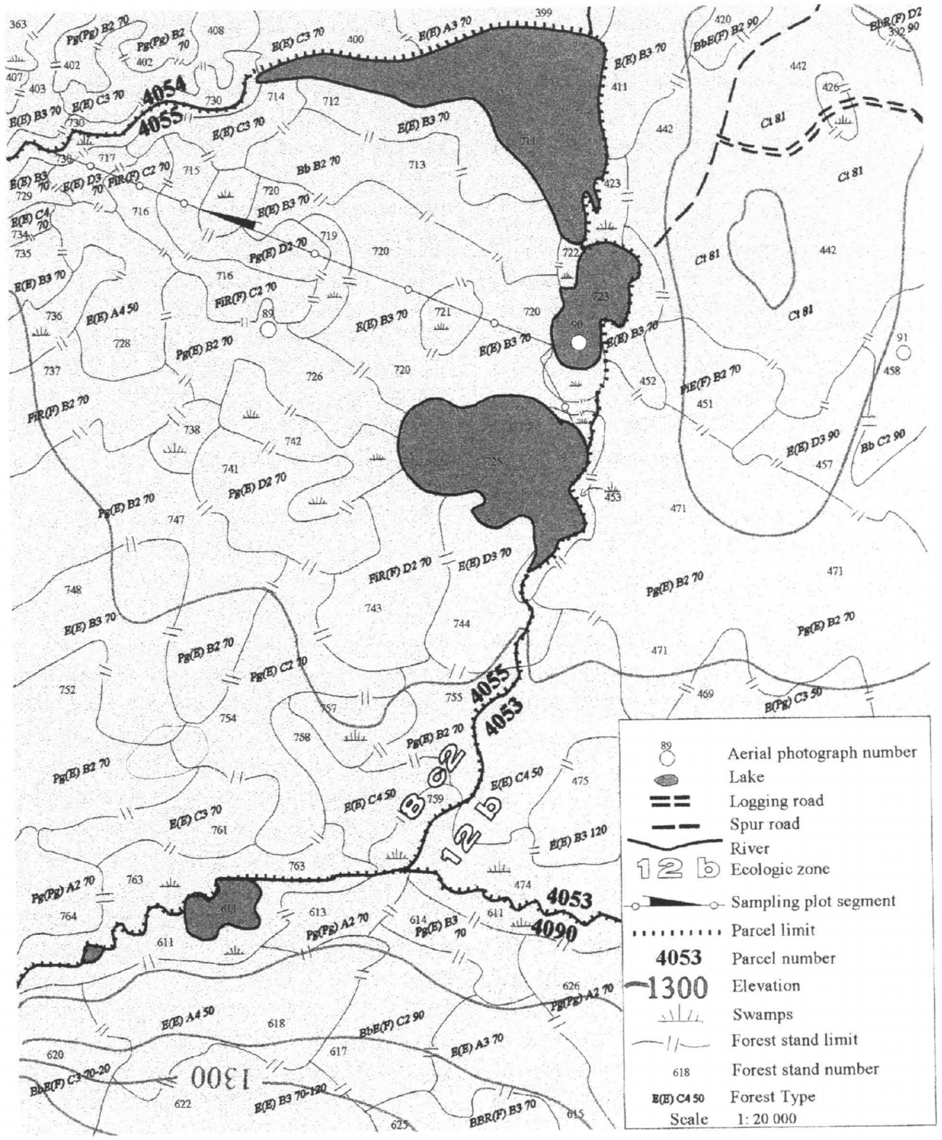

Fig. 2. Typical Quebec forest map.

coordinates can be recorded in the forest and transfered directly from GPS memory storage to a geographical information system for quick and accurate plot location on forest maps, thus providing a direct link to their forest inventory data. This supposes, however, that forest maps are geographically-reference adequately – something that is not usually the case.

Fig. 2 gives an example of a typical Quebec forest map, including forest stand boundaries (or cartographic strata), forest stand numbers, topographic lines, hydrographic lines, cruising transects with their sample plots, aerial photograph centers and administrative boundaries such as management unit boundaries and parcel limits. A parcel is defined here as being a territorial subdivision of a CFA. Parcel boundaries are established in public forests according to visible ground limits such as water streams or roads. On an average, parcels range in size from 1000 ha to 2000 ha. Before the advent of geographical information systems, parcel boundaries were helpful for approximate location of forest entities such as logging sites. For example, forest fire fighters could identify in which parcel a fire was located and, with the help of the *MNR* data bank, logging companies with equipment in the vicinity of the burning area could quickly forward it to the fire area. This equipment could then be assigned to fire suppression operations. However, with the increasing use of GIS in forestry, forest entities can now be located with greater precision without the use of parcel boundaries. For this reason, parcel boundaries are likely to disappear from the Quebec forest data bases in the near future.

Table 3. Typical example of a *MNR-QUEBEC* first report to compile forest stock tables.

T	D	Species	D/H	Age	NP	DBH cm	Vol m^3/ha	RES	DEC	Vol-species (%) *En*	*Eb*	*Sb*	*Pg*	*Me*	*Bb*	*Pt*
M		BBER	C3	0700	1	11.7	31.07	100		100						
M	EL	BBER	C3	0700	1	20.6	53.59		100						100	
M	EL	BBRR	C3	0700	1	14.1	65.48	55	45	43		12			45	
M	EL	BBRR	D2	0700	1	31.1	164.46	44	56	7	27		10		56	
M	EL	BBRR	D2	0900	2	17.1	100.78	74	26	74					26	
M		BBSR	C3	0700	1	27.3	53.75	1	99			1			99	
M	EL	BBSR	C3	0700	4	18.6	102.82	67	33	30	29	8			33	
M		BBSR	D3	0700	1	11.9	21.54	100		95				5		
M		FIRR	C3	0700	1	18.9	240.84	3	97	3						97

Where T is the forest Type (M=mixted, R=coniferous, D=deciduous);
D is the Disturbance type if any (EL=light epidemic);
Species dominant and codominant (BB=white birch, E=black or white spruce , S=balsam fir and FI=intolerant deciduous);
D/H are the crown cover and average height (see Table 1);
Age is the age classe (0700=70yrs and 0900=90yrs);
NP is the number of sample plots per stand type;
DBH is the average tree diameter at breast height;
Vol is the total volume per hectare in cubic meters; and
Vol-species is the percentage of volume per species (RES=coniferous, DEC=deciduous,
En=Black spruce, *Eb*=White spruce, *Sb*=Balsam fir, *Pg*=Jack pine, *Me*=Eastern larch, *Bb*=White birch, *Pt*=Trembling aspen.

2.4 Stocking Table Computation

Once ground sampling is completed within a given sampling unit, a first report is produced by the MNR-inventory service, including mainly cumulative statistics for each sampled cartographic statum. A typical example of such a first report volume content is given in Table 3 with nine different stand types within which one or more sample plots were collected.

These statistics are then analysed in order to produce a second report which includes the grouping of plots sampled within the same stand type and the grouping of stand types having less than five sample plots per cartographic strata. It also includes the total area occupied by each stand type in which at least one sample plot was established. These stand type groupings are made according to similarities of stand types determined from sample plots. Thus, data collected from sample plots having the same or similar photointerpreted forest types are compiled together.

In this particular example, the above-listed nine stand types were considered , among hundreds of other sampled stand types, to be similar and their thirteen sample plots were used to compile a grouped strata called M EL BBRR C3 0700. In the second report, this grouped strata would be listed as shown in Table 4.

In order to produce a third report, the average wood volume per species per diameter class per hectare (i.e., a stock table) is computed from these sample plot data and assigned to all cartographic strata having the same forest type within a given sampling unit. A typical third report with the above mentioned grouped strata M EL BBRR C3 0700 contains the information listed in Table 5.

A fourth report is then produced to give general statistics of all grouped strata computations for a

Table 4. Typical example of a *MNR-QUEBEC* second report to compile forest stock tables.

Grouped strata T	D	Species	D/H	Age	Original strata T	D	Species	D/H	Age	NP	Area (ha)
M	EL	BBRR	C3	0700	M		BBER	C3	0700	1	116
					M	EL	BBER	C3	0700	1	122
					M	EL	BBRR	C3	0700	1	126
					M	EL	BBRR	D2	0700	1	19
					M	EL	BBRR	D2	0900	2	51
					M		BBSR	C3	0700	1	141
					M	EL	BBSR	C3	0700	4	244
					M		BBSR	D3	0700	1	25
					M		FIRR	C3	0700	1	28
					Total					13	872

Where Area is the total area occupied by each inventoried stand type (in hectare). (Symbols – see Tables 1 and 3)

Table 5. Typical example of a *MNR-QUEBEC* third report to compile forest stock tables.

DBH (cm)	Gross merchantable volume per species (m^3/ha) *Sb*	*En*	*Eb*	*Pg*	*Me*	*Bb*	*Pt*	Res	Dec	All
10	0.45	1.56	0.01			0.28	0.11	2.02	0.39	2.41
12	0.69	3.74	0.07		0.03	0.81	0.07	4.53	0.88	5.41
14	1.12	2.80				0.91	0.32	3.92	1.23	5.15
16	0.97	4.42				1.12	0.40	5.39	1.52	6.91
18	0.27	2.71	0.27			2.32	0.72	3.25	3.04	6.29
20		1.57				0.48	0.79	1.57	1.27	2.84
22		1.53				2.14	1.57	1.53	3.71	5.24
24		0.23	1.19			1.64	1.67	1.42	3.31	4.73
26		1.59	0.95			7.85	1.25	2.54	9.10	11.64
28		1.51	0.87			5.94		2.38	5.94	8.32
30			1.03			4.27	0.61	1.03	4.88	5.91
32			1.19					1.19		1.19
34			1.36	0.37		3.80		1.73	3.80	5.53
36			1.53			1.04		1.53	1.04	2.57
42		0.68						0.68		0.68
46			0.75					0.75		0.75
48						0.87			0.87	0.87
Total	3.50	22.34	9.22	0.37	0.03	33.47	7.51	35.46	40.98	76.44
%	4.6	29.2	12.1	0.5		43.7	9.9	46.4	53.6	100.0

Where DBH is the diameter at breast height in centimeters
Sb = Balsam fir, *En* = Black spruce, *Eb* = White spruce, *Pg* = Jack pine, *Me* = Eastern Larch, *Bb* = White birch, *Pt* = Trembling aspen, Res = coniferous, Dec = deciduous and All = Res + Dec.

given sampling unit. In this report, the grouped strata M EL BBRR C3 0700 has the figures shown in Table 6.

It should be noted here that the total average volume (R = 79.08) compiled from the above listed thirteen sample plots (N.P. = 13) is slightly different from the total average volume listed in the third report (TOTAL ALL = 76.44). The 2.66 cubic meters of difference is attributable to the added defoliated volume which does not appear in the previous report.

However, the actual number of different forest types per sampling unit (around 2000 different forest types per sampling unit) is always higher

Table 6. Typical example of a *MNR-QUEBEC* fourth report to compile forest stock tables.

NP	Average volume(R)	Variance S^2	S. dev. S	Mean error $S/N^{0.5}$	Coef. var. S/R	Precision %
13	79.08	1831.84	42.80	42.80	54.12	67.2

than the economic possibility of establishing sample plots in each of the different basic forest stand types (around 300 to 600 sample plots per sampling unit ranging from 100 000 ha to 300 000 ha). Thus, some forest types occupying a relatively small portion of the sample unit may have few or no sample plots. Conversely, forest types that occupy a large proportion of the sampling unit may have several sample plots per forest type. It is thus impossible to compute stock tables for each individual forest type encountered in a sampling unit. For this reason, those basic cartographic strata which were not sampled are combined together with grouped strata having similar photo-interpreted forest types. A fifth report, given in Table 7, is then produced to give the area of each cartographic strata associated with each grouped strata compilation. Thus, the grouped strata M EL BBRR C3 0700 used in this example has its nine forest types into which at least one sample plot was collected plus 35 additionnal forest types which were photo-interpreted within the sampling unit for which no sample plots were collected.

Again, the similarity of photointerpreted forest types is the major criterion for grouping these non-inventoried forest types within a given compiled grouped strata.

These five reports are useful to illustrate the importance of human decision in the process of regrouping forest stands together. For example, it can be noted from the first report that there is only one plot out of thirteen (FIRRC30700) that has trembling aspen (97 %) listed. According to the third report, this single sample plot provides 7.51 m^3/ha to all forest strata grouped under M EL BBRR C3 0700. Since the total area covered by this grouped strata is equal to 2025 ha in the fifth report, this gives a total contribution of approximately 15 000 m^3 of trembling aspen for this grouped strata within its sample unit. Removing this sample plot from this regroupement would have provided no trembling aspen over approximately 1780 ha since some 250 ha of intolerant deciduous forest stands (FIRR) are associated with the M EL BBRR C3 0700 grouped strata because of this single sample plot (FIRR C3 0700).

It is sometimes difficult to find an appropriate match of forest sample plot stand caracteristics for all types, especially for those plots with few replicates. For example, only one sample plot among the sampling unit may have a relatively high percentage of eastern larch (*Larix laricina* K. Koch.). This sample plot will obviously be significantly different from all other sample plots but it will be grouped with other plots having similar photo-interpreted forest types since one sample plot is not enough to compile a dominant larch forest type stock table. Thus, stock tables produced from such mismatched sample plots will assign a high larch volume to all cartographic strata that are included in the grouped strata. Instead of regrouping such mismatched plots, it would be preferable to compile a larch stock table with additional data gathered afterward in the same sample unit or with other larch sample plots from other surrounding sample units.

A forest inventory plan in Quebec is designed in such a way that statistical, geographical and economical constraints are respected (Perron 1985) with a uniform distribution of sample plots across the sampled units. Each grouped stratum may have on an average from 10 to 30 cartographic strata and, despite these groupings, the strata clustering has been proven to be statistically acceptable for a 95 % precision with 95 % confidence as long as it is applied on the grouped strata of the entire territory (Villeneuve 1971). Great deviation from estimated forest stand volumes has, however, been experienced for local uses of these management stock tables – the regrouping of strata being one of the most probable sources of error. For example, if the population sampled to calculate the average volume per hectare of a given grouped stratum was bimodal, the resulting average is likely to be cor-

Table 7. Typical example of a fifth report to compile forest stock tables (symbols – see Tables 1 and 3).

Grouped strata T	D	Species	D/H	Age	Original strata T	D	Species	D/H	Age	NP	Area (ha)
M	EL	BBRR	C3	0700	M		BBER	C3	0700	1	116
					M		BBER	C4	0700	0	11
					M		BBER	D3	0700	0	45
					M		BBER	D3	0900	0	10
					M		BBRR	B4	0900	0	8
					M		BBRR	C3	0700	0	57
					M		BBRR	C3	0900	0	13
					M		BBRR	C4	0700	0	6
					M		BBRR	D3	0700	0	48
					M		BBRR	D3	0900	0	5
					M		BBSR	C3	0700	1	141
					M		BBSR	C3	0900	0	11
					M		BBSR	D2	0700	0	12
					M		BBSR	D3	0700	1	25
					M		FIER	C3	0905	0	4
					M		FIRR	C3	0700	0	28
					M		FIRR	C4	0800	0	11
					M		FISR	D3	0700	0	13
					M	CP	BBER	C3	0700	0	3
					M	CP	BBER	C3	0700	0	30
					M	CP	BBER	D3	0700	0	26
					M	CP	BBSR	C3	0700	0	4
					M	EL	BBER	C3	0700	1	122
					M	EL	BBER	C3	0900	0	110
					M	EL	BBER	D3	0700	0	114
					M	EL	BBER	D3	0900	0	81
					M	EL	BBER	D3	0903	0	16
					M	EL	BBRR	C3	0700	1	126
					M	EL	BBRR	D2	0700	1	19
					M	EL	BBRR	D2	0900	2	51
					M	EL	BBRR	D2	1200	0	13
					M	EL	BBRR	D3	0700	0	128
					M	EL	BBRR	D3	0900	0	8
					M	EL	BBSR	C3	0700	4	244
					M	EL	BBSR	C3	0900	0	40
					M	EL	BBSR	D2	0700	0	53
					M	EL	BBSR	D3	0700	0	56
					M	EL	BBSR	D3	0900	0	1
					M	EL	BBSR	D4	0700	0	18
					M	EL	FIRR	C3	0700	0	54
					M	EL	FIRR	D2	0700	0	21
					M	EL	FIRR	D2	0900	0	50
					M	EL	FIRR	D3	0700	0	41
					M	EL	FISR	D3	0700	0	32
					Total					13	2025

rect if applied over the entire zone. However, if it is applied locally to either sector *A* or *B*, as shown on Fig. 3, the local average volume will be significantly different from the population average. (On this figure, the abscissa unit is the wood volume per hectare per sampled plots and the ordinate unit is the number of sampled plots per wood volume per hectare class.)

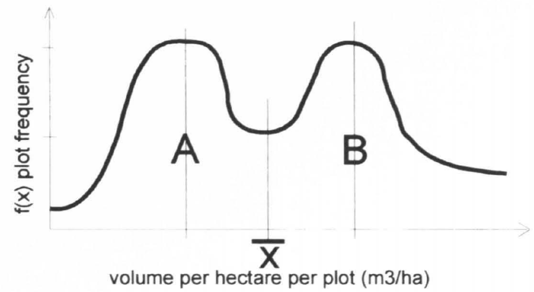

Fig. 3. Bimodal forest sampled population A and B.

Although field plot measurements sometimes differ from their photo-interpreted forest stand designations, the sample plots will be classified according to their photo-interpreted characteristics. Further, the sample plots will be grouped by similarities of photo-interpreted stand classification, rather than by forest stand description from the field measurement, to compile stock tables – the rationale being that each cartographic stratum should not be smaller than four hectares. Thus cartographic strata smaller than four hectares are englobed with adjacent strata. Consequently, if some "erratic" sample plots are located randomly within these englobed small cartographic strata, the field forest type designations are likely to differ from photo-interpreted stand descriptions which were based on larger englobing strata. The use of such erratic sample plot measurements in stock table compilation of forest stratum may have drastic consequences, especially when only a few sample plots are present for a given groupement. For example, if the stock table of a given type of balsam fir forest is compiled with the measurements from 10 plots only, the presence of an erratic plot sampled within a white birch forest type would falsely increase the percentage of white birch within this specific fir type stock table. This is not a problem, however, for adequately sampled groupings as errors will compensate.

All of the above described sources of errors (erratic sample plots, wrong sample plot map positioning, sample plots included within mismatching grouped strata, etc.) appear to have little effect on the precision of the volume estimation from management survey stock tables if applied over the entire area of the sampling unit. The problem is the fact that these management stock tables are extensively used to estimate wood volume over much smaller areas than the whole sampling unit, particularly when a harvest is to be undertaken. Thus, for cut-block volume estimation, it would be advisable to undertake some kind of forest sampling concentrated within the area scheduled to be harvested in order to reduce wood supply problems related to volume estimation accuracy. Such complementary forest harvesting inventory must however be proven effective while respecting economical constraints.

3 Objective of the Study

A common practice in Canadian forestry is to construct roads at least one year before adjacent cut-blocks are harvested. This implies that, in many cases, trees along the road right-of-way are cut and measured at least one year prior to harvesting of adjacent harvest cut-blocks. The hypothesis of this research is that road right-of-way log measurement data can be used to estimate the volume of adjacent cut-blocks with greater accuracy than conventional forest management inventories, with a minimum added cost. This is based on the assumptions that roads are built sufficiently in advance for data to be useful for operational planning and that by the time of road construction, the largest management decisions are still to be taken. Therefore, the primary objective of this study is: to design a road right-of-way log sampling method for volume estimation of adjacent forest cut-blocks, and evaluate its precision relative to existing accepted methods. The two following sampling procedures will be investigated:

a) Using the entire road right-of-way harvested volume as one large continuous sampling plot and applying the measured volume per hectare and tree species ratio to all projected cut-blocks adjacent to the road; and
b) using each section of the road crossing a forest stand as a sampling plot for that stand, and applying the measured volume per hectare and tree species ratio to the individual sampled forest stands.

Examination of these two methods is of particular importance for viable implementation of forest harvesting inventory methods designed for accurate prediction of cut-block volume at minimal costs, such that these two proposed cut-block volume estimation methods are performed within realistic harvest operation conditions in a Canadian natural boreal forest.

4 Experimental Design

4.1 Experimental Site Location

Three logging sites scheduled for harvest in 1992 were selected among CFAs held by *Nordbord Industries* (funding partner company for this study), to experiment with the proposed road tree-sampling methods. These three sites were specifically chosen because they corresponded to the most important experimental specification, namely: cutting blocks scheduled for harvest in 1992 for which logging of access road right-of-way was scheduled and completed in 1991. Cutting blocks scheduled for harvest in 1992 for which access roads were already logged or only scheduled to be cut in 1992 were withdrawn from possible choices for experimental sites. Less than 10 % of the whole harvest were not included in this study because they failed to meet these two conditions.

As shown in Fig. 1, the three experimental sites were selected in administrative region number 08 (Abitibi-Témiscamingue) located in the northwestern part of the province of Quebec, in eastern Canada. This administrative region spans over 50 million hectares of public natural boreal forest and is mainly composed of black spruce, jack pine and balsam fir, along with secondary tree species such as trembling aspen and white birch.

Administrative region number 08 is divided into seven forest management units which are further subdivided into 23 CFAs, which provide wood on a sustained yield basis to several large processing mills (0.2 to 0.5 million cubic meters of wood per year per mill) producing mainly lumber, pulp, paper and panel boards. The average travelling distance between harvest areas and processing mills is approximately 200 km and may be as long as 400 km (L'industrie manufacturière ... 1988).

As shown on Fig. 1, all three selected logging sites were located between the 78th and the 79th degree of longitude. Site numbers one and two are both within management unit number 85 and are respectively located near the 50th and 49th degree of latitude. Site number three is part of management unit number 82 and is located more to the south near the 48th degree of latitude.

A close view of these sites is shown on Fig. 4. On this figure, each site is represented by a large black dot and the common forest areas to which they pertain are shaded with grid lines. Also shown in this figure, sites number one and two are located within CFA number 85-01N and 85-01S, respectively. The third site is within CFA number 82-02S. Both northern sites are located within the black spruce-feather moss ecological zone (Thibault 1985), which is colored in light grey on Fig. 4 map. This ecological zone is characterized by clay soil and glacier-stream deposits such as eskers. The forest cover is dominated by black spruce and jack pine with less than 20 % of balsam fir, trembling aspen and white birch. Both logging sites are located farther than 100 km from populated areas. The southern site is located within the balsam fir-white birch ecological zone, which is colored in medium grey. The soil is generally richer than within the black spruce-feather moss ecological zone, and the vegetation is dominated by balsam fir, white birch and trembling aspen while containing less than 40 % of black spruce and jack pine. This logging site is very close to municipalities. Non-controlled harvest had clearly been practiced in this area, which may explain the rather degraded nature of this forest.

The first experimental site is close to Matis Lake and has an access road length of approximately 6 km. The second site is located nearby Wawagosic Lake with an 11 km road going through the cut-blocks. The third site, located nearby Vaudray lake, has the longest stretch of road with (12 km) to access cutting blocks.

As far as forest management inventory is concerned, management unit numbers 82 and 85 are respectively divided into three and six sampling units. The boundaries of all six sampling units of management unit 85 and those of sampling unit 2

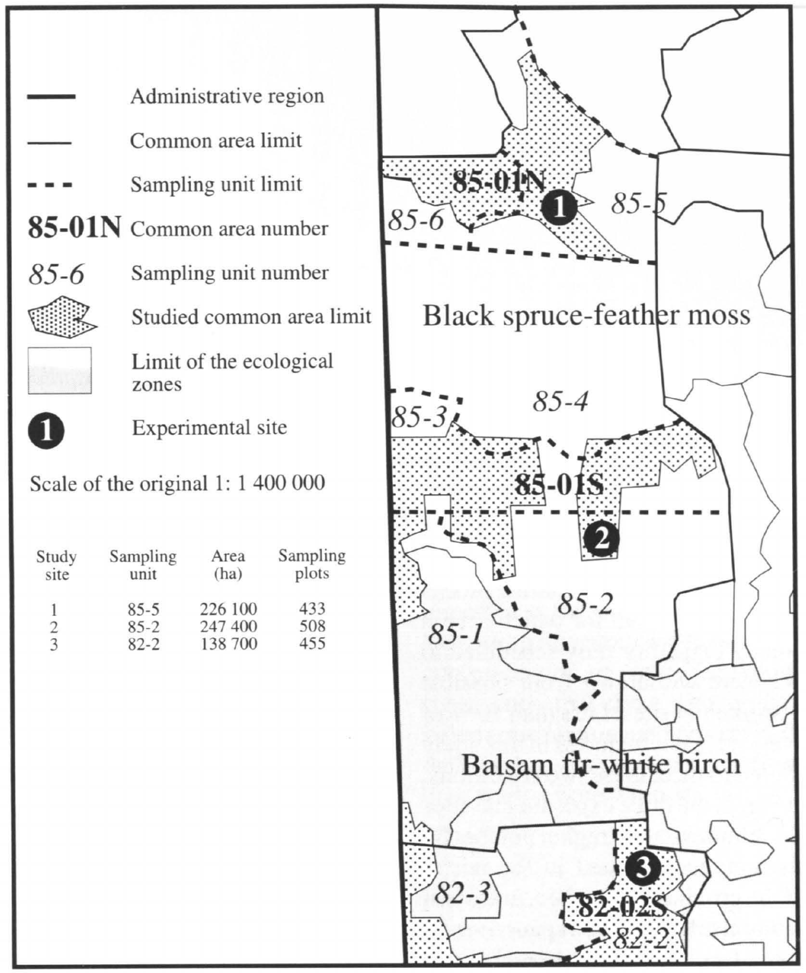

Fig. 4. Location of the three experimental sites on Thibault (1985) ecological map.

and 3 of management unit 82 are drawn with dashed lines on Fig. 4. As shown in Fig. 4, experimental site number one is located within sampling unit 5 of management unit 85 (85-5) for which 433 sampling plots of 0.04 hectare were collected to build up a forest management volume table. Site number two is part of sampling unit 2 of management unit 85 (85-2), where 508 forest sampling plots were collected. The third site is located within sampling unit 2 of management unit 82 (82-2), where 455 sampling plots had been collected. The sampling unit surface area of sites number one to three is approximately 226 100 ha, 247 400 ha and 138 700 ha, respectively.

Sampling units and common areas are two distinct entities, which mean that several sampling units may overlay a single common area. For example, common area number 85-01S, contains parts of sampling unit 85-1, 85-2 , 85-3 and 85-4. This means that four different sets of data must be used to perform calculations to estimate the annual allowable cut (AAC) for common area 85-01S. A close view of sampling unit 85-2 is given on Fig. 5. On this figure, the location of sampling transects are indicated by short thick lines. Each sampling transect contains an average of six to seven circular plots 1/25 hectare in size, where data were collected to build up forest stock tables applicable over the entire sampling unit. This fig-

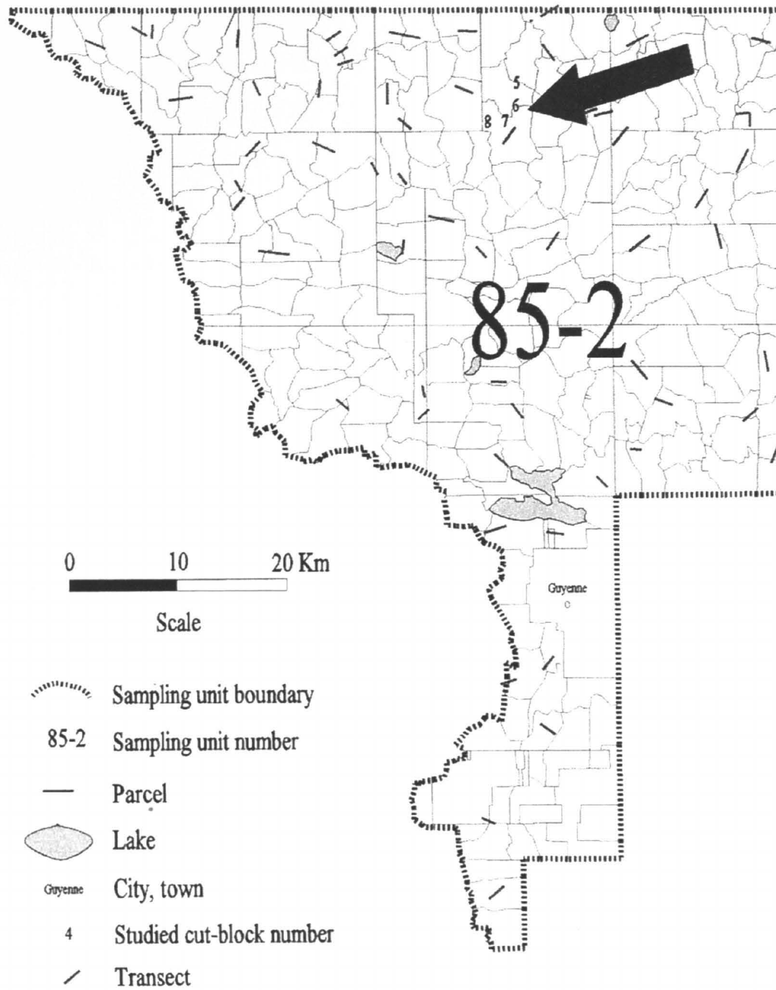

Fig. 5. Location of studied cut-blocks and sampling plot segments within sampling unit 85-2.

ure also indicates by an arrow the four cut-blocks of site number two located nearby Wawagosic Lake. The thin lines indicate the parcel limits of sampling unit 85-2. It can be noted from this figure that all parcel limits are confined within their respective sampling unit boundaries.

4.2 Experimental Methods

Three cut-block volume estimation methods were studied in parallel for all three experimental sites. These are discussed in more detail in the following section. The first method is the standard way of calculating cut-block volume using *MNR* management stock tables. The second method uses the total wood volume cut on the *ROAD* right-of-way adjacent to the cut-blocks as a volume estimate for all cut-blocks. The third method, like the second method, uses data from the wood volume cut along the road, with the difference being that the road sampling is *STRATIFIED* at each forest stand boundary crossing the road. These estimated cut-block volumes are compared against cut-block volumes *MEASURED* after cut. Throughout the rest of the manuscript, the first, second and third method will be referred to as *MNR*, *ROAD* and *STRATIFIED* (or *STRAT*), respectively. The benchmark, which is more accurate relative to actual volume, will be referred to as: *MEASURED*.

4.2.1 Volume Estimation with MNR Tables

Each of the three studied sites contain four cut-blocks for which the total measured wood volume after clear-cut harvest is known. The scaling method used to obtain this total after cut volume is explained in details in Section 4.3. The forest map of each site was digitized using *Terrasoft* GIS software and are illustrated in Figs. 6, 7 and 8. All cut-blocks harvested in 1992 are identified by a number (1 to 12). It should be noted that some non-contiguous harvested forest stands are grouped within unique entities such as cut-block 11 on Fig. 8. Since Diameter at Stump Height (DSH) scaling of piled trees was performed with respect to parcel boundaries, it was necessary to regroup harvested forest stands from the same parcels in order to obtain the total harvested wood volume for all cut-blocks within each parcel. Thus, on Figs. 6, 7 and 8, each cut-block (or group of cut-blocks) was identified with contrasting grey shadings to illustrate the cut-blocks number to which each harvested forest stand belongs. To ease the comprehension of this manuscript, the remaining text will use the term cut-block for all twelve studied cut-blocks, regardless if some of it are made up of a group near cut-blocks.

Fig. 9 shows a close view of cut-block number 2 which is located within experimental site number one near Matis Lake. On this figure, forest stand boundaries are drawn with thin black lines and each forest stand is identified by its cartographic number. This figure is meant to provide the reader with a better understanding of what a cut-block contains.

Associated with each cut-block is a set of harvest information such as that presented in Table 8. In this table, the first and second columns list, respectively, the forest stand numbers and descriptive names of all forest stands harvested within cut-block number 2. The forest stand area, in hectares, estimated using the GIS, is given under the column *AREA* of the same table. The fourth column, *MNR*-m³/ha, gives the wood volume corresponding to each listed stand type in cubic meters per hectare, as provided from *MNR* management stock tables similar to those described in Section

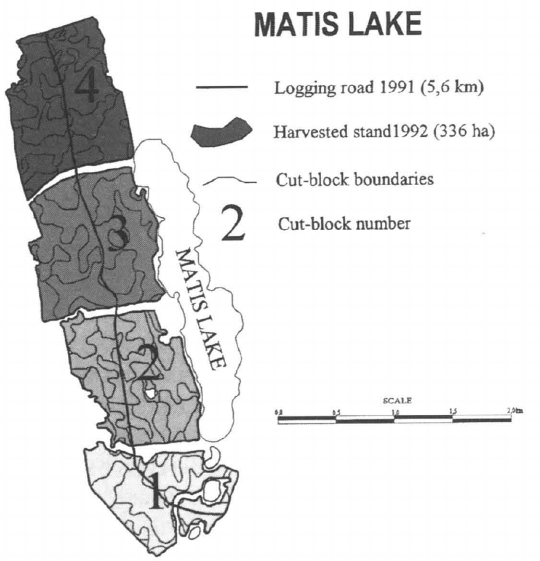

Fig. 6. Cut-block forest map of study site number 1 located near Matis Lake.

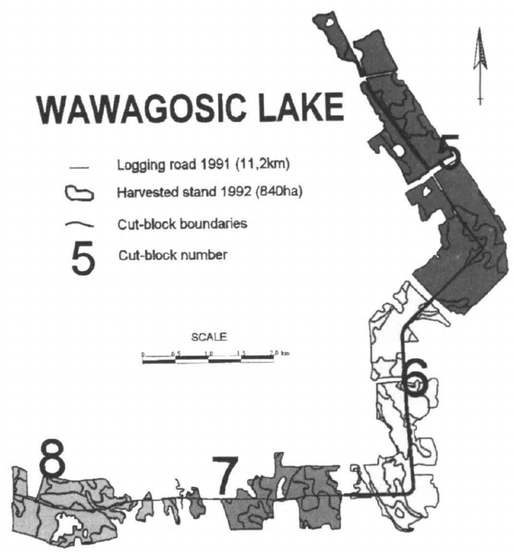

Fig. 7. Cut-block forest map of study site number 2 located near Wawagosic Lake.

2.4. The column *MNR*-m³ results from multiplying the area of each forest stand (*AREA*) by the volume per hectare (*MNR*-m³/ha) to obtain the total wood volume for each forest stand within a given cut-block. Adding all volume per forest stand within a cut-block gives the total harvested volume per cut-block. In Table 8, for example, the total estimated wood volume for cut-block number 2 is 12 825m³. The same procedure was followed for all cut blocks.

4.2.2 Estimation with Total ROAD Volume

A method of estimating volume which is poorly documented in scientific literature, but sometimes used as a rule-of-thumb, consists of estimating cut-block volumes (Vol_{block}) by using the average volume per hectare measured after harvest of trees felled along the road right-of-way adjacent to logging areas over the entire cut block. The road area ($Area_{road}$) is estimated by multiplying the road length ($Length_{road}$) by its average width ($Width_{road}$). The total volume cut along the road right-of-way (Vol_{road}), estimated according to log scaling rules described in Section 4.3, is then divided by the road area ($Area_{road}$) to obtain wood volume per hectare. An estimation of the total volume per cut-block is then obtained by multiplying the average volume per hectare, calculated from the road, by the total area of the cut-block ($Area_{block}$) planned for harvest. Note that this does not consider volumes of individual forest stands and/or strata. The equation for calculation of wood volume per cut-block would then be written as follows:

$$Volume_{block} = \frac{Volume_{road}}{Length_{road} \times Width_{road}} \times Area_{block}$$

This method is mainly used when road right-of-ways are logged the year prior to harvest operations. Thus, forest planners can use the *ROAD* volume estimate a year prior to harvest to verify if it coincides with the cut-block volume estimates obtained through the use of *MNR* management

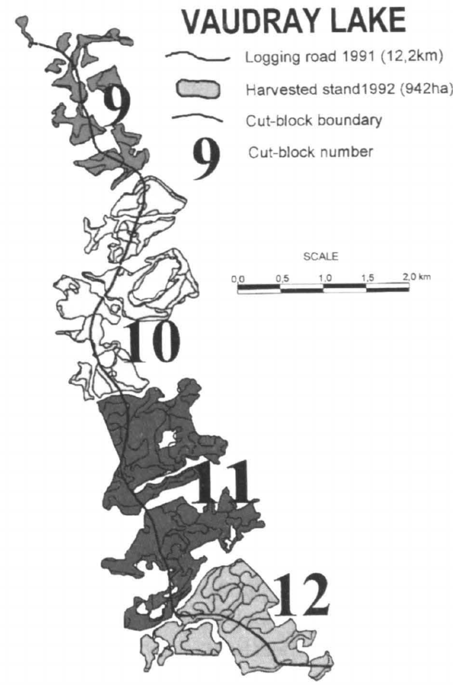

Fig. 8. Cut-block forest map of study site number 3 located near Vaudray Lake.

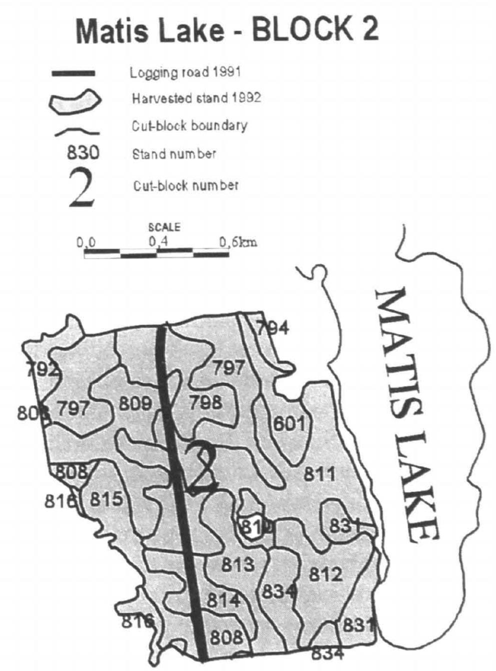

Fig. 9. Closeup view of cut-block number 2 located near Matis Lake.

Table 8. Wood volume estimation for cut-block number 2 near Matis Lake with either *MNR* stock table, *ROAD* sampling method or *STRATIFIED* sampling method.

No	Stand	Area ha	*MNR* m^3/ha	*MNR* m^3	*ROAD* m^3/ha	*ROAD* m^3	*STRATIFIED* m^3/ha	*STRATIFIED* m^3
601	R EE C3 120	6.0	93.2	555	86.2	517	58.7	350
792	R HP EE C3 120	3.6	93.2	333	86.2	310	84.6	302
794	DH	1.5	0.0	0	86.2	129	0.0	0
797	M HP PEER D3 120	23.7	77.4	1834	86.2	2043	100.4	2378
798	R CH 6010	11.8	0.0	0	86.2	1017	73.5	864
808	R EE C3 120	5.5	93.2	509	86.2	474	87.0	475
809	R HP ES C2 120	14.7	98.7	1451	86.2	1267	81.3	1195
810	DS	0.8	0.0	0	86.2	69	0.0	0
811	R EE B2 120	29.8	147.6	4398	86.2	2569	119.9	3573
812	R HP EE D2 120	10.5	68.6	718	86.2	905	133.2	1395
813	R CH 6010	8.8	0.0	0	86.2	759	58.4	512
814	R HP EE D3 120	6.8	68.6	469	86.2	586	89.4	611
815	R EE B3 120	10.1	147.6	1495	86.2	871	146.5	1483
816	DH	2.3	0.0	0	86.2	198	0.0	0
831	M HP PEEF C2 120	6.3	77.4	488	86.2	543	77.4	483
834	R EE C3 120	6.2	93.2	575	86.2	534	87.0	537
Total		148.3	86.5	12825	86.2	12792	95.5	14158

R: Coniferous, M: Mixed, CH: Total windthrogh, HP: Partial windthrogh, DH: Swamps, DS:Bare rock, E: Black spruce, S: Balsam fir, PE: Trembling aspen
Crown cover class (% cover): B(60% to 80%), C(40% to 60%), D(25% to 40%)
Height class (meters): 2(17m to 22m), 3(12m to 17m) Age class: 120 (120years and more)

stock tables, described in Section 4.2.1.

The main difference between the *MNR* and the *ROAD* methods lies in the fact that, for the *MNR*, the wood volume estimates per cut-block are estimated from stock tables originating from several (approximately 500) sampling plots of 0.04 hectare distributed over a larger area than just the cut-block (ranging from 100 000 ha to 350 000 ha) compared to one large sample plot of several dozens of hectares located entirely within the cut-blocks planned for harvest. If the wood volume cut along the road right-of-way is representative of the volume cut within its adjacent cut-block, a large difference between *MNR* and *ROAD* cut-block volume estimates would be a strong indicator that extra forest sampling plots should be collected within the proposed logging area to reduce troublesome differences between estimated cut-block wood volumes and those really harvested.

Experimental sites one to three stretch along a measured length of road of 5.6 km, 11.2 km and 12.2 km, respectively. Since the average road width for all three sites was determined to be around 30 meters, the road area for sites one to three is approximately 16.8 ha, 33.6 ha and 36.6 ha, respectively.

Site	$(Length_{road} \times Width_{road}) / 10^4 m^2/ha$	=	$Area_{road}$
1	(5600 m × 30 m) / $10^4 m^2$/ha	=	16.8 ha
2	(11 200 m × 30 m) / $10^4 m^2$/ha	=	33.6 ha
3	(12 200 m × 30 m) / $10^4 m^2$/ha	=	36.6 ha

The stump diameter of each tree harvested along the right-of-way of the three studied roads were scaled and recorded using the *MNR* scaling standard rules (Lemieux 1991) in use in 1991. Log scaling was conducted by two experienced log scalers. These stump diameter were used with a volume table applicable to each of the three studied sites to estimate the total wood volume per road segment. The volume table provides a volume estimate per stem per species for DBH classes ranging, in this study, from 10 cm to 40 cm inclusively, by increments of two centimeters. These volume tables are specific to a given logging area. The method used to generate these volume tables is explained in more detail in Section 4.3.

Thus, the volume table is a wood volume estimation per stem per species aplicable essentially to trees located in the neighbourhood where tree sampling was performed. This is called a local volume table (Husch et al. 1982). Table 9 gives the volume calculation for wood cut along the road right-of-way for all three experimental sites. In this table, the first row gives the diameter class at stump height (DSH) by increment of two centimeters, going from 10 cm to 48 cm. The next three row give the local volume table in cubic meters per stem per species for the Matis Lake logging sector. The local volume tables for Wawagosic and Vaudray lakes are given lower in the same table. The fifth to eighth rows of the same table give the number of stems per species per DSH class as measured after right-of-way harvest. The ninth to twelfth rows of this table are the result of a multiplication of rows two to four (m^3/stem) by rows five to eight (number of stem per DSH class per species) respectively, to obtain the total wood volume per DSH class per species in cubic meters for the Matis Lake logging site. The total wood volume per DSH class per species for Wawagosic and Vaudray Lakes logging site is given lower in the same table.

The volume per hectare ($Vol\text{-}ha_{road}$) for each studied logging road was obtained by dividing the total wood volume cut along the three studied roads (Vol_{road}) by their respective road areas ($Area_{road}$).

Site	$Vol_{road} / Area_{road}$	=	$Vol\text{-}ha_{road}$
1	1448 m^3 / 16.8 ha	=	86 m^3/ha
2	3159 m^3 / 33.6 ha	=	94 m^3/ha
3	1865 m^3 / 36.6 ha	=	51 m^3/ha

Then, the volume per hectare obtained from the road right-of way (Vol_{road}) was multiplied by the area planned for harvest for each cut-block adjacent to the road ($Area_{block}$) to obtain a volume estimation per cut-block. Wood volume estimation for cut-block number 2 (Vol_{block2}), illustrated in Fig. 9 , would then be:

$$Vol\text{-}ha_{road1} \times Area_{block2} = Vol_{block2}$$

$$86.2\ m^3/ha \times 148.3\ ha = 12\ 790\ m^3$$

4.2.3 Estimation with STRATIFIED Method

The third cut-block volume estimation method is somewhat similar to the *ROAD* method described in Section 4.2.2. It also consists of using the log scaling of trees cut along the road to estimate the total volume in the cut block. The difference is that in this method, the scaling is *STRATIFIED* or segmented at stand boundaries.

First, trees along the road right-of-way are cut in the year prior to harvest of adjacent cut-blocks. Full-trees are skidded to the side of the road with rubber tired-chocker or grapple skidders following maximum spaced skid trails to reduce environmental impacts (Staaf and Wiksten 1984). Harvested trees are not grouped into central landings (Conway 1976). Instead they are left along the roadside as close as possible to their stumps in order to better identify the forest stand from which they were cut.

During the present experiments, feller-bunchers equipped with circular saw heads were commonly used in this region for road right-of-way logging. As shown on Fig. 10, the feller-buncher operators started their working days by cutting the right half of the road and piling all stems along the right side of the road. Then, the operators came back to their starting points by cutting the other half of the road and piling trees along the left side. This way of logging trees along the road right-of way was of common use operationally at the time of the experimentation.

The next step was not an action that took place during normal logging operations. It consisted of measuring with a hip-chain the distance from the beginning of the road, illustrated with number 0 on Fig. 11 (upper right), to the cartographic limit of each forest stand. The numbers at the end of each segment perpendicular to the road on Fig. 11 represent the distance, in meters, from the start of the road to where each forest stand limit crosses Road Number Two near Wawagosic Lake.

The distances between the road starting point to each stand limit were measured by the logging foreman to whom a map similar to the one illustrated on Fig. 11 was given, along with a hip-chain, some cans of paint and red flagging. The hip-chain was tied to the starting point of the road, as indicated on the map, and the foreman walked until he reached the distance separating the road

Table 9. Wood volume in cubic meters per diameter class per species cut along road right-of-way of study site number 1, 2 and 3 near Matis, Wawagosic and Vaudray Lakes.

DSH	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	Total
Site number 1 at Matis lake																					
Volume (m^3/stem)																					
Spruce	0.000	0.000	0.100	0.100	0.120	0.160	0.202	0.250	0.300	0.360	0.420	0.490	0.560	0.640	0.720	0.810	0.900	1.000	1.100	1.200	
Pine	–	–	–	–	–	0.214	0.271	0.328	0.390	–	–	–	–	–	–	–	–	–	–	–	
Fir	0.076	0.078	0.081	0.088	0.109	0.135	0.171	0.209	0.261	0.312	0.380	0.451	0.582	0.621	–	–	0.923	–	–	–	
# Stem																					
Spruce	116	1120	2013	2237	1835	1371	929	564	311	195	87	55	29	15	12	8	6	8	1	1	10913
Pine	0	0	0	0	0	2	2	3	2	0	0	0	0	0	0	0	0	0	0	0	9
Fir	8	30	172	35	35	29	12	7	6	2	1	2	2	1	0	0	1	0	0	0	343
SPF	124	1150	2185	2272	1870	1402	943	574	319	197	88	57	31	16	12	8	7	8	1	1	11265
Volume (m^3/species)																					
Spruce	1.6	39.2	118.8	196.9	223.9	219.4	187.7	140.4	93.3	69.2	36.1	26.3	15.9	9.3	8.4	6.2	5.2	7.6	1.1	1.1	1408
Pine	0.0	0.0	0.0	0.0	0.0	0.4	0.5	1.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3
Fir	0.6	2.3	13.9	3.1	3.8	3.9	2.0	1.5	1.6	0.6	0.3	0.9	1.2	0.6	0	0.0	0.9	0.0	0.0	0.0	37
SPF	2	41	133	200	228	224	190	143	96	70	36	27	17	10	8	6	6	8	1	1	1448
Site number 2 at Wawagosic lake																					
Volume (m^3/stem)																					
Spruce	0.014	0.035	0.059	0.088	0.122	0.160	0.202	0.249	0.300	0.355	0.415	0.479	0.547	0.620	0.697	0.779	0.865	0.955	1.050	1.149	
Pine	0.019	0.048	0.081	0.119	0.163	0.211	0.265	0.323	0.387	0.455	0.529	0.607	0.691	0.779	–	–	–	–	–	–	
Fir	0.074	0.070	0.074	0.085	0.104	0.130	0.164	0.203	0.254	0.310	0.374	0.446	0.575	0.611	0.705	0.807	0.916	1.033	–	–	
# Stem																					
Spruce	914	4315	4359	3229	2405	1550	1172	685	459	250	156	62	22	22	18	9	10	2	7	3	19649
Pine	321	2099	2256	1711	994	625	312	142	82	40	18	9	5	1	0	0	0	0	0	0	8615
Fir	23	114	179	129	98	79	69	54	43	19	16	18	15	6	7	5	3	1	0	0	878
SPF	1258	6528	6794	5069	3497	2254	1553	881	584	309	190	89	42	29	25	14	13	3	7	3	29142
Volume (m^3/species)																					
Spruce	12.8	151.0	257.2	284.2	293.4	248.0	236.7	170.6	137.7	88.7	64.7	29.7	12.0	13.6	12.5	7.0	8.6	1.9	7.3	3.4	2041
Pine	6.1	100.8	182.7	203.6	162.0	131.9	82.7	45.9	31.7	18.2	9.5	5.5	3.5	1.0	0	0	0	0	0	0	985
Fir	1.7	8.0	13.3	11.0	10.2	10.3	11.3	11	10.9	5.9	6.0	8.0	8.6	3.7	4.9	4.0	2.7	1.0	0	0	133
SPF	21	260	453	499	466	390	331	227	180	113	80	43	24	18	17	11	11	3	7	3	3159
Site number 3 at Vaydray lake																					
Volume (m^3/stem)																					
Spruce	0.020	0.030	0.060	0.080	0.115	0.152	0.194	0.242	0.295	0.353	0.417	0.485	0.559	0.638	0.722	0.811	0.905	1.005	1.110	1.220	
Pine	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
Fir	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
# Stem																					
Spruce	2782	5636	5037	3793	2500	1555	954	529	237	141	77	37	15	12	7	3	0	1	0	2	23318
Pine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fir	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPF	2782	5636	5037	3793	2500	1555	954	529	237	141	77	37	15	12	7	3	0	1	0	2	23318
Volume (m^3/species)																					
Spruce	48.1	190.7	279.9	313	286.6	236.3	185.5	128.1	69.9	49.8	32.1	18.0	8.4	7.7	5.1	2.4	0	1.0	0	2.4	1865
Pine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fir	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPF	48	191	280	313	287	236	185	128	70	50	32	18	8	8	5	2	0	1	0	2	1865
Total 3 sites	71	492	865	1012	980	850	706	498	346	232	149	88	50	36	31	20	18	12	8	7	6472

DSH: Stem diameter class at stump height in cm
Spruce: Black spruce, Pine: Jack pine, Fir: Balsam fir

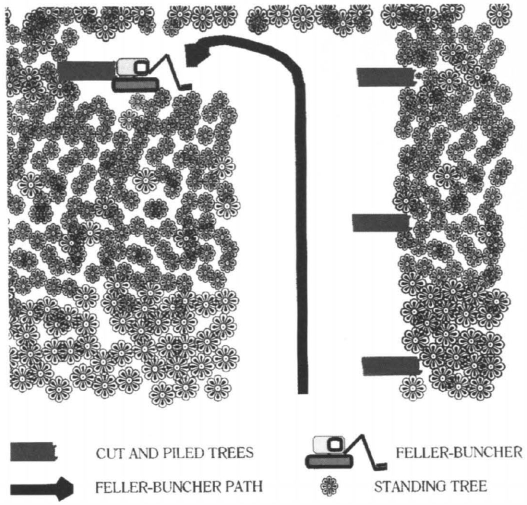

Fig. 10. Feller-buncher path for logging road right-of-way harvest.

starting point from the next forest stand limit as determined from the digitized map. There, this distance (6502 meters for the first limit illustrated on Fig. 12) was marked visibly with paint on the butt end of a piled log. When there were no logs piled, flagging was simply tied to a nearby tree with the distance (6794 meters on the Fig. 12 example) written on it. At this specific point, the foreman measured the width of the road with the hip-chain and recorded it on his map as the stand limit.

All three experimental sites had relatively flat topography. For this reason, little correction had to be done for horizontal distances with respect to slope when considering the length of the road section samples. If steeper slopes had been observed, distances along studied roads would have

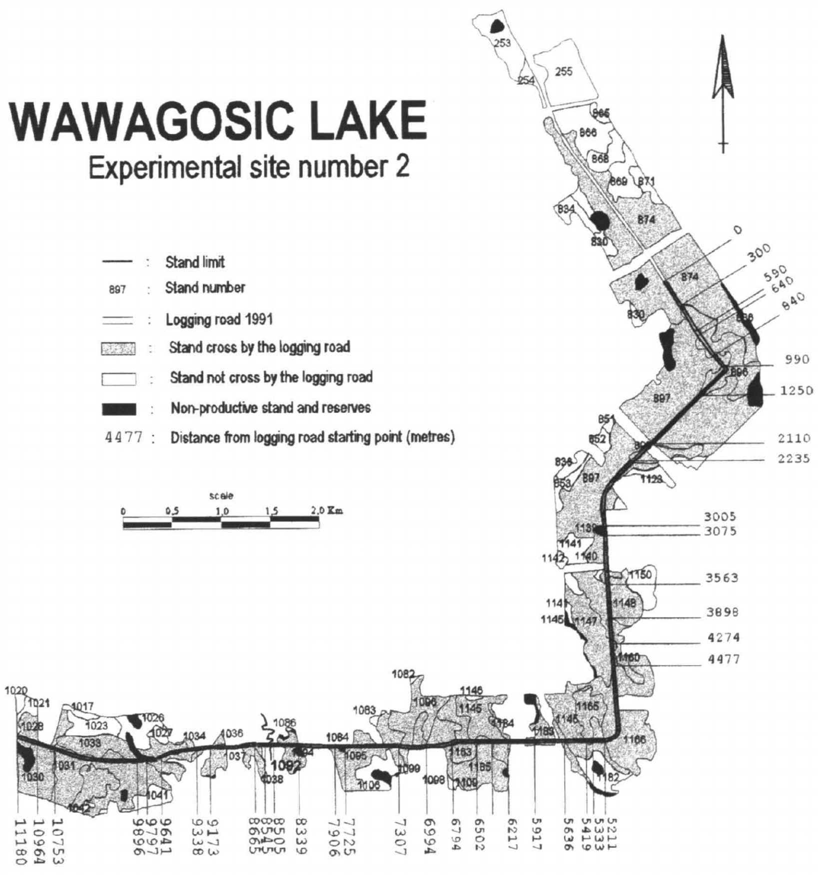

Fig. 11. Mapped distances between stand limits and road starting point for experimental site number 2 near Wawagosic Lake.

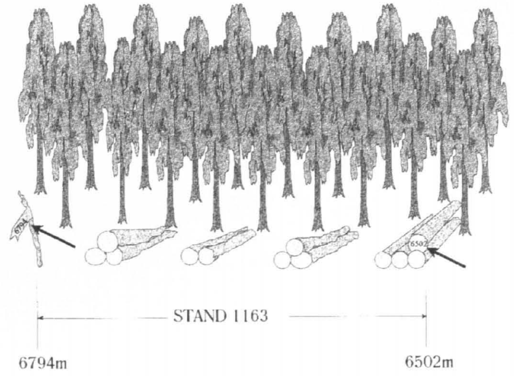

Fig. 12. Stand limits identification with logs marking (6502) or flagging (6794).

had to be adjusted according to slope angles in order to utilize horizontal map distances. However, in general, logging roads cannot exceed 15 % (or 8 degrees) to respect truck transportation limits.This corresponds to a maximum error of one metre per one hundred meters ground distance, which is well below the precision of the hip-chain itself.

In general, the time between felling/bunching/piling and scaling/loading/transportation of trees along the road right-of way was very short. Thus, good communication and coordination between the logging foreman, the feller/buncher operator and the log scalers was necessary to ensure that length measurements between the road starting point and the forest stand limits along with pile marking was properly done.

Measuring of the road distance and the marking of forest stand limits on log piles was followed by the usual course of operations, namely the scaling of each butt diameter piled along the roadside. There was only one step added to the normal way of recording tree butt diameters on tally sheets. Instead of recording butt diameters on tally sheets up until each sheet tally space was filled up, the scalers were asked to change tally sheets each time they reached a new forest stand limit identified by a ribbon or paint on log piles. The distance between the beginning of the road and the starting and ending limit of a given forest stand, marked on each log pile, were recorded on the scaling tally sheets. The width measurements on the road allowed the road area to be estimated. Thus, it was possible to obtain an estimate of the total wood volume for each road right-of-way segment within a given forest stand (*Vol-road*$_{stand}$).

Thus, when compiling scaling data of logs cut along the road right-of way, each tally sheet corresponds to the quantity of wood on the road right-of-way contained inside each mapped forest stand identified on the ground. As shown in Fig. 13, the road length inside each forest stand (*Length-road*$_{stand}$) corresponds to the distance marked on log pilings at the end limit of each forest stand (*Dist-end*$_{stand}$) from which the distance marked at the starting limit of each stand (*Dist-start*$_{stand}$) is subtracted. Thus, it is only necessary to multiply this road length by the average width of the road within a forest stand (*Width-ave*$_{stand}$) that was recorded by the logging foreman at each stand limit ([*Width-start*$_{stand}$+ *Width-end*$_{stand}$]/2) to obtain the forest stand area crossed by the road right-of-way (*Area-road*$_{stand}$). For example, the road length within forest stand number 1163, illustrated in Fig. 13, would be:

$$\text{Length-road}_{1163} = \text{Dist-end}_{1163} - \text{Dist-start}_{1163}$$
$$292\ \text{m} = 6794\ \text{m} - 6502\ \text{m}$$

The road width within the same forest stand would then be:

$$\text{Width-road}_{1163} = (\text{Width-start}_{1163} + \text{Width-end}_{1163})\ /\ 2$$
$$30 = (31\ \text{m} + 29\ \text{m})\ /\ 2$$

The estimated area of forest stand number 1163 located within the road right-of-way (*Area-road*$_{1163}$) is then:

$$\text{Area-road}_{1163} = \text{Length-road}_{1163} \times \text{Width-ave}_{1163}$$
$$8760\ \text{m}^2 = 292\ \text{m} \times 30\ \text{m}$$

The average wood volume per hectare for each forest stand crossed by the road right-of-way (*Vol/ha-road*$_{stand}$) can be obtained by dividing the total wood volume from each scaling tally sheet (*Vol-road*$_{stand}$) by the corresponding forest stand area located within the road right-of-way (*Area-road*$_{stand}$). For the purpose of the experiment, only the coniferous volume was compiled since deciduous species were not present in sufficient quantity to perform standard statistical analysis. The following example gives the scaling tally sheet of forest stand number 1163, illustrated in Fig. 13,

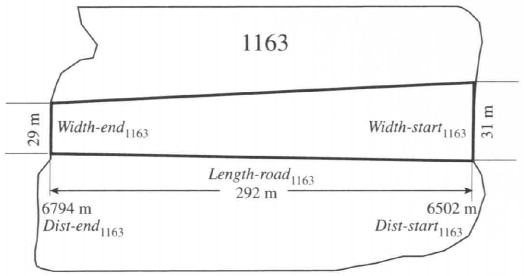

Fig. 13. Dimensions used for road surface calculations within stand number 1163.

which showed a total coniferous harvested volume (*Vol-road*$_{1163}$) of 86 m^3 for this road section. Coniferous volume estimation per hectare for this forest stand (*Vol/ha-road*$_{1163}$) would then be 98.2 m^3/ha:

$$Vol\ /\ ha\text{ - }road_{1163} = \frac{Vol\text{ - }road_{1163}\ /\ Area\text{ - }road_{1163}}{10000\ \text{m}^2\ /\ \text{ha}}$$

$$98.2\ \text{m}^2\ /\ \text{ha} = \frac{86\ \text{m}^3\ /\ 8760\ \text{m}^2}{10000\ \text{m}^2\ /\ \text{ha}}$$

After preliminary trials on coniferous volume estimation per cut-block with stratification at forest stand limits, it was necessary to modify the procedure for locating roads on a map. In reality, several field observations of stand type did not correspond at all to the cartographic descriptions of the forest stands. For example, high per hectare volume estimates were obtained for cartographic strata described as non-productive (e.g. swamps). A bad location of the road on the map appeared to be the most probable explanation for such mismatches between ground data and map forest stand descriptions. Consequently, the ground location of roads, which was done with traditional equipment such as compass and hip-chain, was then verified with GPS equipment.

It was possible to observe, on a GIS overlay of both compass-located road positions and GPS road positions on a digitized forest map, differences as large as 200 m at some points between the same road located in different ways. The GPS equipment used (Magellan Promark V Submeter coupled with a Hachtek base station with antenna for post-treatment of data) was set in a mode to provide X and Y positioning precision within one meter. The forest cover and the quality of the reception of satellite signals was such that the precision of the positioning was more in the neighborhood of plus or minus three metres.

Consequently, the roads of all study sites were re-positioned on their forest map with ground positioning data gathered with GPS equipment. The main purpose of this re-positioning was to provide greater reliability of map locations to studied roads. Since most forest companies in Quebec have access to GIS and GPS, the *STRATIFIED* procedure was modified to include these new technologies to provide more accurate road location than the procedure with hip-chain and compass.

The last two columns of Table 8 provide a detailed example for cut-block number 2 of volume per hectare (m^3/ha) and volume per forest stand (m^3) as calculated with the method using scalings of trees cut along the road right-of-way with stratified sampling at forest stand limits (*STRATIFIED*). For example, the total coniferous volume estimated to be contained within cut-block number 2 nearby Matis Lake according to the *STRATIFIED* method is approximately 14 158 m^3.

It should be noted on this table that the volume per hectare of forest stand number 831, having the classification M HP PEEF C2 120, is the same for both *MNR* and *STRATIFIED* methods. When a forest stand within a cut-block is not crossed by a road, there is no road sampling for this specific stand. Thus, for calculation purposes, all forest stands scheduled for harvest that are not crossed by the logging road have been assigned the volume per hectare provided by the *MNR* stock tables. On Fig. 11, all forest stands not crossed by the road are illustrated in plain white to contrast with those forest stands in brown that are crossed by the road. On this figure, it can be observed that the total area representing stands not crossed by roads is relatively small compared to the total cut-block area. This can be explained by the fact that the economical skidding distance (distance between the logging road and the farthest limit of the cut-block) with conventional cable skidders on flat ground boreal forest is approximately 300 m. Thus, cut-blocks usually take a rectangular shape, with the longer side of the rectangle along side the road, until the maximum allowable block size is reached (50 ha, 100 ha and 150 ha depending on the logging zone). Thus, the conditions present in this study are similar to those which will be encountered in the operational use of the methods developed.

4.3 Log Scaling after Harvest of Cut-blocks

Harvest operations usually regroup several contiguous forest stands within a single area called a cut-block, as shown in Fig. 9, in order to reach sizes of area that facilitate mechanized logging. During the harvest of the cut-blocks, trees cut from all forest stands of a given cut-block will be piled along the side of the road. Thus, in this experiment, it was impossible to distinguish from roadside piles which trees were harvested from which forest stands after cut-blocks were clearcut. In a few cases in this experiment, it was even impossible to obtain volume measurements per cut-block. This was the case for cut-block number 9 from Fig. 8, where trees cut from several clustered logged unit areas were measured together and identified on scaling tally sheets as belonging to the same parcel. However, for the purpose of this study, those clustered logged unit areas were also called cut-blocks since all trees harvested on them were scaled together and recorded on a single tally sheet. Hence, log scaling after harvest of all cut-blocks (or clustered cut-blocks) from all three studied sites provides wood volume measurements for each cut-block illustrated on Figs. 6, 7 and 8.

The stump diameters for each stem cut from each cut-block (or clustered cut-blocks) were measured in a conventional way with scaling rulers, applying *MNR* scaling rules for the non-bucked logs piled at the landing (Fortin and Lemieux 1992).

4.3.1 Scaling Rules for Non-bucked Logs Piled at the Landing

These scaling rules specify among others things that log piles should have a maximum of 2500 stems with all butt ends being accessible and facing the same side. Stump buckings should be as vertical as possible. The height of log piles should not exceed two meters and no additionnal logs can be piled on top of scaled logs. A maximum of 2500 stems can be recorded on a single tally sheet and scalers should change tally sheets each time they move to a new road or logging sector. A number is assigned to each log pile and this number is recorded on its tally sheet and marked visibly on the pile with the total number of stems scaled in the pile. The tally sheet number, the scaling date, the initials of the scaler and its licence number must also be marked visibly on each pile.

Scaling data recorded on tally sheets have (among other informations):

- parcel numbers to identify the location of the log piles while compiling scaling data,
- coniferous species (balsam fir, jack pine, black spruce) and deciduous species (trembling aspen and white birch) and
- stump height diameter class (2 cm class ranging from 10 cm to 48 cm, inclusive) of all trees in the piles.

The non-bucked logs piled at the landing scaling method also requires 170 samples of three stems (510 sample stems) per logging sector. These sample stems must be located on top of piles and be easily accessible with at least 10 cm diameter at butt end and at least one meter in length. Tree sampling frequency within each diameter class must be representative of the actual population's frequency distribution. Hence, tree sampling frequency distribution must be evaluated at least ten times during the logging season to adjust it to the actual population's frequency distribution. Each sample stem is marked at butt end and its location is specifically identified on data registered forms to facilitate verification of measurements. Inner bark diameter is measured every meter along sample stems with a caliper and at butt and top ends. These sectional measurements on individual sampled piled stems were performed on approximately 500 sample trees for each study site. Sectional measurements on single trees are usually done to produce tree volume tables. The resulting relationships from each study site were used to calculate the total wood volume harvested within each cut-block or group of cut-blocks. The relationship between stem volume versus diameter at stump height (DSH) is then established through regression analysis (Schreuder et al. 1993).

5 Analysis and Discussion of the Results

The experimental setup had three study sites with four cut-blocks per study site, for a total of twelve cut-blocks. Despite the relatively small number of cut-blocks, it was possible to make the following observations while comparing measured volumes with estimated *MNR*, *ROAD* and *STRATIFIED* cut-block volumes.

5.1 Comparison between *MEASURED* and *MNR* Methods

Table 10 shows the wood volume estimation from all three studied methods (*MNR*, *ROAD* and *STRATIFIED*). In general, estimated wood volume per cut-block using *MNR* stock tables showed a large percentage difference compared to wood volume *measured* after harvest within each cut-block. As indicated in Table 10, under the column *MNR* (%), the percentage difference between *measured* volumes and those estimated with the *MNR* method ranged from 2.8 % to 75 %. The total wood volume of the twelve cut-blocks was overestimated by 57 707 m^3 compared to the after-cut scaling, which represents 30 % less wood harvested than estimated using the standard *MNR* stock tables. Such a large difference between the estimated harvest volume and that actually cut causes serious problems, especially for forest supply planning concerns. In such a case, long negotiations between contractors and the Quebec Ministry of Natural Resources are required to obtain

Table 10. Comparison between *MEASURED* coniferous volumes after harvest and coniferous volume estimation before harvest operations for each studied methods.

Block	Site	Measured (m^3)	*MNR* (m^3)	*MNR* %	*ROAD* (m^3)	*ROAD* %	*STRATIFIED* (m^3)	*STRATIFIED* %	Area (ha)
1	Matis	13737	9805	−28.6	8067	−41.3	9767	−28.9	104
2	Matis	16041	12825	−20.0	11481	−28.4	14162	−11.7	148
3	Matis	12382	16394	32.4	13265	7.1	14167	14.4	171
4	Matis	12955	14798	14.2	12792	−1.3	11750	−9.3	165
s-total	Matis	55115	53822	−2.3	42263	−17.3	49846	9.6	588
5	Wawagosic	42178	73887	75.2	32657	−22.6	40171	−4.8	346
6	Wawagosic	34217	36602	7.0	21803	−36.3	30070	−12.1	231
7	Wawagosic	10694	18330	71.4	11326	5.9	11535	7.9	120
8	Wawagosic	17382	22852	31.5	13497	−22.4	18258	5.0	143
s-total	Wawagosic	104471	151671	45.2	79283	−24.1	100034	4.2	840
9	Vaudray	12422	18338	47.6	13720	10.4	15273	23.0	367
10	Vaudray	9481	12413	30.9	8150	−14.0	9222	−2.7	218
11	Vaudray	9345	14109	51.0	9384	0.4	8419	−9.9	251
12	Vaudray	6697	6885	2.8	3963	−40.8	4251	−36.5	106
s-total	Vaudray	37945	51745	36.4	35217	−7.2	37165	−2.1	942
Total of 3 sites		197531	257238	30.2	160105	−18.9	187045	−5.3	2370

Measured: Wood volume measured after harvest within each cut-blocks
MNR: Volume estimation per cut-block with Ministry of Natural Resources stock tables
ROAD: Volume estimation using log scaling from road right-of-way harvest
STRATIFIED: Volume estimation using log scaling from road right-of-way harvest within each forest stand crossed by the road

Table 11. Randomized block analysis of variance results.

Source of variation	df	Sum of squares	Mean squares	$F_{calculated}$	Pr > $F_{tabulated}$
Model	14	6141469990	438676428	16.32	0.0001
Error	33	886884321	26875282		
Total corrected	47	7028354311			
Block	11	5721402739	520127522	19.35	0.0001
Treatments	3	420067251	140022417	5.21	0.0047

Specific contrasts from overall ANOVA

Contrasts	df	Sum of squares	Mean squares	$F_{calculated}$	Pr > $F_{tabulated}$
MNR vs Measured	1	148538577	148538577	5.53	0.0249
Road vs Measured	1	58362728	58362728	2.17	0.1501
Strate vs Measured	1	4581508	4581508	0.17	0.6824

agreements for additional wood volume to be cut in order to reduce the economic impact related to lack of wood supply at processing mills. Furthermore, this shortage of wood also makes it necessary to shorten logging activities at a specific site and try to reschedule wood workers and forest equipment elsewhere.

The greatest worry related to the imprecision of *MNR* stock tables, however, is the fact that these tables are used primarily as a data base for the calculation of the AAC for the province of Quebec. Differences between estimated and real volumes may not be as important for AAC calculations on relatively large areas, as it may be for local applications on single forest stands or cut-blocks. It should be noted that for AAC calculations, sample plot data for the whole sampling unit are used to estimate actual and future volumes for the entire sampling unit. Only an extensive study would provide acceptable conclusive evidence concerning the validity of the existing methods used to evaluate forest standing volume and to calculate the forest AAC. Nonetheless, there is no reason to believe that results presented in Table 10 are anomalous and this may be cause for concern relative to the calculation of the AAC province wide.

A random block analysis-of-variance (ANOVA – Sokal and Rohlf 1969) was performed to verify if the observed differences between the estimated harvest volume per cut-block with the *MNR* method and those measured after cut were statistically significant. The results of the random block ANOVA, executed with the SAS statistical software (SAS 1994) are presented in Table 11. The GLM procedure, used here, handles classification variables, which have discrete levels, as well as continuous variables, which measure quantities. Thus GLM can be used for many different analysis including simple, multiple, weighted and polynomial regressions as well as multivariate and repeated measures analysis of variance, partial correlation and analyses of covariance. The GLM procedure is particularly useful for analysis of variance involving unbalanced data. This is the case for the actual analysed data set where cut-blocks volume ranges from 6697m^3 to 42 178m^3.

A Bartlett's test performed on the data set gave an a = 0.026 which is smaller than the tabulated Chi-square = 9.30. Thus, the variances are considered to be homogeneous which allows the ANOVA to be used on the tested variables.

The tested sources of variation with their associated degree of freedom (df) along with their sum of squares (SS) and mean squares (MS) are listed under the four first columns of Table 11, respectively. The two last columns of this table gives the calculated F value ($F_{calculated}$) and the probability level that this value is greater than the tabulated F value (PR > $F_{tabulated}$), respectively. Hence, the calculated F value associated with the MODEL is equal to 16.32. The comparison of both tabulated and calculated F values of the MODEL suggests that there is at least one variable, somewhere in the model, that differs significantly from one group to another.

It can also be noted from Table 11 that the calculated F value associated with the BLOCK shows that the wood volume per cut-block (Table 11), as estimated with the current method using *MNR* volume tables, is significantly different (p = 0.0249) than the volume measured after harvest for all studied cut-blocks. This is to be expected since one block had considerably more volumes than the others.

It should be noticed from Table 10 that the subtotal of the four cut-blocks wood volume estimation from Matis Lake with the *MNR* method (53 822 m^3) is very close to the total volume measured after-cut (55 115 m^3), which is approximately a 2 % difference. The reason for the overall significant difference is due to the nature of the differences between *MNR* and *MEASURED* volume estimations for each cut-block of Matis Lake. These show considerable variation (–29 % to 32 %). Since *MNR* wood volume is not systematically overestimated or underestimated on this site, errors are offset and the total estimated volume is very close to *MEASURED* volume after cut even though the difference for a given cut-block is considerable. Had the differences between *MNR* and *MEASURED* volume after cut been systematically positive or systematically negative and of the same magnitude, it would have been possible to use the *MNR* volume estimation with a correction factor corresponding to the systematic deviation, thereby allowing us to obtain a relatively reliable *MNR-CORRECTED* volume estimation. However, this is not possible due to the tendencies found on the Matis Lake study site. Moreover, the magnitude of the differences for the other sites varies considerably even though the tendency is toward overestimation.

To emphasize this, it should be noted from Table 10 that the *MNR* volume estimates for each cut-block within the Wawagosic and Vaudray Lake sites are systematically greater than the measured volumes after logging of cut-blocks. Although these cut-block volume estimations are always greater than the after-cut measurements, the percentage of differences between *MNR* and *MEASURED* values are extremely variable. According to Table 10, the percentage of differences ranges from 3 % to 75 % and does not appear to be related to the measured volume (or other factors). Thus, due to this lack of consistency in estimation, a correction factor applied to *MNR* values in order to obtain more reliable volume estimations would be rather difficult to apply even for these sites alone.

Overall, the comparison of *MNR* volume estimation with the measured volumes from this experimentation revealed that:

- the MRN volume was overestimated;
- the MRN volume overestimation shown no consistency or systematic bias; and
- the MRN volume estimation was significantly different from log scaling values.

5.2 Comparison between *ROAD* and *MEASURED* Methods

Volume estimations obtained using the *ROAD* method show smaller differences from *MEASURED* volumes than *MNR* estimations for all twelve studied cut-blocks (Table 10). Total estimated *ROAD* volume is 160 105 m^3, which is approximately 19 % less than the *MEASURED* volume after cut (197 531 m^3). Also, the difference between the *ROAD* and *MEASURED* volumes for each individual cut-block is much less variable than those of the *MNR* method. It ranges from –41 % to 10 % (51 %) for the *ROAD* method, compared to –29 % to 75 % (104 %) for the *MNR* method. This means that the *ROAD* volumes are both more precise and accurate than *MNR* volumes.

Compared to the *MEASURED* volume after cut, no biased *ROAD* volume overestimation or underestimation was observed on any of the three studied sites (Table 10). Apart from the Wawagosic site which seems to have a tendency towards underestimation (–23 %, –33 %, 6 % and –22 %), all three sites have over and under estimations with the *ROAD* method compared to *MEASURED* volumes. This suggests that the *ROAD* method is not biased even if the samples (trees cut along the road) were not strictly selected at random. The fact that all trees were sampled along the road right-of-way could have lead to systematic overestimations of adjacent cut-blocks since, in general, logging roads are located preferably over well drained soils which are generally more productive in boreal forests. This was not the case, however. Although this absence of bias is a desirable thing, it might have been expected *a priori* that a tendency towards overestimation might exist for the *ROAD* method (and the stratified method also, for that matter) because of the favorable location of roads. It is worthwhile to examine this in more detail, here.

This lack of observed biased between *ROAD* and *MEASURED* volumes might be explained by the relatively short distance between the roadside and the farthest limits of each cut-block (i.e., the skidding distance). As mentioned in Section 4.2.3, operationally economic constraints cause skidding distances to rarely exceed 300 meters. Thus, little variation in forest type is likely to occur across such a relatively short distance, especially over flat ground and homogeneous boreal forests. Also, the relatively intense sampling relative to the total estimated cut-block area (approximately 4 %) is an important factor that could explain the absence of systematic overestimation of wood volume with the *ROAD* method. That is, the intense sample may have allowed the sample to overcome any potential bias. As shown on Table 12, the percentages of sampled areas with the *ROAD* (and also for the *STRATIFIED*) method compared to the total area of all studied cut-blocks is approximately 3 %, 4 % and 4 % for sites 1, 2 and 3, respectively. This sampled area is extremely large compared to the 500 sampling plots of 0.04 hectare (500 plots × 0.04 ha/plot = 20 ha or 0.2 km^2) used on average with the *MNR* method to estimate the standing volume of forest sample units having, in this case, dimensions of approximately 3000 km^2. This represents a ratio of 0.007 %, which is (0.2 km^2/3000 km^2) × 100, of sampled plot area compared to the total area of the sampled unit. Thus, the ratio of total sampling plot area over the total area sampled is more than 500 times larger for the *ROAD* volume estimation method than it is for the *MNR* method. Note that this is not a criticism of the *MNR* method in general. The *MNR* method is designed to be accurate over a large territory and cannot possibly cover a given cut-block area with the intensity of the *ROAD* sample.

As indicated in Table 11, the random block analysis reveals that there is no significant difference ($p = 0.1501$) between the wood volume per cut-block estimated using the proposed *ROAD* method, the measurement of trees cut along the road right-of-way, and the *MEASURED* volume after the harvest of studied cut-blocks. This means that the null hypothesis, that the means of both *MEASURED* and *ROAD* methods are not different is accepted when using a probability level of 5 % error.

Table 12. Sampled area ratio for *ROAD* and *STATIFIED* methods compared to totalstudied cut-block area.

Site	Sampled area (ha)	Cut-block area (ha)	Percent sampled (%)
1	16.8	588	3.0
2	33.6	840	4.0
3	36.6	942	4.0
Total	87.0	2370	3.7

5.3 Comparison between *MEASURED* and *STRATIFIED* Methods

The third method, *STRATIFIED*, uses exactly the same tree measurements as those of the *ROAD* method to evaluate the wood volume inside each cut-block adjacent to forest roads. In theory, however, it should be possible to obtain better volume estimation reliability per cut-block by dividing the sample into strata of relatively homogeneous forest composition. In fact, Neyman (1934), referred to in Cochran (1977), has demonstrated that samples taken within relatively homogeneous strata generate, in general, smaller variances. Thus, the sum of these individual strata variances is less than the variance of a single large stratum of heterogeneous content.

Since a forest stand is defined as being the smallest forest cartographic unit identifiable from an aerial photograph (minimum 4 ha from a 1:15 000 photographs in Quebec), it would be reasonable to think that one would obtain more reliable cut-block volume estimations when the road sampling is *STRATIFIED* at each forest stand limit than with the *ROAD* method within which no sampling stratification is done. According to Table 10, the total volume of all twelve cut-blocks estimated with the *STRATIFIED* method (187 045 m^3) is on average 5 % smaller than the *MEASURED* volume (197 531 m^3). This difference is clearly smaller than the *ROAD* and *MNR* methods, which had respective average differences of 19 % and 30 %. Moreover, the mean squared errors for these differences (Table 11) are smallest, indicating the greatest precision.

Positive and negative differences are observed for all three studied sites. As with the *ROAD* method, the major potential statistical problem related to the application of the *STRATIFIED* method lies in the fact that the sampling is not really performed at random. All sampled trees come from the road right-of-way, which itself is not located at random as discussed earlier. Again, however, it appears that the high intensity of the sample may have overcome any potential bias.

This absence of cut-block systematic overestimation bias is probably explained by the fact that, on average, the area represented by stands which were sampled (i.e., those crossed by the road) represents more than 80 % of the total cut-block area, and the sampling was fairly intense relative to the *MNR* method. Since each stand represents a relatively homogeneous forest unit, the road-sampling has a very strong level of representation for adjacent cut-blocks, especially when skidding distances do not exceed 300 meters. This can be visualised from Fig. 11, which shows a great proportion of stands crossed by the road-sampling (stands colored in grey) compared to the total cut-block area.

According to the results of the random block statistical analysis, illustrated in Table 11, there is no significant difference ($p = 0.6824$) between the mean estimated wood volume obtained using the *STRATIFIED* road-sampling method and the mean *MEASURED* volume after harvest of all twelve cut-blocks. Thus, the null hypothesis that the means of both the *MEASURED* and *STRATIFIED* methods are similar is accepted when a probability level of 5 % error is used.

5.4 Overall ANOVA Block Effect

The block effect in Table 11 simply means that there was a significant difference ($p = 0.0001$) between wood volume of each cut-block. This volume variation can be explained by the fact that cut-block areas vary greatly (from 104 ha to 367 ha) which generated great variation of the wood volume per cut-block (from 6697 m^3 to 42 178 m^3).

5.5 Economical Considerations

The statistical analysis comparing the three methods estimating the wood volume per cut-block against the *MEASURED* volume after harvest reveals an increasing level of reliability for the *MNR*, *ROAD* and *STRATIFIED* method, respectively. What remains is to compare the costs associated with the implementation of each method, in order to better identify the possible range of applications for each method and to understand what the increase in accuracy and precision will cost an eventual user.

5.5.1 Implementation Costs for the MNR Method

Stock tables associated with the *MNR* decennial inventory program have been developed mainly for applications involving one or more sampling units in their entirety, although current forest practices make extensive use of these over much smaller areas such as cut-blocks or forest stands. However, the present study has demonstrated that it is inappropriate to use *MNR* stock tables to estimate stand volumes for much smaller areas than the original sampling unit even though this is a fairly common practice in Quebec. No additional costs are associated with the use of the *MNR* method since it is the present conventional way of estimating cut-block volumes. If the *MNR* stock tables are meant to remain the main source of information for annual and 5-yr forest planning, it is advisable to increase their level of precision locally. A larger number of sample plots per sampling unit would be the most obvious solution to achieve greater precision associated with *MNR* volume tables.

However, Beaulieu (1994) has shown that even a four-fold increase in samples yields a relatively small improvement in precision for individual grouped strata. The major constraint limiting the forest sampling ratio for the MNR decennial inventory program is strictly economical. With present inventory methods, a greater sampling ratio would not be feasible within the prevailing economical context. Moreover, even if an increase in sampling were feasible, Beaulieu (1994) has shown that other less costly solutions should be investigated to increase the local reliability of *MNR* stock tables thereby reducing differences between measured cut-block volumes after harvest and those estimated using the *MNR* method. More homogeneous sampling unit stratification for forest inventory, improved computerised technologies to aid photo-interpretation, and forest mapping might be possible solutions to achieve greater stock table reliability without causing a prohibitive increase in data collection costs.

Relative to the costs of the *MNR* method in its present form, there may be ways that existing costs can be decreased. Calculation of forest stand areas within each cut-block can be performed much more easily with GIS tools than with conventional manual methods (i.e., dot grids), especially if the area scheduled for harvest is large. Thus costs related to the application of the *MNR* method to evaluate wood volume within cut-blocks should include the use of GIS technology to simplify the calculation of cut-block areas.

Considering the fact that most logging companies operating in the province of Quebec are equipped with GPS positioning tools, it is now becoming a more common practice to achieve greater reliability for road and cut-block locations on forest maps. Although actual GPS technology requires some improvement for use under forest cover, it remains possible to use this geomatic tool to position roads and cut-blocks with precision levels that largely satisfy such needs.

5.5.2 Implementation Costs for the ROAD Method

The *ROAD* forest harvesting inventory method analysed in this study was shown to be advantageous economically with its low application costs. In fact, the scaling of logs harvested along the road right-of-way is a task that is performed within the normal course of forest operations. The additional work required to implement the *ROAD* method is mainly concentrated at the level of the planning and control of scaling operations of trees harvested along the road right-of-way. Road scaling must be executed such that collected tree measurements are associated with the proper roads or cut-blocks. The measurements of all stems harvested along the road right-of-way must be included in the road-sampling, without ignoring some portion of the road where log-scaling could be attributed to adjacent cut-blocks. Note that while this involves relatively small additional planning and control costs for road construction, it completely eliminates the need for costly circular sample plots for standard forest harvesting inventory. With a reported averaged cost of 300 $CAN per sample plot (Dorais 1997), there would appear to be a net cost-savings.

As far as cut-block area calculations are concerned, it is not necessary to use GIS and GPS tools to implement the *ROAD* method. Although the use of GIS eases the calculation of mapped forest areas and GPS provides more accurate road location, these geomatic tools are not indispensable to estimate the wood volume inside cut-blocks located beside a logging road with the *ROAD* method since, in general, there are few cut-blocks per road (less than twelve on average) and each cut-block covers a relatively large area (approximately 50 ha to 100 ha). The *ROAD* method is then affordable even for forest enterprises with relatively small budgets where GIS or GPS equipment is not available. The only direct costs associated with the implementation of the *ROAD* method are reduced to the time dedicated to accurate measurements of the total road right-of-way length and average width. Time dedicated to road right-of-way log scaling compilation, along with cut-block area calculations, are part of normal operations and should not be associated with the implementation of the *ROAD* method. When road right-of-way area and wood volume are known, it takes only few hours to estimate the volume of adjacent cut-blocks with the *ROAD* method.

For the *ROAD* method, it would be preferable to use stem-by-stem measurement technique where each tree, harvested along the road right-of-way and piled along the roadside, has its butt diameter recorded as was done in this study. This technique provides better control over road right-of-way log scaling information, as opposed to weight-scaling methods, where no individual stems measurement are recorded in the forest. Instead, all logging truck loads are recorded at the mill's scale. Butt diameter scaling is only collected from all stems of few sampled logging trucks (selected at random), to obtain a volume per weight estimate applicable to specific harvest sectors. It would be rather difficult to identify and measure at the mill's scale all truck loads transporting logs that were harvested on a specific road right-of-way, since most mills have several trucks coming from several harvesting sites. For this study, the butt diameter of all logs were measured individually in the forest.

If a weight-scaling method was used to calculate the wood volume along the road right-of-way, it would be necessary to implement a method for identifying at the mill's scale all truck loads transporting logs from a specific road right-of-way so that all these logs be measured and compiled independently from other incoming trucks. For example, a truck driver may receive instructions such as: always record the logging road and harvest sector number on transportation sheets when logs are loaded from piles along road right-of-ways. Moreover, experiments would be needed to verify if the *ROAD* method with weight-scaling provides cut-block volume estimations which differ significantly from after-harvest measurements.

5.5.3 *Implementation Costs for the STRATIFIED Method*

Similar to the *ROAD* method, the practical implementation of the *STRATIFIED* method requires good planning and control over road right-of-way log scaling operations. Contrary to the *ROAD* method however, the *STRATIFIED* method is greatly facilitated by the use of GPS equipment, for accurate positioning of forest roads, and GIS, to simplify the numerous calculations of forest stand areas adjacent to the logging road. Although most large-scale North American forest enterprises are already equipped with such geomatic tools, it would be difficult to justify purchasing or renting GIS and GPS equipment solely for the purpose of estimating wood volume of blocks scheduled for harvest with the *STRATIFIED* method. However, those forest enterprises which currently use these geomatic tools already have most of the information and technology needed to apply the *STRATIFIED* method. In fact, most geomatised forest enterprises are using digitized forest maps which include areas of all stands in the forest. Thus, to determine the area of each forest stand within each scheduled cut-block, one simply needs to overlay cut-block polygons on the forest map.

The additional costs (over the currently used *MNR* method) directly related to the application of the *STRATIFIED* method are concentrated on the measurements of the road right-of-way area located within each forest stand. This measurement task involves time investments for:

- GPS positioning of each forest stand limit intersecting the road right-of-way,
- identification of forest stand limits with flagging,
- marking on flagging or log piles with the distance between the beginning of the road right-of-way and the forest stand limits,
- measurement of the road right-of-way width at the start of each stand, and
- compilation of log scaling data for each forest stand to obtain the estimated wood volume per hectare per stand, while dividing by the area of each forest stand within the road right-of-way limits.

The use of the *STRATIFIED* method could be improved by substituting the manual scaling of each piled log by automated computerised log diameter and length measurements, such as with a data capture device installed on the felling head mechanism. More than 80 % of trees harvested in Quebec are cut with mecanical felling heads instead of portable chain saws. Some automated measuring devices already exist commercially, mostly on single and double grip harvesters and processors (Domingue 1994). The cost of these instruments is fairly expensive, ranging from 10 000 US $ to 20 000 US $, and must be handled with care due to their fragility. Nonetheless, equipping a forest harvester with an automated scaling device and then subsequently installing a GPS on the harvester could provide relatively accurate wood volume data associated with their respective stump location for each forest stand crossed by the road right-of-way. What would remain would be to calculate the total wood volume in forest stands adjacent to the road right-of-way divide by the total stand area within the road right-of-way, and use this ratio for the remaing area of the same forest stand located with the scheduled cut-block. This can be done with a computer.

6 Conclusion and Recommendations

The main objective of this research project was to experiment with two forest harvesting inventory methods which are relatively easy to implement and involve low additional costs. These two methods are aimed primarily at estimating wood volumes within cut-blocks adjacent to a road right-of-way with greater accuracy than with conventional methods. The first method, *ROAD*, uses the total wood volume measured after harvest of the road right-of-way, divided by the total road right-of-way area to obtain an average volume per hectare. This volume per hectare is then multiplied by the area of the scheduled cut-blocks adjacent to the road to obtain an estimate of the total wood volume per cut-block. This method was tested over twelve cut-blocks having a total forest area of 2370 hectares. The estimated cut-block volume with the *ROAD* method was compared with the measured wood volume after harvest of all twelve studied cut-blocks.

The total volume of all 12 cut-blocks with the *ROAD* method (160 105 m^3) was 19 % less than the *MEASURED* volume after harvest (197 531 m^3). As shown on Fig. 13, the difference between the estimated *ROAD* volume and the *MEASURED* volume after cut ranged from –41 % to 10 % for all 12 cut-blocks. Furthermore, the statistical analysis comparing both *ROAD* and *MEASURED* volumes for each cut-blocks has shown that the difference between the means of both datasets was not significant at a probability level of 95 %. It is then possible to conclude that the *ROAD* method is a good way to estimate cut-block volume fairly shortly after road right-of-way harvest and before logging operations of adjacent cut-blocks, provided that it is applied within conditions similar to those examined in this study. Under such conditions it is likely that the differences between estimated and measured volumes will be in the order of 20 %.

The second method, *STRATIFIED*, is similar to the *ROAD* method with the difference being that the road-sampling is stratified at the boundaries of each forest stand crossed by the road right-of-way. Although this method requires more time and instrumentation to be implemented, the total wood volume of the same 12 cut-blocks was estimated with much greater accuracy and precision with the *STRATIFIED* method (187 045 m^3) than with *ROAD* method, and was only 5 % less than the *MEASURED* volume after harvest. The difference between the *STRATIFIED* estimation and the *MEASURED* volume after harvest ranged from –36 % to 23 % for all twelve studied cut-blocks. The statistical analysis which compared the *STRATIFIED* and *MEASURED* volumes for each cut-block also revealed that there was no significant difference between both datasets when using a probability level of 95 %. It could then be concluded that the *STRATIFIED* method may be more suitable for cut-block volume estimations that would require less than 5 % difference between estimated and harvested volumes.

Nevertheless, to apply the method elsewhere it would be important to respect similar conditions to those encountered during this experimentation. Generally, the twelve studied blocks were mainly composed of conifers species growing on relatively flat ground. More experimentation would be needed to investigate the possibility of using both proposed cut-block volume estimation methods, *ROAD* and *STRATIFIED*, to mixed or deciduous forests on greater slopes. Such experimentation could help to verify the hypothesis that tree species and ground slopes have little influence on cut-block volume estimation with *ROAD* and *STRATIFIED* methods. Rather, the homogeneity of the sampled cut-blocks and the ratio of forest stand area crossed by the logging road over the total cut-block area may have more influence.

Although cut-block volume estimations for both studied methods (*ROAD* and *STRATIFIED*) proved to be more accurate and statistically reliable than conventional methods using *MNR* stock tables, the experimental results are applicable specifically to relatively small localised forest areas compared to the entire sampling unit. Furthermore, the road-sampling as proposed in this study would be difficult to integrate with conventional forest management sampling since the sample plot size is not constant. Nevertheless, following the general trend to geomatisation of forest information, the *STRATIFIED* inventory method revealed to be a reliable, low cost method to accumulate valuable, specific, localised knowledge of managed territories. At the end of a forest rotation, the *STRATIFIED* road inventory would have collected information on most of the harvestable forest stands over most of the managed territory. Since this information is geomatized, it would be possible to verify that the growth of each inventoried forest stand using the *STRATIFIED* method is comparable to the measured volumes within same forest stands at different points in time.

With the development of GIS/GPS technologies, the proposed method involving clearing for forest roads and marking of trees can be replaced by automatic log measuring devices and GPS installed on felling machines. The results from this study demonstrates that site specific data such as road right-of way volume are worth collecting to enhance the quality of input data used for forest planning.

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