Sampling design and precision of basal area growth and stand structure in uneven-aged northern hardwoods

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ABSTRACT

Sampling design (distribution of plots, plot sizes, and number of sample plots) is an important consideration in planning a field study since it determines the bias and precision of information obtained. In this study, we evaluated the effects of two commonly used sampling designs on the precision of estimates of means related to stand basal area, considered as a whole or by diameter class, and 10-year growth components, in six 2-ha areas located in uneven-aged northern hardwood stands of Quebec managed under selection cutting. The study compares random and systematic sampling designs of one to 10 plots, with plots varying in size from 0.05 ha to 1.25 ha. Increasing the total area sampled (i.e., sampling area) in a stand from 0.05 ha to about 0.25 ha resulted in large precision gains; further increases in sampling area had more limited effects on precision. A sampling area of at least 0.5 ha would be required to obtain a minimally acceptable precision in estimating means of total basal area and 10-year growth components. A much larger sampling area would be required to obtain sufficient precision in estimating mean basal area by diameter class, often required to study stand structure. Precision can also be increased by dividing the sampling area into several smaller plots rather than using a single large plot. We found no clear difference in the results between random and systematic selection approaches.

Key words: sample plot, stand structure, plot size, selection cutting, sampling area, uneven-aged, sampling design

RÉSUMÉ

Le plan d'échantillonnage (répartition, taille et nombre de placettes) est un élément important à prendre en compte lors de la planification d'une étude en sylviculture, puisque celui-ci détermine les biais et la précision de l'information obtenue. La présente étude a permis d'évaluer les effets de deux plans d'échantillonnage couramment utilisés sur la précision des valeurs moyennes estimées de la surface terrière du peuplement, prise dans son ensemble ou dans des classes de diamètre, ainsi que des composantes de l'accroissement décennal, dans six aires de deux hectares situées dans des peuplements feuillus de structure inéquienne et aménagés par la coupe de jardinage. Les plans d'échantillonnage étudiés comprenaient des distributions aléatoires et systématiques, avec une à 10 placettes dont la taille pouvait varier de 0,05 ha à 1,25 ha. Les résultats indiquent que dans l'intervalle de 0,05 ha à 0,25 ha, l'augmentation de la superficie échantillonnée dans un peuplement mène à de très forts gains de précision dans les estimés des moyennes. Des augmentations supplémentaires mènent à des gains plus faibles et de moindre importance. Aussi, les résultats indiquent qu'il serait préférable d'échantillonner au moins 0,5 ha pour atteindre un degré de précision minimalement acceptable pour estimer les moyennes de la surface terrière et des composantes de l'accroissement décennal du peuplement. Une superficie beaucoup plus grande est nécessaire pour estimer avec précision la surface terrière moyenne selon des classes de diamètre, afin d'étudier la structure du peuplement. La précision peut aussi être améliorée en subdivisant la superficie échantillonnée en plusieurs placettes de plus petite taille, plutôt qu'en échantillonnant une seule placette plus grande. De plus, il n'y a pas de différence marquée entre les résultats des distributions aléatoires et systématiques.

Mots-clés : placette, placette-échantillon, structure du peuplement, taille de placette, coupe de jardinage, superficie échantillonnée, inéquienne, plan d'échantillonnage

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Introduction

Designing an appropriate sample (i.e., the size, number, and locations of sample plots) can be challenging in a forest stand, especially when it has a complex structure or when long-term variables, such as growth components, are the objects of study. Samples should be designed to obtain a precise estimate, in relation to the objectives, at the lowest possible cost. The number and size of sample plots influence variability (Shiver and Borders 1996, Bellehumeur *et al.* 1997, Avery and Burkhart 2002) and the frequency distribution of response variables (Smith and Ker 1957, Ghent 1963). Formulas to estimate required sampling intensity and area from a known variance are documented in most forest measurements textbooks (e.g., Avery and Burkhart 2002). However, they require an estimate of population variance, which may be difficult to obtain for variables such as net growth, tree mortality or stand structure in complex stands.

Most statistical procedures also assume a sampling design with known probability. Of these, a simple random sampling design (hereafter called just "random sampling") with equal probability of selection is the simplest, although systematic sampling, often with a grid layout of plots, is more popular in forestry. The latter appears to be a more representative design, in that the sample provides an even distribution of plots over space and, until the advent of global positioning systems (GPS), it was much easier to conduct on the ground (Avery and Burkhart 2002). However, an unbiased estimate of variance cannot generally be obtained for a systematic or a grid design; biased estimators can be calculated using formulae designed for simple random sampling (Lohr 1999).

In the study of selection cuttings in uneven-aged northern hardwoods, most research studies are based on experiments addressing classical forest attributes, such as basal area and growth (Table 1). For these experiments, the number of replicates of each treatment and the size of the experimental unit (i.e., plot size) were variable, ranging from one 0.13-ha to 0.5-ha plot to as many as 17 0.08-ha plots. In experiments, treatments (i.e., type of forest harvest) are then randomly assigned to the experimental unit. Generally, the power to detect differences using these designs was not evaluated prior to or following the establishment of the experiment. In many cases, differences in net stand basal area growth between treatments were not detected. This may have resulted from low power of the statistical tests, due to the small number of replicates and high plot-to-plot variability given small experimental units, rather than the sizes of differences between treatments. Power analysis based on the sizes of differences that are of practical importance is now more commonly done; as a result, any differences that are detected will have practical meaning, or, conversely, failure to reject the null hypothesis means that there are no differences of practical meaning.

As an alternative to experimental design, impacts of selection harvests may be evaluated by sampling a number of stands with different harvest levels. Unlike experimental design, the treatments (i.e., harvest levels) are not randomly assigned to the stands. However, as with experimental design, sampling should be designed to obtain a desired level of precision for the estimated means of various growth components within a stand. The total sampling area (i.e., number of plots × plot size, hereafter termed just "sampling area") affects the observation of stand structure, as noted by Rubin *et al.* (2006) in their review. Janowiak *et al.* (2008) reported that the use of 0.05-ha plots for northern hardwood stands in Michigan yielded inconsistent results in capturing the shape of a diam-

Table 1. Designs used in some experimental studies with selection cutting in northern hardwoods

Study	Number of replicates and sampling area (ha) per replicate	Total sampling area (ha) per treatment	Remarks	References
Argonne Exp. For., Wisconsin	3 rep. 5 plots × 0.04 = 0.20	0.61	15-year net growth varied from 0.53 to 0.74 m^2 ha^{-1} yr^{-1} for the six treatments. No significant differences were detected.	Erdmann and Oberg (1973)
Bartlett Exp. For., New Hampshire	4 rep. One plot : 0.13	0.53	A stepwise regression analysis was used to develop significant relationships between 10-year growth components and 12 stand structures.	Solomon (1977)
Upper Peninsula Exp. For., Michigan	3 rep. 10 to 17 plots × 0.08 = 0.81 to 1.38	2.43 to 4.13	5- to 20-year net growth varied from 0.38 to 0.51 m^2 ha^{-1} yr^{-1} for the 10 treatments (stocking levels and cutting cycles). No significant differences were detected.	Crow *et al.* (1981)
Network of experimental blocks in Québec	5 rep. One plot: 0.5	2.5	10-year net growth varied from 0.15 to 0.33 m^2 ha^{-1} yr^{-1} for the two treatments. No significant differences were detected.	Bédard and Majcen (2001)
	8 rep. One plot: 0.5	4.0	10-year net growth varied from 0.14 to 0.35 m^2 ha^{-1} yr^{-1} for the two treatments. Significant differences were detected.	Bédard and Majcen (2003)

eter distribution, as opposed to larger plots (0.2–1.6 ha). Gray (2003) and Zenner and Peck (2009) also examined the area required for sampling stand structure attributes in conifer stands, but not including diameter distribution.

The objective of this study was to evaluate the precision of different sampling designs on estimates of means for stand growth components, total basal area and basal area per diameter class, for uneven-aged northern hardwood stands managed under selection cutting. The study also offers an opportunity to publish standard deviation estimates for growth components that are essential for sampling design.

Methods

Study sites

The data were collected between 1988 and 1993, in six uneven-aged stands established in southern Quebec (Canada) that were subject to selection cutting (Fig. 1). These stands are distributed in five geographic sectors, with two of them located in the Duchesnay (DU) sector. All five sectors are located in the Great Lakes – St. Lawrence Forest Region (Rowe 1972), and according to Grandtner (1966), are part of the sugar maple (*Acer saccharum* Marsh.)–yellow birch (*Betula alleghaniensis* Britt.) bioclimatic domain. However, the two eastern sectors are located in the yellow birch–balsam fir (*Abies balsamea* [L.] Mill.) bioclimatic domain, according to Saucier *et al.* (1998).

The Sainte-Véronique (SV), Lac à la Truite (LT), Ruisseau Bouleau (BO) and Duchesnay 1991 (DU91) stands are sugar maple–yellow birch–American beech (*Fagus grandifolia* Ehrh.) forest types, while the Temiscaming (TE) and Duchesnay 1993 (DU93) stands are typical sugar maple-yellow birch forest types. A detailed ecological description of these forest types appears in Majcen *et al.* (1984).

Tree marking in preparation for cutting was carried out using the method described in Majcen *et al.* (1990), using a theoretical diameter distribution, which depended on a constant q-ratio, a given basal area, and a maximum diameter outside bark at breast height (i.e., dbh, 1.3 m above ground). Tree marking targeted high-risk trees, which were likely to die or to lose quality during the next cutting cycle. However, the best possible compromise was sought between the desired number of residual trees and tree health, because these stands were previously high-graded at least once by some form of diameter-limit cutting. As a result, few trees remained that were larger than the maximum target dbh, which was approximately 58 cm.

Data collection

One rectangular, 2-ha area (100 m × 200 m) was established in each of the six stands. These 2-ha areas were surrounded by a 25-m buffer strip of a similar forest type, which was similarly treated. Thus, the 2-ha area edges did not correspond to stand edges. In all 2-ha areas, trees with dbh 9.1 cm and larger along a predefined axis were numbered and tallied within 2-cm classes using a calliper. This was done before cutting, immediately after cutting, and 10 years later. Stems were mapped at the 10-year remeasurement, while it was still possible to locate and identify stumps of the cut and dead trees.

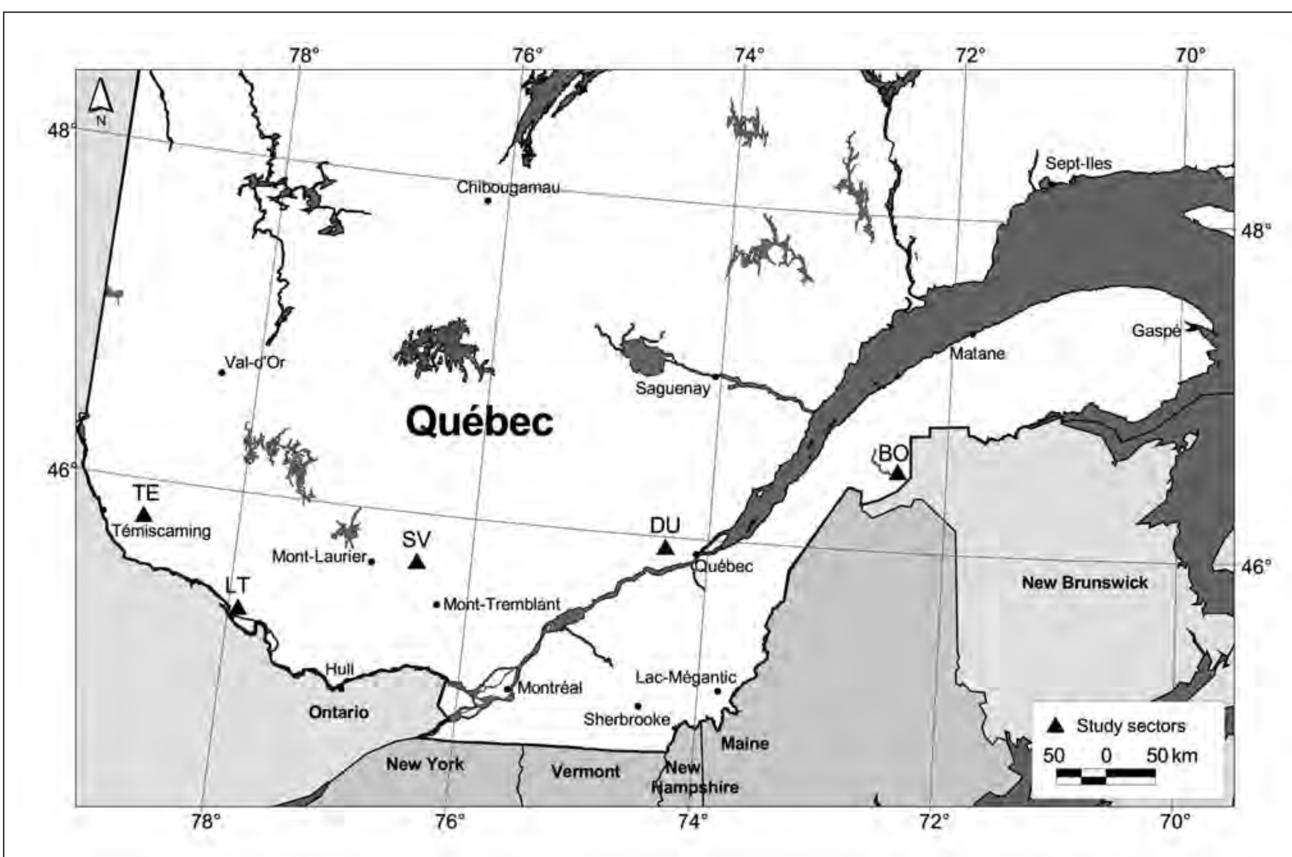

Fig. 1. Locations of the five study sectors (▲).

These six 2-ha areas were considered as a complete enumeration of all trees in a stand (i.e., a population) in the sampling design comparisons.

The variables of interest in this study were the initial total basal area (m² ha^{-1}), the initial basal area per dbh class, the residual basal area immediately after selection cutting, and the following 10-year growth components (after Erdmann and Oberg 1973): survivor growth, ingrowth, gross growth, mortality and net growth (m² ha^{-1} yr^{-1}). Stand structure was represented using the basal area for four grouped dbh classes: pole-size trees (10–22 cm dbh), small sawlog-size trees (24–38 cm dbh), medium sawlog-size trees (40–48 cm dbh), and large sawlog-size trees (50 cm dbh and larger). Stand basal area and structure for each of the six 2-ha areas are shown in Tables 2 and 3.

Analyses

To assess stand-level sampling designs, a number of designs were simulated varying numbers of plots, plot size, and plot selection method. For all sampling designs, square plots were used and the sampling design was repeated 1000 times. First, the effect of plot size was evaluated using random sampling with single plots measuring 0.05 ha, 0.1 ha, 0.25 ha, 0.5 ha, 0.75 ha, 1.0 ha or 1.25 ha. The center of the simulated plot was randomly located within the 2-ha area. Mirage edge correction was used to ensure an equal sampling probability for all trees, while correcting for edge effects (Gregoire 1982, Ducey *et al.* 2001). Second, the effect of sampling a fixed area using a cluster of plots (0.05 ha or 0.1 ha each) was evaluated with five or 10 plots totalling either 0.25 ha or 0.5 ha. These five or 10 plots were aggregated before calculating the sampling error. Plots were chosen using random sampling without replacement, and then repeated using systematic sampling with a random start. In the latter case, plots were evenly spaced and oriented along the longest plot axis (i.e., the 200-m direction of the 2-ha area). Again, mirage edge correction was used to ensure an equal sampling probability for all trees, while correcting for edge effects.

The frequency distribution of the 1000 sampling replicates for each stand, sampling design, and variable was described by calculating the following statistics: 2.5th percentile, 97.5th percentile and standard deviation(s). Precision was estimated using the half-width of the 95% confidence interval (E), which was calculated as half the difference between the 2.5th and 97.5th percentiles.

Estimates of standard deviation are useful for estimating the sample size (n) required to reach a desired standard of precision (E), either outside the sampled study range (>1.25 ha) or for a different error threshold ($\alpha \neq 5\%$). This estimate was calculated using the following formula (for an infinite or large population, Avery and Burkhart 2002):

$$[1] \qquad n = \left(\frac{t_{\alpha/2,n-1} S}{E} \right)^2$$

where $t_{\alpha/2,n-1}$ is obtained from a Student distribution, using the desired probability (α) and n-1 degrees of freedom and S is the estimated standard deviation.

We computed the number of stands for which a higher (E_H) and a lower (E_L) set of precision standards were met, for each studied sampling design and variable. The higher precision level was set to 0.05 m² ha^{-1} yr^{-1} for survivor growth, gross growth, net growth and mortality, to 0.01 m² ha^{-1} yr^{-1} for ingrowth and to 2 m² ha^{-1} for initial and residual basal areas (at α = 0.05). It was set to 0.4 m² ha^{-1}, 0.6 m² ha^{-1}, 0.5 m² ha^{-1}and 0.5 m² ha^{-1} for the basal area of pole-size, small sawlog-size, medium sawlog-size and large sawlog-size trees, respectively. These standards are derived from the standard for the initial basal area (2 m² ha^{-1}) and the approximate proportion of each dbh class (20%, 30%, 25% and 25%, respectively). A precision of ± 0.05 m² ha^{-1} yr^{-1} for survivor, gross and net growth corresponds to the production of ± 1 m² ha^{-1} over a 20-year cutting cycle. This degree of precision may be required to detect fairly large differences in growth between selection cuts, which can lead to a change in the cutting cycle of about five

Table 2. Total basal area and periodic growth of the 2-ha areas

	Basal area (m² ha^{-1})		10-year growth components (m² ha^{-1} yr^{-1})				
Stand	**Initial**	**Residual**	**Survivor**	**Ingrowth**	**Gross**	**Mortality**	**Net**
Ruisseau Bouleau (BO)	28.4	19.4	0.48	0.10	0.58	0.16	0.42
Duchesnay 1992 (DU92)	24.7	18.7	0.32	0.05	0.36	0.13	0.23
Duchesnay 1993 (DU93)	25.7	19.0	0.39	0.10	0.49	0.13	0.36
Lac à la Truite (LT)	25.6	17.5	0.36	0.05	0.41	0.19	0.22
Ste. Véronique (SV)	28.2	20.1	0.34	0.04	0.38	0.15	0.23
Témiscaming (TE)	25.0	17.5	0.40	0.07	0.46	0.07	0.40
Mean	26.3	18.7	0.38	0.07	0.45	0.14	0.31

Table 3. Initial number of trees (n ha^{-1}) and basal area per dbh class in the 2-ha areas

Dbh class (cm)	Ruisseau Bouleau		Duchesnay 1992		Duchesnay 1993		Lac à la Truite		Ste. Véronique		Témiscaming	
	n ha^{-1}	m² ha^{-1}	n ha^{-1}	m² ha^{-1}	n ha^{-1}	m² ha^{-1}	n ha^{-1}	m² ha^{-1}	n ha^{-1}	m² ha^{-1}	n ha^{-1}	m² ha^{-1}
10–22	343	6.3	351	6.6	261	4.2	172	3.0	225	4.4	258	4.0
24–38	156	11.0	130	9.0	122	9.3	90	6.9	137	9.7	86	6.4
40–48	31	4.6	23	3.5	55	8.1	50	7.4	37	5.6	35	5.4
50 +	25	6.4	23	5.5	17	4.1	33	8.2	33	8.6	34	9.3
Total	554	28.4	527	24.7	455	25.7	346	25.6	432	28.2	414	25.0

years. A precision for total basal area of ± 2 m^2 ha^{-1} represents an error of 7% to 11% of the usual basal area of these stands. The lower set of precision standards was set to twice the standards of the higher one (i.e., 0.10 m^2 ha^{-1} yr^{-1}, 0.02 m^2 ha^{-1} yr^{-1}, 4 m^2 ha^{-1}, 0.8 m^2 ha^{-1}, 1.2 m^2 ha^{-1}, 1.0 m^2 ha^{-1}, and 1.0 m^2 ha^{-1}, respectively).

Results

Fig. 2 illustrates the relationships between sample plot area (ha) and the half-width of the 95% confidence intervals (E) of the 10-year growth components, as well as basal areas (BA). These results show the effects of random selection with one plot. The half-width of the 95% confidence interval for the 11 basal area variables decreases sharply with sampling area, from 0.05 ha to 0.25 ha, then more gently for larger sampling areas. Most curves are close to each other for the six stands. The effect of using five or 10 plots, chosen randomly or in a systematic cluster, are summarized in Fig. 3. Splitting a fixed sampling area into five or 10 plots slightly reduced the half-width of the 95% confidence intervals for the mean of growth variables. There was no apparent difference between random and systematic designs. The ranges of the corresponding standard deviations are reported in Appendix A. Table 4 summarizes results for total basal area and growth components, in terms of precision standards. None of the precision standards were met for sampling areas below 0.25 ha. The higher precision standard was rarely met. None of the precision standards were met for the basal area for each broad dbh class (stand structure).

Total basal area

For some stands, the threshold for estimating mean initial and residual basal area with the lower precision standards (± 4 m^2 ha^{-1}) was met using a sampling area of at least 0.5 ha (Table 4). The precision of estimates is slightly improved by dividing this area into five or 10 plots (Fig. 3c). In most cases, the variability of basal area changes only very slightly after a first selection cutting (Fig. 2f,g), as shown by the similar curves for the half-width of the 95% confidence intervals, for both initial and residual mean basal areas. The only exceptions were the Duchesnay 1993 and Lac à la Truite stands, where the curves were slightly lower for residual basal area, compared to initial basal area.

Basal area growth components

The trends observed for survivor and gross growth were similar because the values of the former represent about 85% of the latter (Table 2). In many cases, the lower precision standards were met using at least one 0.5-ha plot (Table 4). More precise estimates were obtained with five or 10 plots or with one larger plot (Fig. 3a). Among the seven basal areas components under study, survivor growth met the precision criteria with the smallest sampling area, closely followed by gross growth.

In some stands, the lower precision standards for ingrowth could be met using a 0.5-ha sampling area, but only if the area was split into five or preferably 10 plots. Otherwise, a larger area was required.

Results for mortality and net growth were similar because the death of only a few large trees generates very high variability within stands, and directly affects variability in net growth. The lower precision standards were met, in many cases, using sampling areas between 0.5 ha to 1.0 ha (Table 4). Once again, estimates for the mean were more precise for designs in which the total area was divided into multiple plots compared to those using a single large plot (Fig. 3b). Variability in mortality and net growth was much higher in the Lac à la Truite stand than the five other stands (Fig. 2d,e and Appendix A). This is explained by the presence of a narrow strip of dead trees (broken and wind-thrown) along the east–west axis of dominant winds.

Stand structure

The thresholds to meet the lower precision standard for estimating mean basal area per dbh class were not met by any sampling area under study, for any stands or sampling design (Fig. 2h,i,j,k). Precision was slightly better when splitting the sampled area into five or 10 plots (Fig. 3d). Values of the half-width of the 95% confidence intervals were less for basal area per dbh class than for total basal area (Fig. 2f). However, absolute values for sampled basal area within each class were also less, which increased relative variability and decreased estimate precision. The variability of the residual basal area per dbh class was generally lower than the initial basal area per dbh class (results not shown).

Discussion

This study illustrates the direct relationships between the precision of estimates for basal area and 10-year growth components and the sampling design in northern hardwood stands having undergone a first selection cutting. Increasing the total sampling area in a stand from 0.05 ha to about 0.25 ha resulted in very large precision gains; the gain in precision from a further increase in sampling area is more linear and limited (Fig. 2, Table 4). Dividing the sampling area into several plots also improves the precision (Fig. 3, Table 4).

In a northern hardwood stand under selection management, a relatively large sampling area is required to obtain precise estimates of means for basal area, 10-year growth components, and diameter structure (Fig. 2, Table 4). Sampling at least 0.5 ha (≥25% of the 2-ha stands) split into 10 plots was required in order to meet most of lower precision standards set; however, this area was not sufficient for estimating mean basal area per dbh class at this level of precision. For studies particularly interested in stand structure, it may be desirable to increase the sample size in order to gain more precision for estimates within dbh classes, especially when the presence of large trees is of concern. The sampling area must be large enough to include sufficient numbers of trees in all classes.

A larger area (≥0.75 ha) split into five to 15 plots could have given better results than those presented in this paper. However, it was not possible to test this hypothesis with our data and methods. Given the 2-ha areas representing each stand, the total stand area was too small to allow random selection of plots covering more than 25% of the area. These 2-ha areas were not designed specifically for this study.

We also simulated random sampling of plots located on a grid of 40 0.05-ha plots. Although these results (not shown) were not obtained with a method comparable to those presented, they support the hypothesis that a total sampling area of 0.75 ha to 1.0 ha, composed of 0.05-ha or 0.1-ha plots,

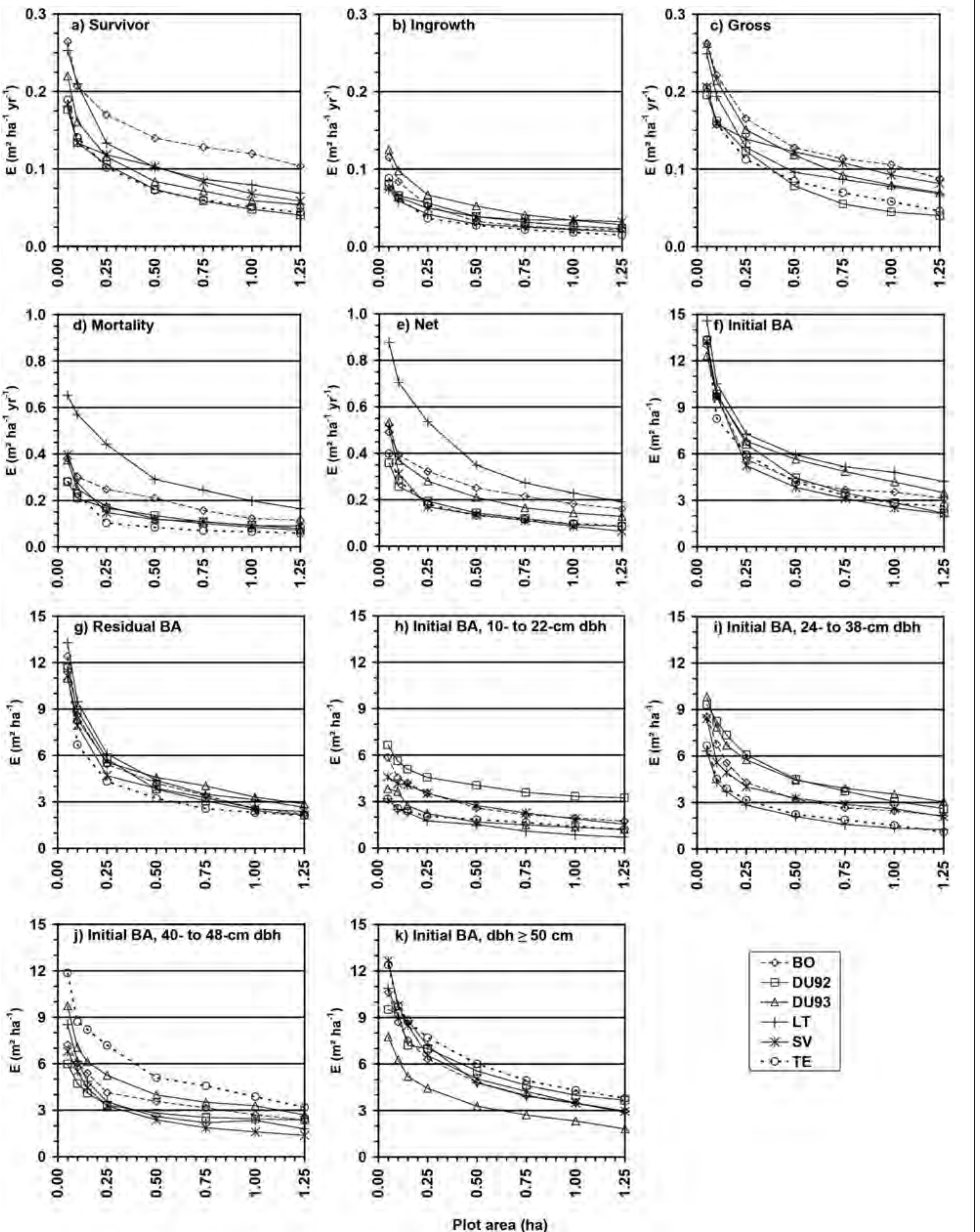

Fig. 2. Relationships between the half-width of the 95% confidence intervals (E) of the 10-year growth components and basal area (BA), and the sample plot area (ha) of the six studied stands. Single plots of various sizes were used in deriving these results.

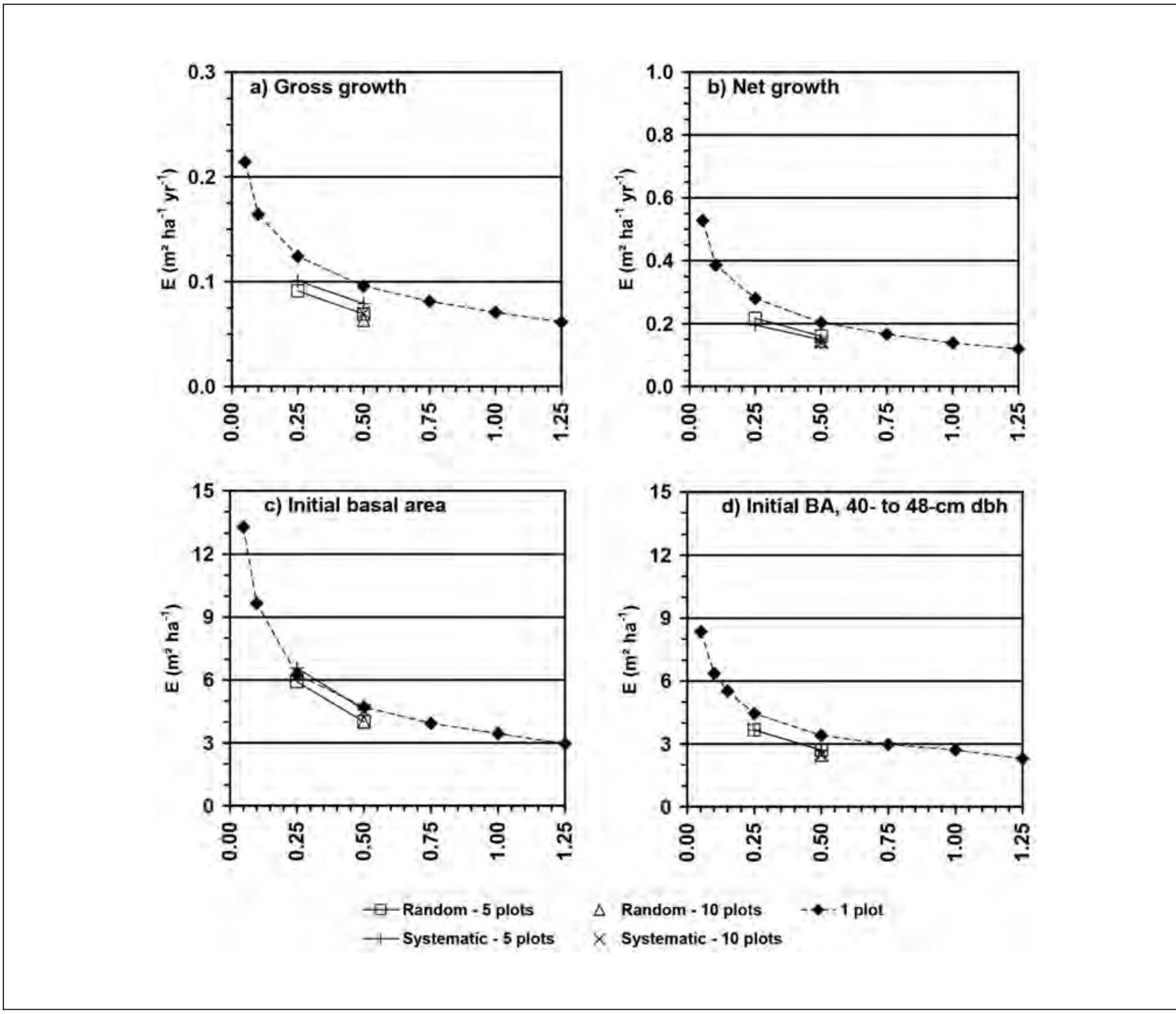

Fig. 3. Relationships between the mean (six stands) half-width of the 95% confidence intervals (E) of gross growth, net growth, initial basal area and initial basal area of medium sawlog-size trees, and the sampling area (ha) of different sampling designs.

could meet the lower precision standards for estimating means of almost any total basal area and growth component in the six studied stands.

The use of a single large plot per stand is slightly less efficient than the use of several smaller plots that sum to the same area for estimates of basal area and 10-year growth components. On one hand, the use of one large plot may emphasize local differences relative to the 2-ha plot mean. However, on the other hand, this effect is reduced by using a relatively large plot (e.g., 0.5 ha) within a 2-ha stand (25% of the stand area). If we had studied larger stands, then the difference between one large plot and several smaller plots might have been more pronounced.

Our results obtained from random sampling designs were similar to those from systematic sampling designs (Table 4). Our results are also consistent with those of Kulow (1966). He observed that plot distribution affected the precision and accuracy of basal area estimates, but not decisively so, because differences varied between stands. However, in another study, Payandeh and Ek (1971) concluded that systematic sampling of basal area should usually perform as well as or better than random sampling. Their observation supports the theories of Lohr (1999). One weakness of our systematic designs was the use of only one linear cluster along the longest plot axis. Consequently, the number of different combinations was limited, and some linear clusters did not appear to be very representative of the 2-ha areas. The use of another systematic design could have produced different results.

The use of 2-cm dbh classes measured with a calliper generated a higher variability in survivor growth than could have been expected using a diameter tape and 1-mm dbh classes. However, in this study, the basal area of survivor growth did not show the largest variations (Fig. 2 and Table 4), especially in terms of relative precision. Moreover, with a relatively large sampling area and a time period of at least 10 years, this variation is thought to mostly average out. To verify this, we calculated the proportion of trees for which the dbh changed over the 10-year period, and compared it to growth results reported for similar stands using 1-mm dbh classes. Only a few trees (13%) did not migrate to a higher dbh class, and

Table 4. Number of stands at which 1) the higher (top) and 2) the lower (bottom) precision standards were met, for a given metric, sampling area (ha) and sampling design

	Design	Random							Random			Systematic		
	No. plots	1							5		10	5		10
Sampling area (ha) Metric	Criteria	0.05	0.10	0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.50	0.25	0.50	0.50
Initial	1) ± 2 m^2 ha^{-1}	–	–	–	–	–	–	–	–	–	–	–	–	–
	2) ± 4 m^2 ha^{-1}	–	–	–	1	4	4	5	–	3	3	–	1	–
Residual	1) ± 2 m^2 ha^{-1}	–	–	–	–	–	–	–	–	–	–	–	–	–
	2) ± 4 m^2 ha^{-1}	–	–	–	3	6	6	6	–	6	6	–	4	6
Survivor	1) ± 0.05 m^2 ha^{-1} yr^{-1}						2	2	–	–	1	–	–	1
	2) ± 0.10 m^2 ha^{-1} yr^{-1}	–	–	1	5	5	5	6	4	6	6	3	5	6
Ingrowth	1) ± 0.01 m^2 ha^{-1} yr^{-1}	–	–	–	–	–	–	1	–	–	–	–	–	–
	2) ± 0.02 m^2 ha^{-1} yr^{-1}	–	–	–	–	1	3	4		1	3		1	3
Gross	1) ± 0.05 m^2 ha^{-1} yr^{-1}	–	–	–	–	–	1	2					1	1
	2) ± 0.10 m^2 ha^{-1} yr^{-1}	–	–	–	3	4	5	6	3	6	6	2	4	4
Mortality	1) ± 0.05 m^2 ha^{-1} yr^{-1}	–	–	–	–	–	–	–	–	–	–	–	–	–
	2) ± 0.10 m^2 ha^{-1} yr^{-1}	–	–	1	1	2	4	4	–	2	2	2	3	3
Net	1) ± 0.05 m^2 ha^{-1} yr^{-1}	–	–	–	–	–	–	–	–	–	–	–	–	–
	2) ± 0.10 m^2 ha^{-1} yr^{-1}	–	–	–	–	–	3	3	–	–	–	–	2	2

most trees (74%) gained 2 or 4 cm. This distribution of dbh growth among 2-cm dbh classes is consistent with the average dbh growth reported for similar stands, which is about 3 cm in 10 years (Bédard and Majcen 2001, 2003). Consequently, this measuring method may not have been a major factor in explaining the high variability in net growth.

The history and structure of the stands may be important contributors to the relatively high variation observed for all stand descriptors. The stands studied are old-growth forests that have undergone at least one diameter-limit cut (high-grading), a few decades preceding the first selection cutting. Many cull and high-risk trees were present among the larger diameter classes when selection cutting was initiated, and it was not possible to remove them all at the time of the first cut. Mortality within these dbh classes is known to be high (Guillemette *et al.* 2008). Because there are only a few large trees per hectare and they make up a significant part of the stand's basal area, a large part of the stand's basal area is removed when they die. Even though tree marking was done with a concern to maintain a relatively uniform basal area within the stands, spatial variability remained high and was comparable to the initial condition (Fig. 2f,g). It was not possible to drastically change the high within-stand variation of basal area in the first cut. There will always remain a large variation in basal area when these stands are observed using a small sampling area. Indeed, the admixture of a few residual large trees (8–21 trees/ha with dbh ≥50 cm), cutting small gaps (50–200 m^2), and many smaller trees, cannot be reproduced exactly on small areas such as the common 0.04-ha plots.

Sampling area has been related to the precision of some basic stand measures (Reich and Arvanitis 1992), diameter distribution (Majcen *et al.* 1985, Grenier *et al.* 1991, Janowiak *et al.* 2008) and structural characteristics (Zenner and Peck 2009). However, none of these studies addressed growth components under uneven-aged management. Nonetheless, there is some consistency about the order of magnitude of the required sampling area between these studies and our results. From seven 3.2-ha plots located in Michigan northern hardwood stands, Janowiak *et al.* (2008) concluded that at least 0.4 ha was required to accurately capture the shape of a diameter distribution, and perhaps a larger area would be required in unmanaged stands. They also reported that the use of 0.05-ha plots yielded inconsistent results, compared to larger plots (0.2 ha, 0.4 ha, 0.8 ha and 1.6 ha). In eight mature managed red pine stands (1.21-ha plots) in Minnesota, Zenner and Peck (2009) reported that commonly used stand descriptors were accurately estimated in plots ≥0.5 ha, while estimating attributes of old stands required larger plot sizes (0.75–1.0 ha). Majcen *et al.* (1985) compared diameter distributions within 22 1-ha plots in Québec northern hardwood stands, and concluded that two to three 0.25-ha plots were required to obtain a distribution that was not significantly different (χ^2 test) from the 1-ha plot.

Grenier *et al.* (1991) concluded that sampling at least 1 ha was required to give a good representation of the population's structure in a 18-ha Québec northern hardwood stand, at a probability level of 90% and with a confidence level of 5% (χ^2 test). However, their work contains some methodological weaknesses. First, they applied the χ^2 test to very small plots (83–1000 m^2), while the stand's diameter distribution included some very large and rare trees (e.g., 70 cm dbh or greater, 1.3 expected trees/ha). The χ^2 test is thought to be inappropriate in the presence of a zero value in one dbh class, or when more than 80% of the dbh classes have expected values smaller than five (Cochran 1954, Yates *et al.* 1999). They inevitably met these situations frequently. Second, they performed the χ^2 test on number of trees (frequencies) per hectare, rather than actual numbers of trees in the sample, which are recommended for the use of χ^2 tests. We tested these both methods with our data and concluded that using per-ha tree frequencies artificially increases the power of the χ^2 test for plots smaller than a hectare (unpublished data).

Conclusions

For the study of one stand (or one replication), our results indicate that a total sampling area of at least 0.5 ha, and preferably a little more, would be required to obtain a minimally acceptable precision of estimates for means of most common stand attributes and 10-year growth components. However, it is preferable to split this area into several plots (five, or preferably 10, in this study) in order to increase precision. If only one large plot is to be used, then it should be larger than 0.5 ha; still, there is a risk for low precision on certain estimates, especially for net growth. A larger sampling area would be required if the objective is to estimate changes in stand structure (basal area by dbh class) or basal area growth by species.

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Appendix A

Table A.1. Minimum (top) and maximum (bottom) standard deviations (m^2 ha^{-1}) for the seven studied stand attributes and the sampling designs for the six stands.

Design		**Random**							**Random**			**Systematic**		
No. plots		**1**							**5**		**10**	**5**		**10**
Sampling area (ha) **Metric Criteria**		**0.05**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**0.25**	**0.50**	**0.50**	**0.25**	**0.50**	**0.50**
Initial basal area		6.58	4.23	2.68	1.94	1.62	1.28	1.16	2.89	1.83	1.84	2.72	1.71	2.00
		7.11	5.06	3.48	2.88	2.62	2.43	2.20	3.23	2.13	2.12	3.79	3.04	2.92
Residual basal area		5.42	3.49	2.23	1.61	1.30	1.11	1.02	2.49	1.53	1.63	2.39	1.36	1.61
		6.67	4.74	3.17	2.35	1.97	1.71	1.51	2.81	1.97	1.83	3.33	2.64	1.90
Survivor		0.089	0.069	0.049	0.038	0.030	0.023	0.021	0.038	0.031	0.026	0.034	0.026	0.024
		0.134	0.107	0.087	0.072	0.066	0.060	0.053	0.056	0.044	0.037	0.075	0.064	0.059
Ingrowth		0.040	0.032	0.019	0.013	0.011	0.009	0.008	0.016	0.012	0.010	0.015	0.012	0.008
		0.064	0.054	0.034	0.026	0.021	0.020	0.019	0.030	0.024	0.022	0.029	0.026	0.021
Gross		0.099	0.074	0.053	0.041	0.032	0.024	0.021	0.041	0.033	0.028	0.035	0.028	0.020
		0.137	0.111	0.081	0.064	0.058	0.054	0.051	0.058	0.046	0.040	0.081	0.068	0.065
Mortality – 5 stands		0.159	0.118	0.066	0.049	0.040	0.034	0.029	0.070	0.043	0.044	0.049	0.030	0.033
		0.222	0.167	0.124	0.090	0.076	0.063	0.058	0.095	0.077	0.065	0.098	0.075	0.069
	LT stand	0.371	0.287	0.204	0.153	0.129	0.113	0.096	0.155	0.121	0.100	0.134	0.096	0.111
Net – 5 stands		0.192	0.139	0.092	0.066	0.053	0.045	0.036	0.082	0.058	0.055	0.056	0.039	0.039
		0.253	0.198	0.152	0.120	0.108	0.093	0.085	0.111	0.092	0.077	0.139	0.115	0.112
	LT stand	0.420	0.330	0.235	0.179	0.147	0.125	0.105	0.176	0.137	0.113	0.139	0.115	0.112
Initial basal areas per dbh class														
	Poles	1.64	1.35	1.27	0.96	0.70	0.51	0.42	0.34	0.72	0.53	0.46	0.50	0.41
		3.24	2.80	2.54	2.40	2.25	2.00	1.91	1.78	1.25	1.03	0.79	1.91	1.74
	Small	3.19	2.15	1.87	1.41	1.03	0.80	0.68	0.58	1.38	0.93	0.91	1.06	0.76
		5.25	4.24	3.78	3.17	2.49	2.11	1.77	1.56	2.17	1.68	1.42	2.63	2.24
	Medium	3.59	2.75	2.23	1.65	1.22	0.99	0.86	0.77	1.54	1.07	0.99	1.66	1.14
		5.85	4.10	3.61	3.07	2.45	2.08	1.81	1.59	2.15	1.70	1.48	2.39	1.78
	Large	4.81	3.79	3.19	2.49	1.75	1.35	1.14	0.94	2.17	1.46	1.36	2.17	1.26
		7.29	5.23	4.58	3.96	3.08	2.67	2.38	2.15	3.07	2.16	2.07	3.55	2.80