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Monitoring changes in timber volume using aerial photo plots and field plots in a two-phase sampling design

D. A. Stellingwerf and A. de Gier

Forestry Department, International Institute for Aerospace Survey and Earth Sciences (ITC), P.O. Box 6, NL 7500 AA Enschede, Netherlands

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Abstract

Standing timber volumes and mean periodic volume increment (of Norway spruce, age 40-100 years) were determined over a period of 10 years (1974-1984) in a 3000 ha forest area. The results of a Two-Phase Linear Regression Sampling (TPLRS) method (using $n = 112$ circular photo plots in the first phase, and $n' = 55$ dependent field plots in the second phase, each covering 0.05 ha) were compared with those of a Simple Random Sample (SRS) of only field plots ($n = 112$). The crown cover percentages per plot were taken as independent variables in the TPLRS. They were stereoscopically determined on the 1:10 000 scale black and white infrared aerial photographs of 1974 and 1984.

The TPLRS estimates of the population mean spruce timber volumes were for 1974: $\hat{\bar{Y}}_{74} = 487.91$ m^3 ha^{-1}, for 1984: $\hat{\bar{Y}}_{84} = 458.39$ m^3 ha^{-1} and for the thinnings (based on the 1974 condition): $\hat{\bar{Y}}_{t74} = 134.14$ m^3 ha^{-1} 10 year^{-1}. The estimate of the population mean periodic volume increment $\widehat{\overline{MPI}} = 10.46$ m^3 ha^{-1} year^{-1}.

For the SRS the results were $\hat{\bar{Y}}_{74} = 489.88$ m^3 ha^{-1}, $\hat{\bar{Y}}_{84} = 459.73$ m^3 ha^{-1}, $\hat{\bar{Y}}_{t74} = 125.23$ m^3 ha^{-1} 10 year^{-1} and $\widehat{\overline{MPI}} = 9.51$ m^3 ha^{-1} year^{-1}.

The in every respect acceptable results of the TPLRS as compared to those of the SRS with only field plots and the fact that reenumeration of the field plots at the end of the period i.e. in 1984 is not required anymore, may be a stimulant to use this method in practice.

Introduction

Intensively managed forests require frequent and intensive inventories for periodic evaluation of the effectiveness of management activities. The manager is responsible for a continuous comparison between planned and actual situations, in order to take the necessary actions. Insight in dynamic developments, which occur during a certain period, can be considered of equal or more importance than knowledge of facts which have a static nature. Changes in volume of standing timber are important for the manager and they are usually estimated with the help of samples by using various sampling methods. Because forestry activities take place in the forests, periodic measurements of trees in sample plots in the forests is a standard procedure. Detailed instructions for measuring trees usually exist, in order to guarantee an accurate determination of the volumes of standing trees.

The forest in which the research was carried out covers approximately 3 000 ha in Austria. It is a closed, well-managed forest in which the main species is Norway spruce (Picea abies) which occurs in pure and mixed stands – the latter mainly with beech, fir and some pine and larch. The forest is regenerated by natural seedlings for 99 % of the time. A strip selection cutting technique to stimulate natural regeneration is used at stand ages of 80 to 100 years, the latter being approximately the rotation age. Because of this natural regeneration, forest stands are subdivided into 20-year age classes.

Usually a combination of permanent and temporary plots is preferred for the sampling designs at successive occasions, however, only permanent plots were used in this experiment. The object of the study is to test whether it is possible to determine timber volume and timber volume increment of spruce in pure and mixed stands using a two-phase sampling design. The data involved are derived from (1) field plots, which were enumerated once in 1974, and (2) photo plots, which were enumerated in 1974 and 1984.

Because thinnings usually start at the age of approximately 35 years and regeneration cuttings take place from approximately 80 years onward, the 112 plots were subject to these cuttings during the 10-year period from 1974 to 1984. Because thinnings take place with a 5-year interval, the selected plots are expected to be subject to two thinning operations during the 10-year period.

Materials and methods

Photo and field plot enumeration

Several aerial photographic coverages with different scales were available of the area, of which the ones of 1974 and 1984 were taken. The film used was black and white infrared, on which conifer and broad-leaved tree species were easily distinguishable. The photographic scale of 1:10 000 was taken, because it facilitated the location of the photo plot centres in the field. A two-phase sampling method was applied and in the first phase in 1974 a number of 112 photo plots were randomly selected in the category pure and mixed stands of spruce of 40 years and older. The crown cover percentages of the trees in the individual plots were determined on the aerial photographs of the same year, using a transparant overlay, marked with a circle of the defined plot size i.e. with a diameter of 2.5 mm, which was divided into 11 sectors of which 2 with a 5 % and 9 with a 10 % area coverage of the circle. In this way, crown cover percent classes were distinguished with the following midpoints: 2.5, 7.5, 15, 25, . . . and 95 %. For the determination of the crown cover percentages, the Norway spruce crowns in the plots were visually crammed together in one or more classes during the stereoscopic study of the plots. In the second phase a number of 55 plots was selected out of the 112 photo plots in such a way that as much as possible equal numbers, randomly selected, in the crown cover percent classes were present. In 1974 the spruce trees were numbered and measured in these plots in the field, after locating their plot centres with the help of the 1:10 000 scale stereo photos. The volume table of Krenn (1948), after adjustment for local conditions, was used for the calculation of the volumes of the standing spruce trees in the plots.

In 1984, new aerial photographs, also with a scale of 1:10 000, were taken of the area and the 112 plot centres were stereoscopically transferred to them from the 1974 photographs. The crown cover percentages in these 112 plots were determined under the stereoscope in the same way as in 1974 and used for the estimation of the plot volumes in 1984.

Combining the same photo plots of 1974 and 1984 under the stereoscope revealed the trees that were cut during the period 1974-1984, so that their crown cover percentages per plot could be estimated. The field volumes of these trees per plot were already known from the enumeration of the plots in 1974.

Regression equation second phase

The volumes of all the trees per plot in 1974 (Y_{74}) together with the 1974 volumes of the trees per plot that were cut in the period 1974-1984 (Y_{t74}) were plotted against the respective crown cover percentages per plot on the X-axis. This means that there are 110 paired observations. A linear regression model $Y = b_0 + b_1 X$ was used to estimate the population regression line. The calculated coefficients of the sample regression equation were $b_0 = 1.5687$ and $b_1 = 9.6899$. It was suggested that the line should go through the origin, because when the crown cover percentage is zero there is no volume per plot. The applied t test also indicated b_0 not to be significantly different from zero. Therefore a new coefficient was determined. Because the distribution of the Y-deviations proved not to be heteroscedastic:

$$b_1 = \sum^{110} XY / \sum^{110} X^2.$$

The final regression equation then is $\hat{Y} = b_1 X = 9.7235\, X$. In Fig. 1 the graph of this regression equation and the plotted data are given.

Results

Application of regression equation

The two-phase regression estimate of the population mean plot volume of all trees per plot for 1974 ($\hat{\bar{Y}}_{74}$) was calculated after substitution of $X = X_{i74}$-values of the 112 individual plots of the first phase:

$$\hat{\bar{Y}}_{74} = \sum^{112} \hat{Y}_{i74}/112 = 487.91 \text{ m}^3 \text{ ha}^{-1}.$$

The two-phase regression estimate of the population mean volume per plot of the

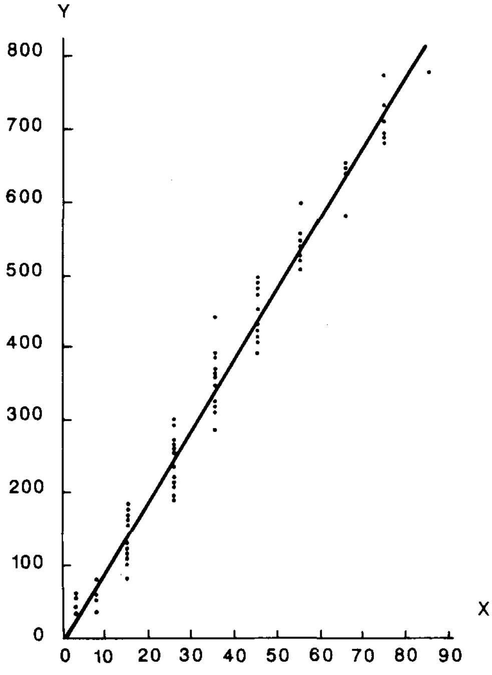

Fig. 1. Relationship between volume per plot (Y) and crown cover percentage per plot (X): $\hat{Y} = 9.7235 X$. Number of plots is 110. $Y = \hat{Y}_{74} + \hat{Y}_{t74}$ (volume per plot of all trees plus thinnings, situation 1974, in $m^3 ha^{-1}$).

thinned trees ($\hat{\bar{Y}}_{t74}$) was calculated after substitution of $X = X_{it74}$-values of the individual 112 plot data:

$$\hat{\bar{Y}}_{t74} = \sum^{112} \hat{Y}_{it74}/112 = 134.14 \text{ m}^3 \text{ ha}^{-1} \text{ 10 year}^{-1}.$$

For the calculation of the estimate of the population mean volume of the remaining trees per plot in 1984 the same regression equation was used:

$$\hat{\bar{Y}}_{84} = \sum^{112} Y_{i84}/112 = 458.39 \text{ m}^3 \text{ ha}^{-1}.$$

The same results would have been obtained substituting $X = \bar{X}_{74}$, $X = \bar{X}_{t74}$ and $X = \bar{X}_{84}$.

The estimate of the population mean periodic volume increment ($\hat{MPI}$) of the remaining stand is derived from:

$$\hat{MPI} = (\sum^{112}(\hat{Y}_{i84} - \hat{Y}_{i74} + \hat{Y}_{it74}))/112 = 10.46 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}.$$

Variances of means of 2-phase sample plots

Ignoring the unknown variance due to the volume table of Krenn, the variances of

$\bar{Y}_{74}$, $\hat{\bar{Y}}_{84}$, $\hat{\bar{Y}}_{t74}$ and $\hat{MPI}$ can be determined. Considering first the regression equation, the squared standard error of estimate is:

$$s^2_{Y.X} = (\sum^{110} Y^2 - (\sum^{110} XY)^2 / \sum^{110} X^2)/(110-1)$$
$$= (15706429.2 - (1602798.05)^2/164837.5)/(110\text{-}1) = 121616.3450/109$$
$$= 1115.7463.$$

The variance of b_1 is:

$$\text{var}\, b_1 = s^2_{Y.X} / \sum^{110} X^2$$
$$= 1115.7463/164837.5000$$
$$= 0.006769.$$

The variance of the estimated mean volume for 1974 follows from:

$$\text{var}\, \hat{\bar{Y}}_{74} = b_1^2 \text{ var}\, \bar{X}_{74} + \bar{X}_{74}{}^2 \text{ var}\, b_1$$
$$= 9.7235^2\,(2.0750) + 50.18^2\,(0.006769)$$
$$= 196.1839 + 17.0446$$
$$= 213.2285\ (\text{m}^3\,\text{ha}^{-1})^2.$$

$$\sqrt{\text{var}\, \hat{\bar{Y}}_{74}} = 14.60\ \text{m}^3\,\text{ha}^{-1}.$$

The calculations of $\sqrt{\text{var}\, \hat{\bar{Y}}_{84}}$ and $\sqrt{\text{var}\, \hat{\bar{Y}}_{t74}}$ follow in the same way:

$$\sqrt{\text{var}\, \hat{\bar{Y}}_{84}} = 16.56\ \text{m}^3\,\text{ha}^{-1}$$

$$\sqrt{\text{var}\, \hat{\bar{Y}}_{t74}} = 9.98\ \text{m}^3\,\text{ha}^{-1}\ 10\ \text{year}^{-1}.$$

The variance of the estimated mean periodic volume increment is written as

$$\text{var}\, \hat{MPI} = b_1^2 \text{ var}\, \bar{X}_{MPI} + \bar{X}^2_{MPI} \text{ var}\, b_1$$

in which $\bar{X}_{MPI} = \bar{X}_{84} - \bar{X}_{74} + \bar{X}_{t74}$.

$$\text{var}\, \bar{X}_{MPI} = (\sum^{112} X^2_{iMPI} - (\sum^{112} X_{iMPI})^2)/(n(n-1))$$
$$= 0.2190.$$

Here $X_{iMPI} = X_{i\,84} - X_{i\,74} + X_{i\,74}$. Therefore:

$$\sqrt{\text{var}\, \hat{MPI}} = 9.7235^2\,(0.2190) + 10.7600^2(0.006769)$$
$$= 21.4894\ (\text{m}^3\,\text{ha}^{-1}\ 10\ \text{year}^{-1})^2$$

$$\sqrt{\text{var}\, \hat{MPI}} = 4.6357\ \text{m}^3\,\text{ha}^{-1}\ 10\ \text{year}^{-1}$$
$$= 0.4636\ \text{m}^3\,\text{ha}^{-1}\,\text{year}^{-1}.$$

Check with field plots

In order to check the results which were obtained from the two-phase sampling method with 112 photo plots and 55 field plots, the 112 photo plots were enumerated in the field in 1974 and 1984. The estimated mean field plot volume in 1974:

$$\hat{\bar{Y}}_{74} = (\sum^{112} \hat{Y}_{i74})/112 = 489.88\ \text{m}^3\,\text{ha}^{-1}$$

and in 1984:

$$\hat{\bar{Y}}_{84} = (\sum^{112} \hat{\bar{Y}}_{i84})/112 = 459.73 \text{ m}^3 \text{ ha}^{-1}.$$

The estimate of the mean thinning volume per plot for 1974:

$$\hat{\bar{Y}}_{t74} = (\sum^{112} \hat{\bar{Y}}_{it74})/112 = 125.23 \text{ m}^3 \text{ ha}^{-1} \text{ 10 year}^{-1}.$$

Finally the estimate of the mean periodic volume increment of the remaining stand:

$$M\hat{P}I = (\sum^{112} (\hat{\bar{Y}}_{i84} - \hat{Y}_{i74} + \hat{\bar{Y}}_{it74}))/112 = 9.51 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}.$$

Variances of means of 112 field plots

Ignoring again the unknown variance due to the volume table of Krenn, the variances of $\bar{Y}_{74}$, $\hat{\bar{Y}}_{84}$, $\hat{\bar{Y}}_{t74}$ and $M\hat{P}I$ which result from the simple random sample with 112 field plots were determined using the variance formula:

$$\text{var } \bar{Y} = (\sum^{n} Y_i^2 - (\sum^{n} Y_i)^2/n)/(n(n-1)),$$

in which for the volumes in 1974 $Y_i = \hat{Y}_{i74}$, and in 1984 $Y_i = \hat{\bar{Y}}_{i84}$; for the volumes of the thinnings in 1974 $Y_i = \hat{\bar{Y}}_{it74}$; and for the mean periodic volume increment of the remaining stand $Y_i = MPI_i = X_{i84} - X_{i74} + X_{it74}$.

$$\sqrt{\text{var}}\, \hat{\bar{Y}}_{74} = 14.58 \text{ m}^3 \text{ ha}^{-1},$$

$$\sqrt{\text{var}}\, \hat{\bar{Y}}_{84} = 16.36 \text{ m}^3 \text{ ha}^{-1},$$

$$\sqrt{\text{var}}\, \hat{\bar{Y}}_{t74} = 9.45 \text{ m}^3 \text{ ha}^{-1} \text{ 10 year}^{-1}$$

$$\sqrt{\text{var}}\, M\hat{P}I = 0.32 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}.$$

Discussion

The obtained results are summarized in Table 1. This table shows that the two-phase sampling method with 112 photo plots and 55 field plots gives strikingly good results for the estimates of the mean volumes in 1974 and 1984 when compared with the data resulting from the 112 field plots. For 1974 the difference is only 0.4 % and for 1984 it is only 0.3 %. The respective differences for the mean thinning volumes and the mean periodic volume increment are 7.1 and 10.0 %. However, these dif-

Table 1. Mean timber volumes, mean periodic volume increment and their variances resulting from (1) a two-phase linear regression random photo-field sample and (2) a simple random field sample.

	Mean timber volumes						Mean periodic volume increment (m^3ha^{-1} $year^{-1}$)	
	1974 trees (m^3 ha^{-1})		1984 trees (m^3 ha^{-1})		thinned trees (m^3 ha^{-1} 10 $year^{-1}$)			
	$\hat{\bar{Y}}_{74}$	$\sqrt{\text{var}}\,\hat{\bar{Y}}_{74}$	$\hat{\bar{Y}}_{84}$	$\sqrt{\text{var}}\,\hat{\bar{Y}}_{84}$	$\hat{\bar{Y}}_{t74}$	$\sqrt{\text{var}}\,\hat{\bar{Y}}_{t74}$	$M\hat{P}I$	$\sqrt{\text{var}}\,M\hat{P}I$
TPLRS	487.91	14.60	458.39	16.56	134.14	9.98	10.46	0.46
SRS	489.88	14.58	459.73	16.36	125.23	9.45	9.51	0.32

ferences are not significant, given the standard errors of the means.

It should be noted that in the two-phase sampling design, the measurements in the field of all trees in the 55 plots used for the regression were done once in 1974, for the determination of Y_{i74} and Y_{it74}. The enumeration in the field of these plots in 1984 is not required anymore, because the regression equation of 1974 can be used. Only the crown cover percentages of all 112 first-phase sample plots were again determined in 1984 on newly taken aerial photographs. Of course the expenditure for the photography in 1974 and 1984 is to be made. These photographs, however, are also useful for other purposes, such as the revision or reconstruction of forest management maps, stand description, etc. This means that part of the total cost of the photography can be recouped on these activities.

In the introduction it was mentioned that thinnings take place with an interval of five years. This means that in the given period the plots are subject to two thinnings, which will not take place in the same year. This means that the mean thinning volume in the 1974-1984 period will not be the same as the mean thinning volume in 1974. The years in which the thinnings took place are not known exactly and it is therefore assumed that the thinnings took place in 1979 and their volumes were calculated for that year. The estimate of the population mean thinning volume in 1979 is 13.68 m^3 ha^{-1} $year^{-1}$, against 12.52 m^3 ha^{-1} $year^{-1}$ for 1974. Research to assess the usefulness of the 1979 aerial photography for a better determination of this thinning volume has started.

Acknowledgement

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Reference

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