Cost-Plus-Loss Analyses of Forest Inventory Strategies Based on *k*NN-Assigned Reference Sample Plot Data

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The usefulness of *k*NN (*k* Nearest Neighbour)-assigned reference sample plot data as a basis for forest management planning was studied. Cost-plus-loss analysis was applied, whereby the inventory cost for a specific method is added to the expected loss due to non-optimal forestry activities caused by erroneous descriptions of the forest state. Four different strategies for data acquisition were evaluated: 1) *k*NN imputation of sample plots based on traditional stand record information, 2) imputation based on plot-wise aerial photograph interpretation in combination with stand record information, 3) sample plot inventory in the field with 5 plots per stand, and 4) sample plot inventory with 10 plots per stand. Expected losses were derived as mean values of differences between the maximum net present value and the corresponding value obtained when the treatment schedule believed to be optimal (based on data simulated according to method 1–4) was selected. The optimal choice of method was found to depend on factors such as stand maturity, stand area, and time to next treatment (thinning or clearcutting). In general, the field sample plot methods were competitive in large mature stands, especially when the time to the next (optimal) treatment was short. By in each stand (within an estate) employing the method with the lowest cost-plus-loss rather than choosing the method that performed best on average for the entire estate, the total cost for inventory at the estate level could be decreased by 15–50%. However, it was found difficult to identify what method should optimally be employed in a stand based on general stand descriptions.

Keywords data acquisition, imputation, uncertainty, forestry planning

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1 Introduction

1.1 Background

Planning ideally answers the questions of where, when, and how a certain action should be carried out in order to reach a certain goal. In forestry, one important basis for planning is data describing the state of the forests. A plethora of forest inventory methods have been developed over the years (e.g. Loetsch and Haller 1973, Schreuder et al. 1993) to meet the demands for cost-efficient data acquisition, but often there is no consensus about what method should be applied for a certain purpose.

Typically in forest planning, data from inventories are used as input to different kinds of decision support systems (e.g. Jonsson et al. 1993, Siitonen 1995). Within the systems, forecasts are made for different management options and the treatment schedules that best meet the specified objectives are selected. Perfect forecasts of growth and yield can never be made (cf. Gertner 1987, Ståhl and Holm 1994, Kangas 1996; 1997; 1999), but the more accurately the present state is described, the better the forecasts will be (Kangas 1998, Nyström and Ståhl 2001). Thus, planning based on accurate data should generally, not surprisingly, result in better decisions than planning based on poor data. On the other hand, it is expensive to acquire accurate data from all parts of a forest, and in practice there is a trade-off between how much money should be spent on inventories and what losses can be accepted due to non-optimal decisions.

Cost-plus-loss analysis has been suggested as a suitable approach to assess the appropriateness of an inventory method (Cochran 1977, Hamilton 1978). With this kind of analysis, the inventory cost is added to the expected loss due to non-optimal decisions, yielding a total cost of the inventory. The total cost of an inventory should, ideally, be as low as possible. The most difficult part of cost-plus-loss analysis is how to calculate the expected loss. Quadratic loss functions have been suggested (e.g. Cochran 1977, Hamilton 1978) due to the simplicity whereby they can be applied from a statistical point of view. These kinds of loss functions are, however, simplifications and in more comprehensive studies the entire planning process must typically be captured in the analysis (e.g. Ståhl et al. 1994, Eid 2000). To estimate the expected loss, simulation is often applied (e.g. Larsson 1994, Kangas and Kangas 1999, Eid 2000).

Looking closer at what kind of methods that are available for forest inventory, a first division can be made between field based methods and methods based on remote sensing. Field based methods tend to be either fast and judgemental, i.e. subjective ocular estimates are made rather quickly to cover large geographical areas (e.g. Ståhl 1992), or more carefully performed for a sparse sample of the forest (e.g. Lindgren 1984). The latter methods, termed objective, are often of interest in long-term planning, since data without systematic errors are important in such cases (e.g. Jacobsson 1986). Objective field methods usually require careful, and thus expensive, measurements. A statistically sound sample is necessary in order to obtain a valid representation of the entire forest. For a small forest holding, the cost per area unit for collecting such data usually becomes very high.

Forest inventory methods based on remote sensing have been motivated by their potential to cover large areas at low cost (e.g. Leckie 1990, Stellingwerf and Hussin 1999, Franklin 2001). Well known methods involve interpretation in aerial photographs (e.g. Åge 1985) and digital analysis of satellite images (e.g. Poso et al. 1987, Hagner 1990, Bauer et al. 1994). Many different new sensors, both spaceborne and airborne, currently provide data that are very promising from the point of view of forest planning (e.g. Næsset 1997, Hyyppä et al. 2000).

Due to the vast number of inventory methods available, cost-plus-loss analysis is a useful approach to determine what method, or what combination of methods (e.g. Poso et al. 1999, Holmström and Fransson 2003), which are most appropriate for a specific planning purpose. However, very few examples exist where this kind of analysis has actually been applied in practice (e.g. Siitonen and Nuutinen 1996). One reason is that it is difficult to model all uses of data, and set up a calculation system whereby it is possible to derive the expected loss due to non-optimal decisions. Another reason is that different methods provide data in different formats; e.g., with objective field inventories forest data are often obtained for single trees on sample plots, whereas remotely sensed data seldom show such high resolution. Thus, a straightforward comparison of methods is difficult. However, if data can be made available in comparable format, one obstacle for performing cost-plus-loss analysis is avoided.

Many of today's advanced forest planning systems require data at the single tree level (e.g. Wykoff et al. 1982, Jonsson et al. 1993, Lundström and Söderberg 1996). Such data can be made available using almost any kind of data (and access to a set of reference plots) by applying some sample plot imputation technique, such as the *k* nearest neighbour (*k*NN) method (Kilkki and Päivinen 1987, Muinonen and Tokola 1990, Tomppo 1990). With this method, existing field reference plots (or similar data) are assigned to areas which are only known by their values in some other data source, common for the entire forest area of interest. The latter kind of information has been termed "carrier data" by Holmström et al. (2001), since these data can be thought of as carrying values from a field reference plot to a specific target area.

The *k*NN method has mostly been used with optical satellite data (e.g. Tomppo 1992, Nilsson 1997), sometimes supported by additional in situ information (e.g. Tokola and Heikkilä 1997). Applications based on aerial photograph interpretation and stand record information are presented by Holmström (2002) and Holmström et al. (2001).

1.2 Objective

The objective of this study was to analyse the possibilities of using *k*NN-assigned reference plots as input to forestry planning and, specifically, to compare different methods for providing stand level data by applying cost-plus-loss analysis. The data sources compared were 1) traditional stand record information based on ocular assessment, 2) plot-wise aerial photograph interpretation in combination with stand record information, 3) sample plot inventory in the field with 5 plots per stand, and 4) sample plot inventory with 10 plots per stand.

2 Material and Methods

2.1 Overview of Analyses

Stand level cost-plus-loss analyses were carried out and results at forest estate level were obtained by aggregation of the stand level results. To determine the expected losses due to non-optimal decisions, a set of forest stands with known states were used as evaluation objects. Based on the known true states, stand record data and aerial photograph interpretations were simulated. Using the *k*NN method, reference sample plot data were then assigned to each stand based on the simulated values. To evaluate the cost-plus-loss from sample plot inventory in the field, bootstrapping was used.

Using the sample plot data from each simulation (or resampling) in the Forest Management Planning Package (FMPP; Jonsson et al. 1993), a treatment schedule resulting in an optimal net present value for these data was obtained. Correspondingly, a treatment schedule optimal for the true data was also derived. The loss due to nonperfect decisions was obtained as the difference in net present value between the two treatment schedules, basing the calculations on the true data. A mean value of the losses, from 50 simulations in each stand, was derived and added to the inventory cost to obtain the cost-plus-loss of an inventory method in a particular stand. Results were compiled both for single stands and for two fictitious forest estates.

2.2 Test Sites and Field Data

Data from two test sites, Brattåker and Remningstorp, were used in the study. Brattåker is located in northern Sweden (63º35'N, 20º15'E, 150–400 m a.s.l.) while Remningstorp is located in the south-western part of the country (58º30'N, 13º40'E, 120–145 m a.s.l.). The forest conditions at the two test sites differ considerably, and thus evaluations were made separately for each site. For example, the average potential productivity is about 10 m^3 ha^{-1} yr^{-1} for the southern test site but less than half of this in the northern site.

Field data from 33 stands at Brattåker and 35 stands at Remningstorp were acquired (in 1993 and 1999, respectively). The stands were inven-

Table 1. Descriptive statistics of the evaluation stands at Brattåker, $n = 33$, and at Remningstorp, $n = 35$.

Variable	Brattåker Average	Brattåker Min.	Brattåker Max.	Remningstorp Average	Remningstorp Min.	Remningstorp Max.
Plots (stand^{-1})	7.4	3	9	11.4	9	14
Area (ha)	18.2	2	55	5.0	1	19
Stem volume (m^3 ha^{-1})	146.6	10	250	233.8	74	426
CV, stem volume (%)[a]	37.1	18	95	33.4	16	77
Age (yrs)	86.3	30	152	56.4	26	107
SI, H100 (m)[b]	21.0	18	24	27.3	18	31
Pine (%)	43.0	0	83	21.4	0	98
Spruce (%)	43.7	13	80	69.3	0	100
Broad-leaved (%)	13.3	0	50	9.3	0	33

[a] Estimated coefficient of variation for plots (with 10 m radius) within stands.
[b] According to Hägglund and Lundmark (1981).

Table 2. Descriptive statistics of the reference sample plots used at Brattåker, $n = 2924$, and at Remningstorp, $n = 3937$.

Variable	Brattåker Average	Brattåker Min.	Brattåker Max.	Remningstorp Average	Remningstorp Min.	Remningstorp Max.
Stem volume (m^3 ha^{-1})	128.6	0	499	184.6	0	955
Age (yrs)	70.0	0	212	53.2	0	219
SI, H100 (m)[a]	20.8	11	27	27.4	13	39
Pine (%)	47.5	0	100	36.2	0	100
Spruce (%)	36.8	0	100	50.6	0	100
Broad-leaved (%)	15.7	0	100	13.1	0	100
Mean tree height (dm)	124.9	0	257	146.1	0	309
Stocking (%)[b]	54.8	0	155	63.2	0	354

[a] According to Hägglund and Lundmark (1981).
[b] According to Jonson (1914), a measure of ‘present stem density’ in relation to a fully stocked reference plot.

toried according to instructions of the FMPP, prescribing a systematic sample of approximately 10 circular plots (using square lattice; distance between plots depending on stand area), with 10 m radius, per stand. At the plots, the diameter at breast height was measured for all trees and additional measurements were made on a sub-sample of the trees. Other data, e.g., site conditions, were also recorded for the plots. No stands younger than 25 years were inventoried.

Although the true state in the stands was not perfectly captured by the inventory, the field data from these stands were used as the truth in the analyses. From the point of view of validity of the analyses, it does not matter that the actual conditions in the stands most likely differ slightly from the descriptions obtained from the sample plots (i.e. assuming that what is referred to as the true states of the stands are described by the plots). A summary description of the stands is given in Table 1.

The 33 stands in Brattåker and the 35 stands in Remningstorp were assumed to form two different fictitious estates for which optimal inventory strategies were sought. Since it is very likely that results on optimal strategies will differ depending on the composition of stands on an estate, an overview of what kind of stands made up the fictitious estates at the two sites is given in Fig. 1.

Reference sample plot data for the *k*NN estimations were acquired from several different FMPP inventories conducted during 1985–2000 in neighbouring areas, corresponding to the same growth regions as defined by Söderberg (1986). With additional limitations upon latitude and altitude, the reference data were collected within a search radius of approx. 100 km to the test sites. A reference material of 2924 and 3937 sample plots was used for Brattåker and Remningstorp, respectively (Table 2).

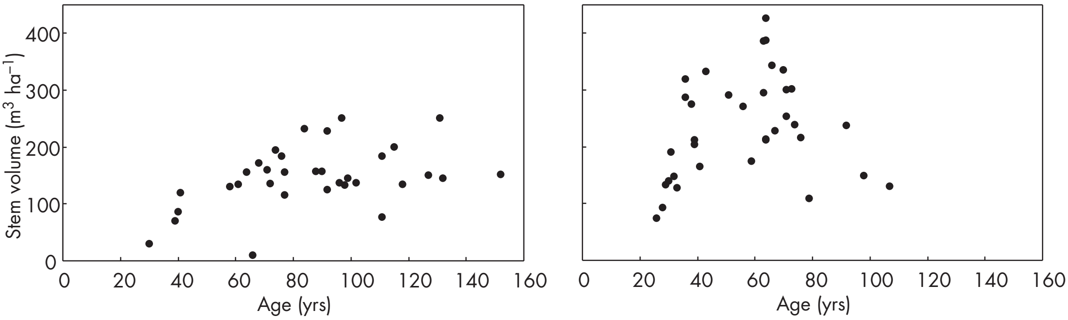

Fig. 1. Composition of stands in the fictitious Brattåker estate (left) and the corresponding Remningstorp estate (right).

2.3 Cost-Plus-Loss Analysis

In cost-plus-loss analysis, the difficult part is generally to determine the expected loss (Hamilton 1978, Larsson 1994, Ståhl et al. 1994). In this study, the expected loss was determined by studying the consequences of using erroneous data through the entire planning system, i.e. the FMPP (Jonsson et al. 1993).

The FMPP allows for detailed growth forecasts and economic yield calculations. Input data from forest stands must be provided at the level of individual trees on sample plots. The system is based on projections in 5-yr periods where treatments are assumed to take place in the middle of each period. A large set of treatment alternatives can be tested for each stand, and thus it is straightforward to select the treatments that result in a maximum net present value. More advanced options to optimisation are also available, where restrictions are imposed regarding the distribution of net income over time (Jacobsson 1986). In this study, however, traditional net present value maximisation was employed, without any restrictions. It is well known that, in this case, the problem of maximising the net present value at the forest estate level can be broken down to a set of sub-problems of maximising the net present value in each stand within the estate (e.g. Johansson and Löfgren 1985). Thus, all basic analyses were performed for single stands. Only treatment schedules with even-aged forestry were considered.

The treatments simulated were thinning and clearcutting. With regard to thinning, different types were tested (normal thinning, thinning from below and thinning from above) as well as different thinning grades (normal, light, and strong). Silvicultural and harvest costs, timber and pulpwood prices, etc., were fixed throughout the infinite planning horizon. The input data used for these characteristics were derived from the Forest Owners Association's price lists and national forestry statistics (Statistical yearbook... 2001). Two different annual rates of interest, 2% and 4%, were applied in the analyses. Results from standard baseline analyses with the FMPP for the evaluation stands are presented in Table 3.

The cost-plus-loss of a method was derived in a standard way (e.g. Hamilton 1978) by adding the inventory cost of a specific method to the expected loss due to non-optimal decisions. The loss is the result of decisions other than the optimal ones, due to a non-perfect description of the present state of a stand.

The inventory costs for each method (*IC*s) are given in Table 4. Two different levels of costs were evaluated, one where the inventory was seen as a stand-alone activity within an area, without any possibility to reduce costs by coordination of activities. The second, lower, level was chosen to reflect a case where the inventory activities are coordinated. The figures in Table 4 were obtained from leading Swedish forest inventory consultants and correspond to a stand area of 5 ha. For the field sample plot methods, no differentiation of costs was made on different stand areas, although the time for walking between plots may vary slightly depending on the area. The cost for aerial photo interpretation (in combination with stand record information) was set to depend on stand area, since costs for photos and some initial parts of the interpretation work must be shared

Table 3. Results from baseline analyses with the FMPP for the evaluation stands at Brattåker and at Remningstorp, using the interest rates (r) 2% and 4%.

Variable	Brattåker Average	Brattåker Min.	Brattåker Max.	Remningstorp Average	Remningstorp Min.	Remningstorp Max.
$r = 2\%$						
Net present value (SEK ha^{-1})[a]	28969	2207	59249	61389	19403	104777
Treatment (5-yr periods)[b]	3.8	1	11	2.7	1	5
Clearcutting (5-yr periods)[c]	9.2	1	22	7.5	2	13
Rotation age (yrs)	130.5	94	175	91.9	73	144
$r = 4\%$						
Net present value (SEK ha^{-1})[a]	16946	199	53582	40025	11886	81469
Treatment (5-yr periods)[b]	2.7	1	11	1.5	1	4
Clearcutting (5-yr periods)[c]	6.0	1	21	4.5	1	10
Rotation age (yrs)	114.6	79	169	76.8	58	129

[a] 1 SEK = 0.11 EUR (2001-06-01).
[b] Time to next treatment (thinning or clearcutting) from time of inventory.
[c] Time to clearcutting from time of inventory.

Table 4. Inventory cost, IC, for the inventory methods compared in the cost-plus-loss analyses (for stand area = 5 ha). Two different cost levels were tested, to reflect the costs when inventories are not coordinated and when they are coordinated within a region.

M	Method	IC (SEK stand^{-1}) No coordination	IC (SEK stand^{-1}) Coordination
1	*k*NN, stand record information [a]	50	25
2	*k*NN, aerial photograph interpretation	300	150
3	Field inventory, 5 plots per stand	1560	1250
4	Field inventory, 10 plots per stand	2080	1675

[a] Stand record information was assumed to be available; the cost is from updating-procedures, etc.

by all stands within a stereo model. Thus larger stands received slightly higher costs (approx. 2.5 SEK ha^{-1} in the case of coordination, and approx. 8 SEK ha^{-1} in the case of no coordination). The cost for the method based on stand record information only, also was set to depend on stand area, due to an assumption that each new estate needs specific routines for updating the existing information. If there are only a few large stands on the estate, the cost per stand becomes higher than if the estate is composed of many small stands (1 SEK ha^{-1} in the case of coordination and 2 SEK ha^{-1} in case of no coordination). The analyses are based on the assumption that an old forestry plan exists for the estates. Thus, no costs were required for the delineation of stands.

Derivations of losses due to non-optimal decisions, i.e. inoptimality losses (*IL*s; Jacobsson 1986) were made with the FMPP. Data for each inventory method were simulated (or resampled) 50 times for each stand. Based on these data, and *k*NN imputations of sample plots, the treatment schedule believed to maximise the net present value (*NPV*) was selected. When this treatment schedule was applied to true data, the difference in *NPV* between this schedule and the truly optimal schedule was calculated, and taken as the inoptimality loss. However, since it is not realistic that data acquired today should be used for decisions in a very distant future, only decisions (including 'no treatment') in the first two 5-yr periods were considered. Thus, the *IL*s were derived by comparing the optimal schedule based on the true data with a schedule with optimal decisions according to simulated data for the first two 5-yr periods; from period 3 and onwards the stands were treated optimally with due regard to the possibly erroneous decisions already carried out in the first two periods (this meaning, with given treatments in the first two periods, choosing the schedule with the highest *NPV*). To handle this technically, a special version of the FMPP was developed.

Thus, an average inoptimality loss, $\overline{IL}$, was estimated for each stand according to

$$\overline{IL} = \frac{1}{50}\sum_{i=1}^{50}\left(NPV^{opt} - NPV_i^*\right) \tag{1}$$

where NPV_i^* indicates the net present value for simulation *i*, obtained when a treatment schedule based on non-perfect data was selected; NPV^{opt} denotes the maximum net present value. By assuming a certain stand area, *A*, a total cost was estimated according to

$$TC = IC + \overline{IL}A \tag{2}$$

Stand areas ranging from 1 to 10 ha were analysed. Estate level results were obtained by adding the stand level results for the two fictitious estates.

2.4 Carrier Data Simulation

As mentioned above, stand record data and aerial photograph interpreted data were simulated before *k*NN was applied to assign sample plot data to the evaluation stands. Bootstrapping (Efron and Tibshirani 1993, Hjort 1994), i.e. resampling of plot data belonging to the specific stand, was used to provide input data for the two field based sample plot methods, and thus there was no need to simulate carrier data for these.

Stand record data and aerial photograph interpreted data, *x*, were simulated from the corresponding true values, *y* (stand level data for stand record variables and plot level data for aerial photo interpreted variables) according to

$$x_i = y + \Delta + z_i\,SD \tag{3}$$

where

i = index for simulation (1–50),
Δ = bias component,
SD = standard deviation of the random error term,
z = correlated random number [~N(0,1)].

This procedure was used above certain threshold values for the different *y*-variables. Below these thresholds, another model was used for the simulation

$$x_i = y + y\Delta' + z_i\,ySD' \tag{4}$$

In this case, the size of both the systematic errors and the random errors increase with the size of the true value of the variable of interest. The reason for specifying the error structure according to Eqs. 3 and 4 was that previous studies on subjective inventory methods (e.g. Ståhl 1992) have shown errors of this kind, i.e. errors that increase in size up to a certain threshold value, after which the size of the errors stay on a rather constant level.

The correlated random numbers were obtained by standard procedures (e.g. Ripley 1987), using a lower triangular matrix *C* and solving the entries of *C* according to

$$\boldsymbol{CC}^{T} = \Sigma \tag{5}$$

where Σ is the correlation matrix (see Tables 6 and 7).

For each stand or plot, and each simulation, a column vector *z* was derived from a vector of independent normally distributed [~N(0, 1)] random numbers, z^*, as

$$z = \boldsymbol{C}z^* \tag{6}$$

The random numbers were truncated at 2 standard deviations. Further, simulated data were truncated to avoid negative values and values (and sums of values) above 100%.

The parameters in the simulations were set in order to resemble the quality of data that can be expected in practise. Parameters for stand record information based on ocular methods were derived from Eriksson (1990), Ståhl (1992), Holmström (2002), and Holmström et al. (2001). Parameters for plot level aerial photo interpretation were derived from Holmström (2002) and Holmström et al. (2001), corresponding to results actually obtained in the two test areas in previous studies.

Error components and correlations used in the simulations of stand record variables and aerial photo interpreted variables are presented in Tables 5, 6, and 7.

Table 5. Systematic, Δ and Δ’, and random, *SD* and *SD*’, error components used in the simulations of stand record information (at the stand level) and aerial photograph interpretation (at the plot level). Values are given pairwise; the left value corresponds to Δ or *SD* in Eq. 3, the right value to Δ’ or *SD*’ in Eq. 4.

Variable	Brattåker		Remningstorp	
	Δ / Δ’	*SD* / *SD*’	Δ / Δ’	*SD* / *SD*’
Stand record information				
Stem volume, (m^3 ha^{-1})[a]	–2.7 / –0.02	32.9 / 0.24	–8.6 / 0.03	88.8 / 0.69
Age (yrs)[b]	5.6 / 0.07	17.6 / 0.21	–4.1 / –0.04	14.9 / 0.32
SI, H100 (m)[c]	0.9 / 0.05	3.2 / 0.16	0.7 / –0.02	2.9 / 0.12
Pine (%)[d]	0.0 / 0.00	10.0 / 0.50	0.0 / 0.00	10.0 / 0.50
Spruce (%)[d]	0.0 / 0.00	10.0 / 0.15	0.0 / 0.00	10.0 / 0.15
Broad-leaved (%)[d]	0.0 / 0.00	10.0 / 0.50	0.0 / 0.00	10.0 / 0.50
Aerial photo interpretation				
Mean tree height (dm)[e]	–7.9 / –0.06	16.4 / 0.12	–7.9 / –0.22	19.6 / 0.24
Stocking (%)[f]	–1.1 / –0.12	14.4 / 0.24	–2.1 / 0.27	17.1 / 0.70
Pine (%)[d]	25.6 / 0.75	30.0 / 0.75	25.6 / 0.75	30.0 / 0.75
Spruce (%)[d]	–19.6 / –0.32	34.4 / 0.55	–19.6 / –0.32	34.4 / 0.55
Broad-leaved (%)[d]	–6.0 / –0.71	32.0 / 0.75	–6.0 / –0.71	32.0 / 0.75

[a] Threshold value 150 m^3 ha^{-1}, [b] Threshold value 50 yrs, [c] Threshold value 25 m,
[d] Threshold value 50%, [e] Threshold value 120 dm, [f] Threshold value 50%.

Table 6. Correlation, ρ, of residuals in the simulations of stand record variables.

Variable	ρ					
	Stem volume	Age	SI, H100	Pine	Spruce	Broad-leaved
Stem volume (m^3 ha^{-1})	1					
Age (yrs)	0.3	1				
SI, H100 (m)	0.2	–0.4	1			
Pine (%)	0.2	0.0	–0.1	1		
Spruce (%)	0.0	0.0	0.2	–0.5	1	
Broad-leaved (%)	–0.1	0.0	0.1	–0.3	–0.2	1

Table 7. Correlation, ρ, of residuals in the simulation of aerial photograph interpreted variables.

Variable	ρ				
	Mean tree height	Stocking	Pine	Spruce	Broad-leaved
Mean tree height (dm)	1				
Stocking (%)	0.2	1			
Pine (%)	–0.1	0.1	1		
Spruce (%)	0.2	0.2	–0.6	1	
Broad-leaved (%)	–0.1	–0.2	–0.3	–0.4	1

2.5 *k*NN Imputation

Based on simulated stand record information and simulated plot level aerial photograph interpretation, reference sample plot data were assigned to the evaluation stands using the *k*NN method (Kilkki and Päivinen 1987, Muinonen and Tokola 1990, Tomppo 1990). Using stand record information only, *k* = 5 reference plots were assigned to each evaluation stand. With aerial photograph interpretation combined with stand record information, *k* = 1 reference plot was assigned to each plot within a stand. All reference plots were given equal weights in the analyses, due to practical considerations when running the FMPP. Nearness was defined as a weighted Euclidian distance metric, *d*, in the feature space of 5 variables (indexed by *i*) between target, *t*,

Table 8. Variables and corresponding weights used in the distance metric *d*.

i	Variable v_i	Weight w_i
1	Stem volume (m^3 ha^{-1})	1.32
2	Age (yrs) [a]	1.03
3	SI, H100 (m)	0.59
4	Pine (%)	0.98
5	Spruce (%)	0.88

[a] The weight for age was constant up to 70 years, then it decreased linearly up to 150 years where it had half the nominal size. From 150 years upwards it was constant.

and reference sample plot, *r*, according to (cf. Manly 1986)

$$d_{t\,r} = \sqrt{\sum_{i=1}^{5} w_i \left[\left(v_{t\,i} - v_{r\,i} \right) / SD_i \right]^2} \tag{7}$$

where

v = variable value associated with target and reference sample plot,

w = weight for a variable, and

SD = standard deviation of a variable.

Variables values were available for the reference sample plots from field measurements. The weights corresponding to certain variables are presented in Table 8. These weights were obtained from preceding studies of correlations between different variables and *NPV*s, and hence, depending on the models (for, e.g., growth and yield) used in the planning procedure. A kind of standardisation procedure, division by *SD*, was used in order to make the distance insensitive to the range of a certain variable and what units were used.

Dealing with stand record information, the variable value of $v_{t\,i}$ in equation (7) was set to the corresponding simulated stand record value. Using plot level aerial photograph interpretations, the values of $v_{t\,1}$ and $v_{t\,2}$ were derived from regression functions using the aerial photo interpreted and stand record variables as regressors. The details are given in Holmström (2002) and Holmström et al. (2001). Site index was set equal to the simulated stand record value, while the proportions of pine and spruce at the target plots were set as a weighted average value of the simulated aerial photo interpretations (weight 2/3) and the stand record information (weight 1/3).

Table 9. The average inoptimality loss, $\overline{IL}$, for different inventory methods at Brattåker and Remningstorp, using interest rates (*r*) 2% and 4% in the calculations.

Inventory method	$\overline{IL}$ (SEK ha^{-1}) Brattåker r = 2%	 Brattåker r = 4%	 Remningstorp r = 2%	 Remningstorp r = 4%
M1	405	398	680	1345
M2	365	324	524	1150
M3	108	151	175	144
M4	65	91	117	78

3 Results

In Table 9, basic results showing the average *IL*s of the different methods are presented. Results are given for two different interest rates, 2% and 4%. Abbreviations used for the methods are

M1: stand record information,
M2: aerial photograph interpretation combined with stand record information,
M3: objective field inventory with 5 plots (radius 10 m) per stand, and
M4: objective field inventory with 10 plots (radius 10 m) per stand.

Assuming all the stands within the fictitious estates in Brattåker and Remningstorp to have equal size (2, 5, or 10 ha), results on total costs on the estate level were derived for the different methods, assuming different inventory cost levels and interest rates. The results are presented in Tables 10–11.

With small stands, imputation based on stand record information only or stand record information combined with aerial photograph interpretation was optimal if a single method should be selected for all stands within an estate. By in each stand selecting the method providing the lowest cost-plus-loss, the total cost could be decreased considerably.

With large stands, field inventory with 5 or 10 plots per stand resulted in the lowest total cost, provided one specific method should be used in all stands within the estate. In this case as well it was possible to reduce the cost-plus-loss considerably by in each stand selecting the best method.

Table 10. Total cost, *TC*, for different stand areas, *A*, for two different inventory cost levels, *IC*. Interest rate $r = 2\%$ in the calculations. **Bold** indicates minimum *TC*, for the method performing best on average.

Inventory method	*TC* ($\mathrm{SEK\ ha^{-1}}$)					
	Brattåker			Remningstorp		
	$A = 2$ ha	$A = 5$ ha	$A = 10$ ha	$A = 2$ ha	$A = 5$ ha	$A = 10$ ha
IC: no coordination						
M1	**427**	**415**	411	702	690	686
M2	504	425	399	**663**	584	558
M3	888	420	**264**	955	**487**	331
M4	1105	481	273	1157	533	**325**
M integration[a]	*290*	*189*	*140*	*507*	*362*	*268*
IC: coordination						
M1	**416**	410	408	691	685	683
M2	436	395	381	**595**	554	540
M3	733	**358**	233	800	**425**	300
M4	902	400	**232**	954	452	**284**
M integration[a]	*247*	*163*	*123*	*456*	*322*	*239*

[a] In each stand selecting the inventory method with the lowest cost-plus-loss (values in *italics*).

Table 11. Total cost, *TC*, for different stand areas, *A*, for two different inventory cost levels, *IC*. Interest rate $r = 4\%$ in the calculations. **Bold** indicates minimum *TC*, for the method performing best on average.

Inventory method	*TC* ($\mathrm{SEK\ ha^{-1}}$)					
	Brattåker			Remningstorp		
	$A = 2$ ha	$A = 5$ ha	$A = 10$ ha	$A = 2$ ha	$A = 5$ ha	$A = 10$ ha
IC: no coordination						
M1	**420**	408	404	1367	1355	1351
M2	463	**384**	358	1289	1210	1184
M3	931	463	307	**924**	**456**	300
M4	1131	507	**299**	1118	494	**286**
M integration[a]	*329*	*246*	*188*	*656*	*372*	*245*
IC: coordination						
M1	409	403	401	1356	1350	1348
M2	**395**	**354**	340	1221	1180	1166
M3	776	401	276	**769**	**394**	269
M4	928	426	**258**	916	413	**246**
M integration[a]	*293*	*219*	*169*	*568*	*321*	*214*

[a] In each stand selecting the inventory method with the lowest cost-plus-loss (values in *italics*).

In the transition from small to large stands, gradually more accurate data acquisition methods should optimally be employed. This is illustrated in Fig. 2–3 where the proportion of stands that should optimally be inventoried with a specific method are shown for the different cases.

When in each stand selecting the inventory method with the lowest cost-plus-loss, field methods (with 5 or 10 plots per stand) were more frequent than methods based on imputation for the Remningstorp estate (Fig. 3), compared to the corresponding selection at the Brattåker estate (Fig. 2).

The results presented in Tables 10–11 and Fig. 2–3 depend on the composition of the two fictitious estates. Different compositions would have yielded different results. Therefore, in order to provide an option to put together results for other fictitious estates and to provide an overview of what the results look like in individual stands, a sample of stand level results are given in Tables 12–13.

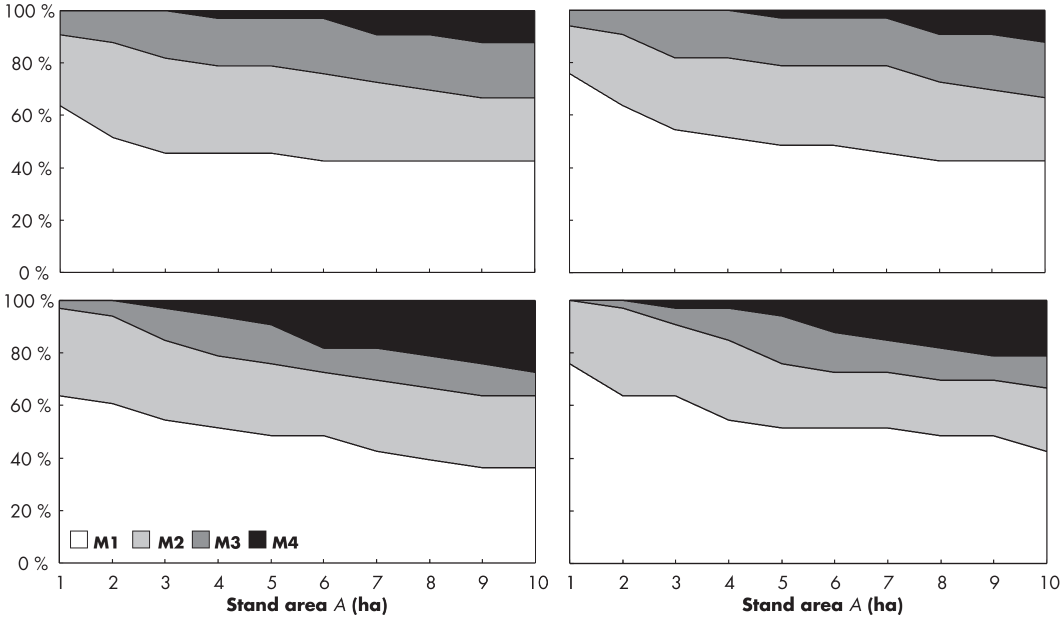

Fig. 2. Combination of methods that minimizes the cost-plus-loss at the estate level, for the Brattåker estate, assuming different stand areas. The upper two figures correspond to 2% interest rate, the lower figures to 4% interest rate. The left figures correspond to the case when costs are reduced by coordination of inventory activities, the right figures to the case without coordination.

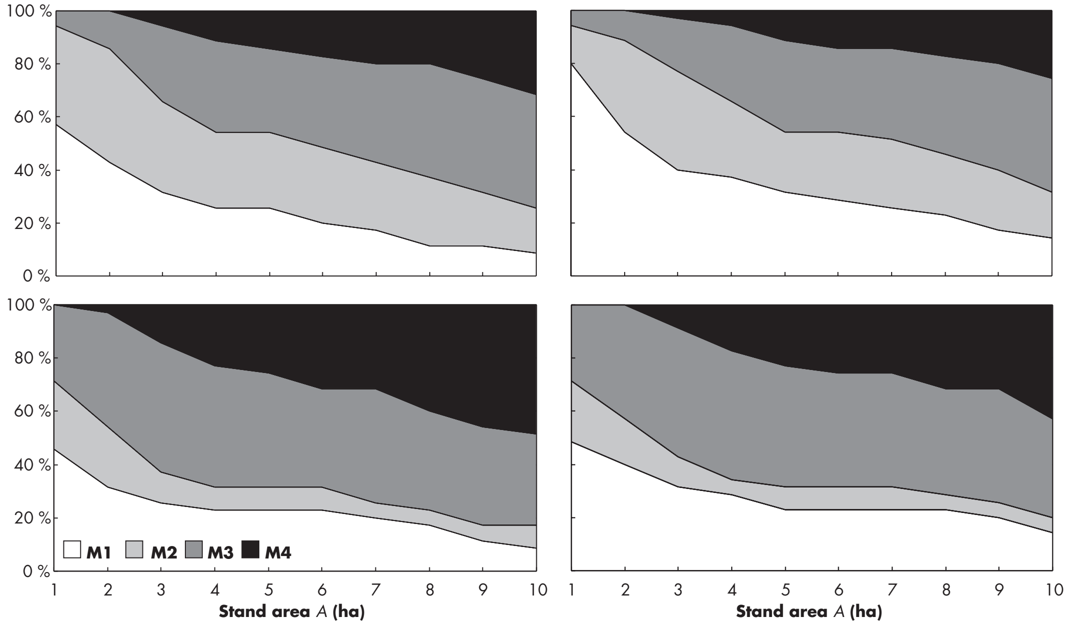

Fig. 3. Combination of methods that minimizes the cost-plus-loss at the estate level, for the Remningstorp estate, assuming different stand areas. The upper two figures correspond to 2% interest rate, the lower figures to 4% interest rate. The left figures correspond to the case when costs are reduced by coordination of inventory activities, the right figures to the case without coordination.

Table 12. Stand level cost-plus-losses for a sample of stands from Brattåker and Remningstorp, interest rate $r = 2\%$.

Estate / stand	Age (yrs)	Stem volume ($m^3\ ha^{-1}$)	Next treat-ment [a]	TC (SEK ha^{-1})			
				M1	M2	M3	M4
Brattåker[b]							
1	40	86	T 1	1155	799	466	379
2	41	119	T 1	94	239	264	260
3	58	130	T 4	219	150	238	238
4	71	160	T 2	660	289	340	219
5	92	228	T 1	1061	399	221	272
6	115	200	C 4	175	127	316	250
7	118	134	C 6	27	98	159	226
8	131	250	C 1	1775	2100	125	168
Remningstorp[c]							
1	26	74	T 1	460	541	655	683
2	36	286	T 1	2805	1840	522	416
3	38	275	T 1	1625	1598	348	416
4	41	165	T 4	287	179	336	427
5	64	213	C 5	285	168	336	430
6	64	426	C 4	1761	696	513	456
7	70	335	C 3	742	746	354	416
8	71	253	C 4	366	599	785	796

[a] Entries on left side: T = thinning, C = clearcutting; on right side: 5-yr period.
[b] Based on stand area A = 10 ha and with coordination of inventory activities.
[c] Based on stand area A = 5 ha and without coordination of inventory activities.

Table 13. Stand level cost-plus-losses for a sample of stands from Brattåker and Remningstorp, interest rate $r = 4\%$.

Estate / stand	Age (yrs)	Stem volume ($m^3\ ha^{-1}$)	Next treat-ment [a]	TC (SEK ha^{-1})			
				M1	M2	M3	M4
Brattåker[b]							
1	40	86	T 2	112	143	215	230
2	41	119	T 1	220	297	202	192
3	58	130	T 3	128	144	227	279
4	71	160	T 1	732	540	396	248
5	92	228	C 2	441	304	369	356
6	115	200	C 1	1598	903	436	284
7	118	134	C 3	132	348	364	295
8	131	250	C 1	333	121	125	168
Remningstorp[c]							
1	26	74	T 3	57	93	466	509
2	36	286	T 1	1972	1126	384	416
3	38	275	T 1	1900	953	312	416
4	41	165	T 4	834	154	373	430
5	64	213	C 2	396	475	617	591
6	64	426	C 1	3366	2750	312	416
7	70	335	C 1	2906	2780	312	416
8	71	253	C 1	2137	2312	481	542

[a] Entries on left side: T = thinning, C = clearcutting; on right side: 5-yr period.
[b] Based on stand area A = 10 ha and with coordination of inventory activities.
[c] Based on stand area A = 5 ha and without coordination of inventory activities.

At the stand level, the cost-plus-losses vary considerably between the different inventory methods. Especially, the imputation techniques sometimes show very high inoptimality losses. While valuable mature stands often require accurate descriptions, this is not always the case. The time to the next treatment appears to be an equally important factor to consider. This unless the optimal time for clearcutting is not by far passed, in which case even a simple stand description indicates that clearcutting as soon as possible is optimal (e.g. stand 8 in Brattåker; Table 13).

4 Discussion

The results indicate that the optimal choice of inventory method depends very much on stand type. Somewhat simplified it can be said that in large mature stands, with a relatively short time to the next treatment, accurate methods should be employed, while in small less valuable stands more simple methods may be used. By using different methods in different stands on an estate, considerable gains in net present value can be reached compared to the case when a single method is used in all stands. However, unfortunately it is not straightforward to identify what stands should optimally be inventoried with a certain method. This is illustrated in Fig. 4–5, where stand volume and (optimal) time to the next treatment are plotted versus stand maturity. The relative maturity is defined as the age in relation to the optimal economical rotation age depending on site index class (cf. Eid 2000). For the Brattåker estate, these rotation ages varied between 98 and 155 years when using the interest rate 2%, and 90 and 135 years when using the interest rate 4%. For Remningstorp, the corresponding reference ages varied between 70 and 110, and 65 and 95 years.

The difficulty of identifying what stands should optimally be inventoried using a certain method is partly due to random errors in the estimates of inoptimality losses, since these are based on 50 simulations, only, due to time considerations.

The sizes of total costs correspond to findings by Larsson (1994) and Eid (2000). Ståhl et al. (1994) obtained lower total costs, which might have been the result of a too simplistic planning model. The numbers of plots in the field inventories in this study falls well within the ranges suggested by Ståhl (1994a), in a study of the optimal number of sample plots based on cost-plus-loss analysis.

The optimal choice of methods did not depend very much on what interest rate was used in the calculations. This is slightly surprising, since it is well known (e.g. Dykstra 1984, Davis et al. 2001) that the interest rate very much affects rotation times and net present values in the calculations. Different results may, however, be obtained regarding what the composition of stands on an estate looks like. Other inventory costs would have had impact upon the results, and this should be regarded in particular when new sources of information are constantly becoming available (as well as when already accessible sources are becoming available to lower costs).

The estates used in the evaluations were somewhat non-typical since they did not comprise any stands younger than 25 years. If such stands had been present, it is very likely that the cheap imputation methods on average had performed better than the results show. Moreover, it was assumed that a stand map was already available for the estates. In a situation where a stand map should have been part of the result from the inventory, it is likely that the aerial photo interpretation method had performed better on average, since aerial photo interpretation is a very efficient method for the delineation of stands (e.g. Næsset 1999).

Methodologically, cost-plus-loss analysis can be performed in many different ways. In this study, the entire (formal) planning process was considered by entering the data to the FMPP. This is the only way of fully considering the effects of poor data on the outcome of planning. However, the timing of the inventory activity was not considered. Instead it was assumed that all stands should be immediately inventoried, and that the data should be used for decisions for ten years. After this point, it was assumed that perfect decisions would be made. Including the timing of inventories in the cost-plus-loss analyses is complicated. One possibility to do this is to use a Bayesian description of the forests in connection with stochastic dynamic programming

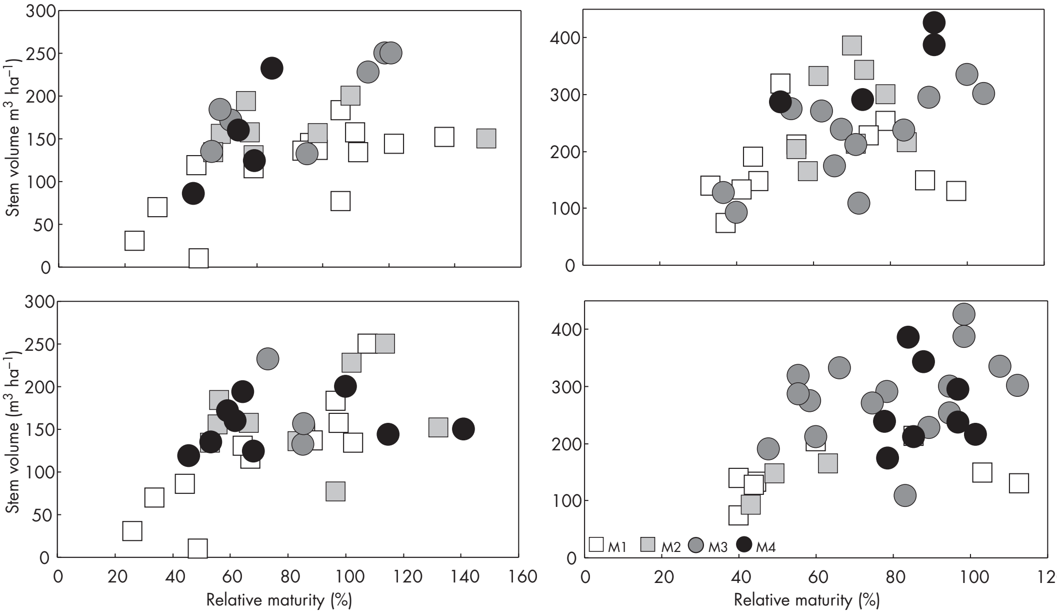

Fig. 4. Stem volume plotted versus relative maturity; the method with the lowest cost-plus-loss in each stand is shown. The upper two figures correspond to 2% interest rate, the lower figures to 4% interest rate. The left figures show stands in Brattåker (*A* = 10 ha, with coordination), the right figures show stands in Remningstorp (*A* = 5 ha, without coordination).

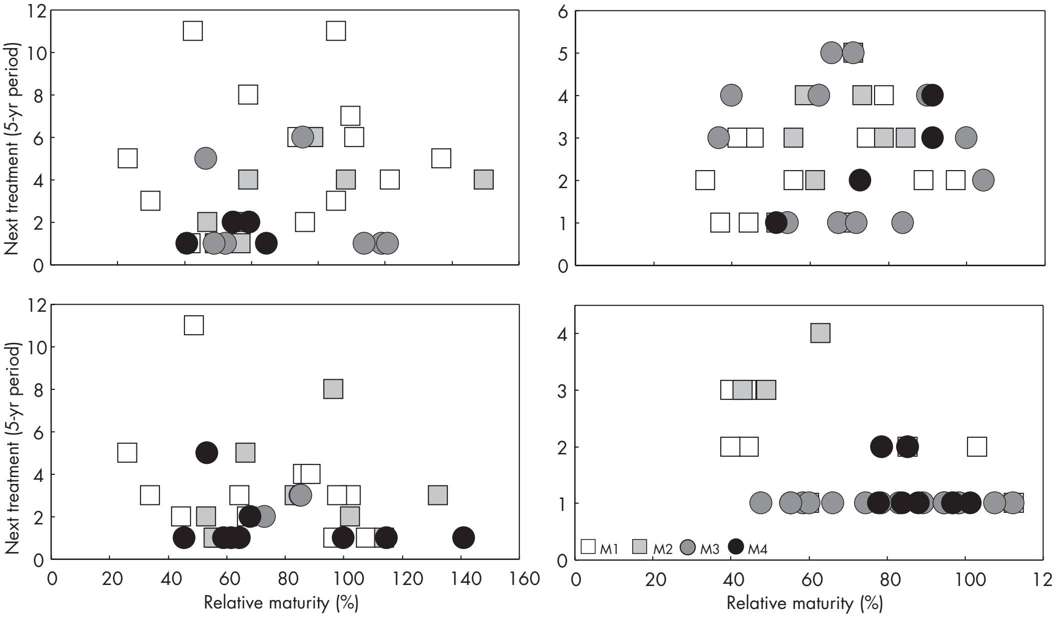

Fig. 5. The period in which next treatment (thinning or clearcutting) is optimal plotted versus relative maturity; the method with the lowest cost-plus-loss in each stand is shown. The upper two figures correspond to 2% interest rate, the lower figures to 4% interest rate. The left figures show stands in Brattåker (*A* = 10 ha, with coordination), the right figures show stands in Remningstorp (*A* = 5 ha, without coordination).

(Ståhl et al. 1994). In the present case this was not possible.

In the *k*NN-imputations, all plots within a stand were given equal weights. Theoretically it would have been possible to give the plots different weights, but for two reasons this was not done. Firstly, it would have required further modifications of the FMPP; secondly, a single plot would sometimes have represented a very large part of the stand in the imputations based on stand record information. Thus, all plots were given equal weight in order to obtain reasonable within-stand variability and to reduce the risk for extreme outcomes. In practice, a higher within-stand variability often follow from larger compartments. Such a condition would then emphasise the need for accurate inventory methods in large stands. However, if this variation becomes very high it is likely that the stand delineation is re-evaluated in a preceding step (before the choise of inventory method).

With bootstrapping, the results obtained may be unrealistic if they are based on too few original sample plots (although the resampling is done with replacement). Ståhl (1994b) suggested a correction of the losses obtained with a factor $n/(n-1)$, to compensate for a too limited within-stand variability. This factor is based on an assumption that the original sample is selected by simple random sampling. In the present study, no corrections were made.

Finally, it is important to keep in mind that the analyses have been carried out under the assumptions that the goal is maximisation of the net present value and that factors like timber prices, etc., are constant over time. On the one hand, one could argue that the importance of accurate information is even higher if prices vary over time. In this case it is important to know what stands to harvest when the price levels are currently favourable for the species and dimensions occurring there (cf. Ståhl 1994a, Kangas et al. 2000). On the other hand, decisions often consider many other factors than timber prices and maximisation of the net present value. Harvest decisions may be made in order to improve the hunting conditions, or a harvest may be cancelled due to the negative effects on the scenic values. In these cases the value of accurate information of the kind discussed in this study is lower.

4.1 Conclusions

In this study, an approach to evaluate the appropriateness of different inventory methods for providing data to forestry planning is outlined. A key feature is that the *k*NN imputation technique provides a link between seemingly very different kinds of information and the plot level data that are often required in advanced forest management planning systems. The cost-plus-loss analyses show that large amounts of money can be spared by a proper selection of inventory method in each stand. In large valuable stands, quite intensive field sampling should be carried out, while in less valuable small stands, aerial photo interpretation or pure ocular assessment is sufficient. However, it is not always straightforward to decide what stands should be inventoried with a certain method.

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