Forest inventory estimation using remotely sensed data as a stratification tool - a simulation study

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Abstract

It is well known that remotely sensed data and forest variables are correlated. For inventories like the Swedish National Forest Inventory (NFI) covering large geographic areas, the design for the sample plot layout is often either systematic sampling or simple random sampling. It is reasonable to assume that the design could be more cost efficient if remotely sensed data are used as auxiliary information. A simulated model has been constructed to evaluate the gain in precision when stratified sampling, based on remotely sensed data, is used.

A grid map was created to correspond with a landscape in the northern part of Sweden. First, the map area was divided into forest stands, and a vegetation class was assigned randomly according to a probability distribution obtained using NFI data from Norrbotten and Västerbotten counties, Sweden. Thereafter, for each grid element of the map both wood volume and spectral values were simulated. The wood volumes were simulated using field data from the NFI and the spectral values were simulated with a regression function based on the wood volumes that correspond to a Landsat TM scene with a 30m$\times$30m resolution.

Based on the spectral values the grid elements were classified into different strata. Stratified sampling was then performed and compared with simple random sampling without replacement. The comparisons show that the stratified sampling, based on remotely sensed data, produce much more precise inventory estimates of volume than simple random sampling.

1 Introduction

In recent years, the quality of remotely sensed data has improved, and, in combination with better computing resources, the possibilities for ground predictions have increased. This has also led to the possibility of using remotely sensed data as a stratification tool for improving the precision of inventory estimates. In Poso *et al.* (1987) the stratification approach, with unsupervised classifications, was used in a two-phase design to increase the precision of inventory estimates of volume and age under relatively small scale study conditions in Finland. In McRoberts *et al.* (2002) the stratification approach was used to improve the precision of forest area estimates in the states of Indiana, Iowa, Minnesota and Missouri in the United States. In this study a flexible simulation model was introduced. It was developed so that it was possible to both evaluate forest area estimates with stratified sampling and to check how the different components of the constructed model affect the stratification result. It is also possible to use the model for variables other than the wood volume, which was considered here.

The Swedish National Forest Inventory (NFI) is an inventory covering a large geographic area. It is an inventory incorporating field data from the whole of Sweden for many forest variables and also for some nonforest variables. The NFI started in 1923 and a systematic design of clusters, chosen with systematic sampling, has been used since 1953. Remotely sensed data have not been invoked yet but that is an option for the design in the future.

The effects of stratified sampling, for inventories like the NFI were evaluated with a simulation model. In the model, a grid-based map with values of field data and remotely sensed data corresponding to the Swedish counties Norrbotten and Västerbotten (see *Figure* 1), was created. Initially an area was divided into polygons, with each polygon created to correspond

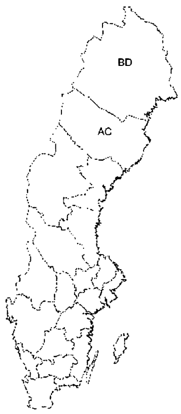

Figure 1, map of Sweden, BD - Norrbotten and AC - Västerbotten. *Courtesy © Lantmäteriverket 1998. Ur GSD - Blå [alt.] Gröna kartan, dnr 507-98-4720.*

to a forest stand. For each stand a vegetation class was assigned according to a probability distribution obtained from NFI data recorded from Norrbotten and Västerbotten counties. The stand map was created using two different tessellation methods, namely the standard Poisson process and a Dirichlet cells approach. The map polygons for these two methods differ, both in shape and size. It is therefore possible to draw conclusions about the effect on the variance of the stratified sampling when different methods are used to create the polygons.

For each grid element of the forest stand map, field data were simulated to correspond to wood volume in areas from the northern part of Sweden. The simulated wood volumes were based on field data from the NFI between 1993 and 1998. With a regression function based on the wood volume, developed by Nilsson and Ranneby (1997), the remotely sensed data were simulated to correspond to the spectral values of a Landsat TM scene.

In order to investigate whether stratified sampling could be useful for the Swedish NFI, stratified sampling and simple random sampling without replacement were compared for the simulated map. The strata were created from the remotely sensed data using a contextual classification method. This classification method was based not only on information about the pixel itself, but also on information about the classes and the data in the neighboring pixels. The comparisons were done under different conditions as described in Section 4.

2 Field data and remotely sensed data

The field data were based on data collected between 1993 and 1998 by the NFI in the northern part of Sweden for the land use class "forest". The "forest" was used, as digital map information is available to define the "forest" on a remotely sensed image. The simulated data could be seen as a map filtered from land use classes other than forest. The sample plots of the NFI are located systematically along the sides of a squared cluster called "tracts" (Ranneby *et al.*, 1987). Each tract consists of either twelve temporary plots with radii of 7 meters or eight permanent plots with radii of 10 meters. The permanent plots are remeasured every fifth year whilst the temporary plots are measured only once. The field data in this study were based on the temporary plots.

The remotely sensed data were based on a Landsat TM scene acquired over Sweden on 6 July 1991 (path 194, row 15), geometrically precision corrected to the Swedish National Grid. In order to reduce the computing time only bands 4 and 5 of the Landsat TM bands were used, as they are known to be most useful for prediction of wood volume.

3 Simulation study

Maps with simulated values of wood volume per hectare and spectral reflectances for elements corresponding to a pixel were created. The objective was to construct guidelines for an efficient design for the NFI and similar inventories; a design using remotely sensed data as auxiliary information. The simulation study was built up in 4 main steps:

- Construction of a grid-based map with areas divided into polygons, which are randomly assigned to a forest stand class.
- Simulation of field data for each pixel in the map.
- Simulation of spectral values for each pixel in the map.
- Classification of each pixel into an age class, and performance of stratified sampling on the classes.

3.1 The map

To make possible the evaluation of different sampling strategies, a forest stand map, corresponding to a hypothetical area in the northern part of Sweden, was created. The map was divided into 480×480 quadratic pixels each of area 900 m^2. Each pixel consisted of 6 rectangular sample plots, each with an area of 150 m^2. Pixel size was determined to correspond to the size of a Landsat TM scene, and each sample plot corresponded in size to a temporary sample plot of the Swedish NFI. The average stand size on the map was alternated at three levels, 7.3, 14.6 and 29.2 hectares/stand, where the 14.6 hectare level is the one best corresponding to the true stand size. To simulate a map with these average stand sizes, and also with a good distribution of the sizes and shapes of the stands, two different approaches were tested. One map was created from a Dirichlet cells approach and the other using the standard Poisson lines process. With both techniques each pixel contained 25 grid elements. The pixels were divided into grid elements to retain information about the location of a potential border in the pixel. After the stands were generated, the identities of the 6 sample plots within a pixel were decided from the 25 grid elements of the pixel. The class identities of the plots within each pixel were defined based on the proportions of each class among the 25 grid elements.

The Dirichlet cells approach started with simulation of points from a Poisson point process with intensity λ. At a location equidistant from two neighboring points, borders were created, and at the same time a polygon net developed. Each pixel of the map was assigned to the polygon in which it was placed, see *Figure* 2. Theoretical properties of the Dirichlet cells (also called Voronoi diagrams) and their simulation are described in Okabe *et al.* (2000).

For the standard Poisson line process a line a with a uniformly distributed length l between 0 and $\sqrt{2} \times 1200$ and a uniformly distributed angle θ between 0 and 2π was simulated. A second line b was drawn perpendicular to a. If any part of the line b was inside the region [-1200,1200]×[-1200,1200] (that region was used due to the map size of 2400×2400 pixels) it was used to create polygons. The number of lines b to be generated with this approach was simulated from a Poisson distribution with intensity μ. A polygon net was generated from the m lines that were retained, *see Figure* 3.

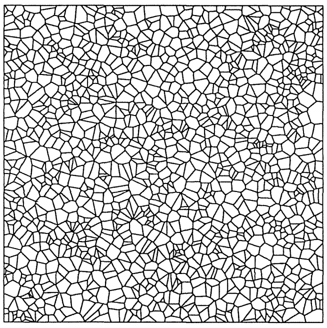

Figure 2. Grid-based map created with the Dirichlet cells technique.

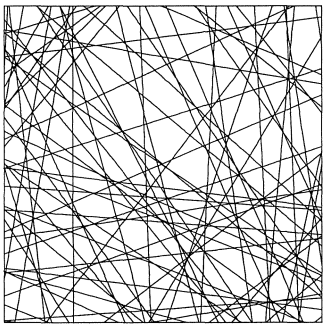

Figure 3. Grid-based map created with the Standard Poisson line process.

The statistical properties of the Poisson line process were first considered by Goudsmit (1945) and the statistical properties have since been investigated by Miles (1964a,b). Statistical properties for the generation of polygons from the Poisson line process are summarized in Santalo (1979) and an algorithm for the generation of the standard Poisson process is included in Crain and Miles (1976).

The two techniques for creating polygons will give polygons with different properties. The standard Poisson line process will generate many small and a few relatively large polygons compared to the Dirichlet cells approach which tends to give polygons more similar in size. The polygons of the standard Poisson line approach will also be narrower and also longer than those from the Dirichlet cells approach which are more circular in shape. Every polygon in each map was developed to correspond to a forest stand, and was assigned an age class with three different probabilities of the youngest age class relative to the other classes. In the first case considered, the probabilities were based on the empirical distribution for the classes, i.e. the proportions of each class in the NFI data. In the second case the probability of assigning a polygon of the youngest age class was decreased, whilst in the third this probability was increased, in comparison with the empirical distribution. The probabilities of the other classes in the later two cases had the same relation between them as the first case with the exception of last case where class 2 had to be revised to a higher probability at the expense of class 3 to avoid numerical difficulties. The probabilities for each of the three cases are given in *Table* 1. The following four age intervals were used, 0-10, 11-30, 31-80, and > 80 years.

	Probabilities of each class			
	0-10	11-30	31-80	> 80
empirical	0.121	0.049	0.437	0.393
more old forest	0.050	0.053	0.473	0.425
more young forest	0.200	0.050	0.392	0.358

Table 1

3.2 Wood volumes

For each grid element of the forest stand map, field data were simulated to correspond to wood volume in areas from the northern part of Sweden. The wood volumes were obtained by a three-step approach based on NFI data from 1993 to 1998. In the first step, for each forest stand with a given age class c, a sample **s** of size k=50 was drawn from each forest stand given an age class c in the NFI data. k elements, instead of the whole NFI data of the class, were used to make it possible to develop stands of the same age class but with different statistical properties applying to the sample. Secondly, for every sample plot of the stand, one observation was drawn randomly from the sample **s**. To create wood volumes over an area corresponding to a pixel the sample plots within the pixel were thereafter averaged. The size of the pixel was determined to correspond to a pixel in a Landsat TM scene to make possible the inclusion of remotely sensed data in the sample design. The area of each pixel was $30m \times 30m$.

In the third step the spatial dependency was incorporated. Spatial dependency models are necessary owing to the distance dependency that exists in the forest. This dependency was investigated by Wallerman *et al.* (2001) with semivariograms from the Brattåker area in the Västerbotten county, Sweden. Using equation (1) below the wood volumes, $\nu_{i,j}$, were adjusted for the spatial dependency. The map created consisted of 480 elements (pixels) in both horizontal and vertical directions, and equation (1) was performed for all elements except the map borders:

$$\nu_{adj,i,j} = w_1\nu_{i,j} + w_2\nu_{i-1,j} + w_3\nu_{i,j+1} + w_4\nu_{i+1,j} + w_5\nu_{i,j-1},$$

$$i = 2, ..., 479, j = 2, ..., 479, \tag{1}$$

where $\sum_{k=1}^{5} w_k = 1$, all weights w_k are chosen to be positive, i is the position in the east-west direction and j is the position in the north-south direction of the map. *Figure* 4 and *Figure* 5 give a picture of the amounts of wood volume for both map approaches.

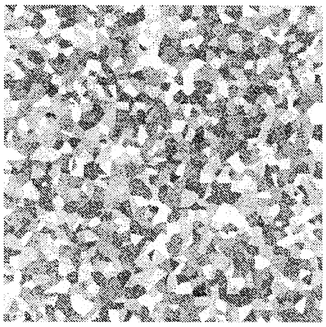

Figure 4. Contour map of amount of wood volume, created with the Dirichlet cells technique.

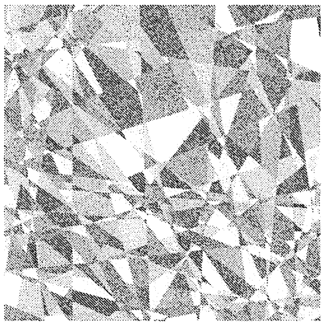

Figure 5. Contour map of amount of wood volume, created with the Standard Poisson line process.

The spatial dependency model was validated with the semivariograms mentioned above. These agreed well with those from the simulated data and the weights $w_1 = 0.8$ and $w_k = 0.05$, k=2,...,5 best fitted to the data. To check the influence of the spatial dependency model for different settings the weights $w_1 = 0.9$ and $w_k = 0.025$, k=2,...,5 were used also.

3.3 Spectral values

The spectral values were simulated as a function of wood volume ν using a regression technique. Nilsson and Ranneby (1997) constructed the regression model used to create pixelwise simulated spectral values for bands 1-5 and 7 of a Landsat TM image. The model was:

$$DN_i = e^{\alpha_i + \beta_i \ln(\nu) + \zeta_i}, i = 1 - 5, 7, \tag{2}$$

where DN_i denotes the digital numbers, i denotes the spectral band and ζ_i are correlated random errors for the spectral bands. The unknown parameters α_i and β_i, i=1-5,7, and the unknown covariance matrix $\mathbf{\Sigma}_{i,j}$, i,j=1-5,7, of the correlated random components ζ_i, i=1-5,7, in this study were estimated from a Landsat TM scene, see Nilsson and Ranneby (1997).

3.4 Sampling

With a simulated map, it is possible to compare traditional sampling designs, such as systematic sampling and simple random sampling without replacement, with sampling designs using remotely sensed data as auxiliary information. The spectral values were used to assign every pixel to a stratum, with the stratum based on the same age classes as in Section 3.1. After the classification, stratified sampling with both proportional and optimal allocation was applied.

3.5 The classification method

For the created map, the neighboring pixels are dependent and it is therefore reasonable to use a Bayesian contextual classification method. The contextual methods differ from non-contextual classification methods in that they do not only classify on the basis of the pixel itself, but information from neighboring pixels also influences the result. Several authors have developed contextual methods, for example Owen and Switzer (1982); Haslett (1985); Kartikeyan *et* *al.* (1994); Sharma and Sarkar (1998); Khazenie and Crawford (1990); Watanabe *et al.* (1994) and Flygare (1993).

For a contextual classification method it is often assumed that the feature vector is a sum of two independent components, where the data are influenced by the classes and the first order neighbors:

$$\boldsymbol{X}_{i,j} = \boldsymbol{Y}_{i,j} + \varepsilon_{i,j}, \tag{3}$$

where $\boldsymbol{X}_{i,j}$ is the observed spectral reflectance, $\boldsymbol{Y}_{i,j}$ is the true spectral reflectance and $\varepsilon_{i,j}$ is the class independent, possibly spatially correlated, noise. The vectors $\boldsymbol{Y}_{i,j}$ are assumed to be conditionally independent given their classes. A model for the classifications is:

$$\boldsymbol{Y}_{i,j}|C_{i,j} = k \sim N(\mu_k, (1-\theta)\boldsymbol{\Sigma}), \tag{4}$$

$$\varepsilon_{i,j} \sim N(0, \theta\boldsymbol{\Sigma}), \tag{5}$$

$$cov(\varepsilon_{i,j}, \varepsilon_{i+l,j+m}) = \rho^{\sqrt{l^2+m^2}}\theta\boldsymbol{\Sigma}, \tag{6}$$

where $\boldsymbol{\Sigma}$ is the covariance matrix for $\boldsymbol{X}_{i,j}$, the parameter ρ describes the spatial dependency between neighboring pixels, $\theta, 0 \leq \theta \leq 1$, determines how much of the variation of $\boldsymbol{X}_{i,j}$ that is due to the noise $\varepsilon_{i,j}$ and $C_{i,j}$ denotes the true, in reality unknown, class of the pixel.

For the classifications only three patterns (called X, L and T) of neighborhoods were allowed as proposed in Owen (1984). The neighborhoods considered consist of a pixel t=(i,j) and its four nearest neighbors. Imposing compass directions on the grid of pixels gives the neighbors the labels Nt, Et, St and Wt. Formally, a pattern is a partition of the set {t, Nt, Et, St, Wt}. In the X-pattern all five pixels are of the same class. The L-type patterns consist of {{Nt, t, Et}, {Wt, St}} and rotations of this pattern through multiples of 90 degrees, while the T-type patterns consist of {{Nt},{t, Et, St, Wt}} and rotations thereof. No other patterns are considered, as those rarely exist in reality.

For all of the estimations, training data of 50 pixel neighborhoods were taken from 100 maps to imitate the real situation. 100 maps were used, as the total size of these maps would then correspond to the size of a Landsat TM scene.

The pixels were classified to four different strata from the simulated spectral values $\boldsymbol{X}$; the same age classes that were used for the simulation of the stand map. From the training data parameter estimations of the mean of each stratum, the covariance matrix and the spatial dependency parameter were derived. The spatial dependency parameter ρ was derived using a method described in Hjort *et al.* (1985). This method gave an unstable estimator but with clear signs of a value of ρ close to zero. It was possible to obtain the same result with the autocorrelation function of the simulated data. The spectral values were therefore assumed to be independent and ρ=0 was used. The independence assumption is required owing to the lack of a spatial dependency model for the spectral values.

Each pixel is assigned to the class with the highest posterior probability. The prior probabilities $\pi(k)$, k=1,..,4, were all 0.25 and the conditional probabilities $\pi(k|m)$, k,m=1,...,4, were estimated with the conditional frequencies from the training data. Equal probabilities for the priors were used instead of estimated priors as the classes with low frequencies are normally poorly represented with a Bayesian approach. With more equally sized classes the result of the stratified sampling is generally better.

4 Results

Two variants of classification were performed; one based on the spectral values DN_4 and DN_5 according to equation (2), and one based on $\ln DN_4$ and $\ln DN_5$. For both variants the classification results were of a similar nature, see *Tables* 2 and 3 for the confusion matrices when the parameter setting best corresponding to real data (i.e. when the simulations were based on the empirical age distribution, the spatial dependency weight 0.8 and the average stand size 14.6) was used. In the classifications performed, the youngest stands were classified with a high accuracy but the older stands were classified with a rather high error rate. These results were expected owing to the well-known fact that predictions of wood volumes, based on remotely sensed data, give good results for sparse forests and poor results for dense forests. Since the two variants of classification produced similar results, we only used the one based on DN_4 and DN_5 for the creation of strata.

Confusion matrix from the Dirichlet cells approach

	DN				*ln DN*			
i,j	1	2	3	4	1	2	3	4
1	0.733	0.160	0.051	0.057	0.751	0.143	0.052	0.054
2	0.123	0.470	0.223	0.185	0.148	0.457	0.225	0.170
3	0.033	0.277	0.260	0.430	0.041	0.279	0.273	0.408
4	0.012	0.154	0.222	0.612	0.015	0.157	0.238	0.591

Table 2

Confusion matrix from the standard Poisson lines process

	DN				*ln DN*			
i,j	1	2	3	4	1	2	3	4
1	0.750	0.156	0.046	0.048	0.773	0.138	0.043	0.046
2	0.103	0.484	0.235	0.177	0.133	0.488	0.216	0.163
3	0.025	0.272	0.276	0.426	0.034	0.292	0.267	0.407
4	0.009	0.143	0.234	0.613	0.011	0.160	0.233	0.596

Table 3

The stratified sampling was performed, and compared to simple random sampling for some settings. The results, based on 1000 replicates, are shown in *Tables* 4-7 with 100 times the average of the quotient between the variances of the stratified sampling and the simple random sampling, respectively, for the specific settings. The standard error of the average estimator of the quotient is presented in brackets in the tables. The gain in precision with proportional allocation, for both map techniques, with the empirical distribution (based on the proportions of each class in the NFI data) and an average stand size of 14.6 m^3/hectare, was about 34% when the stratified sampling was compared with the simple random sampling without replacement.

Results from the Dirichlet cells approach, proportional allocation

	av.size: 7.3		av.size: 14.6		av.size: 29.2	
weights	0.9	0.8	0.9	0.8	0.9	0.8
empirical	68.25(0.033)	68.13(0.034)	66.62(0.049)	66.08(0.047)	65.52(0.069)	64.76(0.070)
more old forest	80.08(0.031)	79.76(0.032)	78.92(0.045)	78.09(0.045)	77.53(0.063)	76.94(0.065)
more young forest	59.40(0.034)	59.12(0.030)	57.64(0.042)	57.04(0.043)	56.32(0.059)	55.33(0.059)

Table 4

Results from the standard Poisson line process, proportional allocation

	av.size: 7.3		av.size: 14.6		av.size: 29.2	
weights	0.9	0.8	0.9	0.8	0.9	0.8
empirical	67.34(0.070)	67.24(0.073)	66.21(0.094)	65.99(0.096)	65.40(0.137)	65.13(0.135)
more old forest	79.16(0.065)	78.83(0.068)	78.09(0.091)	77.94(0.091)	77.63(0.128)	77.45(0.129)
more young forest	58.52(0.064)	58.00(0.067)	57.33(0.089)	57.19(0.090)	56.09(0.120)	55.91(0.116)

Table 5

Results from the Dirichlet cells approach, optimal allocation

	av.size: 7.3		av.size: 14.6		av.size: 29.2	
weights	0.9	0.8	0.9	0.8	0.9	0.8
empirical	66.89(0.037)	67.20(0.038)	64.68(0.057)	64.44(0.053)	62.93(0.081)	62.44(0.081)
more old forest	79.80(0.033)	79.54(0.034)	78.46(0.048)	77.66(0.048)	76.80(0.069)	76.30(0.070)
more young forest	56.46(0.040)	56.57(0.037)	53.73(0.052)	53.48(0.052)	51.53(0.072)	51.10(0.072)

Table 6

Results from the standard Poisson line process, optimal allocation

	av.size: 7.3		av.size: 14.6		av.size: 29.2	
weights	0.9	0.8	0.9	0.8	0.9	0.8
empirical	65.60(0.080)	65.95(0.081)	63.84(0.110)	63.63(0.111)	62.64(0.161)	62.36(0.158)
more old forest	78.71(0.069)	78.52(0.072)	77.45(0.099)	77.33(0.099)	76.77(0.141)	76.59(0.143)
more young forest	54.95(0.077)	54.80(0.079)	53.07(0.107)	53.05(0.107)	51.01(0.145)	50.89(0.141)

Table 7

To check whether the form of the stand affects the result, the two map techniques described in Section 3.1 were used. The results in *Tables* 4 and 5 show a small difference for the parameter setting best corresponding to real data. For some other parameter settings the result of the proportional allocation does give a recognizable difference, indicating that the form of the stands does affect the results of the stratification. For all of the settings, the gain in precision for stratified sampling is more variable for the standard Poisson line process. The gain was more with smaller stands and less with larger stands in comparison with the Dirichlet cells approach. This is probably due to the more variable number of stands that the standard Poisson process approach causes.

The size was alternated at three levels, 7.3, 14.6 and 29.2 hectares/stand, where level 14.6 hectares/stand is the one best corresponding to the hypothetical area. A notable difference in results for both proportional and optimal allocation of the stratified sampling was obtained when the average stand size was alternated for all alternatives of the probability distribution of the classes. The average stand size does affect the results; the precision improves as the size of the stands increases.

To check the stability of the spatial dependency model, two different settings of weights were used. With these settings the results for the standard Poisson line process did differ slightly. On the other hand the results for the Dirichlet cells technique had a recognizable difference. It was concluded that badly chosen weights are likely to cause a smaller effect on the maps created with the Dirichlet cells approach.

When the stand class distribution was changed, the results showed a similar pattern for the stand form, the average stand size, and the spatial dependency model as for the empirical distribution. The gain for the stratified sampling compared to simple random sampling does change though. When the youngest class had a higher probability the gain was larger, and when the probability was lower the gain was less. This depends mainly on different inclusion probabilities for the age classes but also marginally on better results of the classifications.

If the variances of the wood volumes for each stratum are known, or if it is possible to obtain a reliable estimate of them, the optimal allocation is advisable. In other cases the proportional allocation is often preferable. For the simulated remotely sensed data, the variance was low for the youngest age class whilst the other classes had a variance that was higher and similar. The difference between the optimal allocation and the proportional allocation for the simulated data was therefore substantial only for the case with more young forest. Proportional allocation is therefore recommended unless the inventory is performed in an area with a high proportion of young stands.

5 Discussion

The results show that stratified sampling, with remotely sensed data used as auxiliary information, gives better precision than simple random sampling without replacement. It should be kept in mind though that there are some assumptions included. Some of them are worth noting, and are discussed in this section.

The wood volumes were simulated pixelwise within each stand, based on NFI data, through a sampling approach with a simple model for the spatial correction used to correct the data for the spatial dependency between neighboring values. Owing to the difficulty of finding a parametric probability distribution that fits the data well, this empirical use of data seems to be a better alternative than simulation of values strictly from a parametric probability distribution. An alternative method of acquiring wood volumes would be to use a Kriging based approach, and to then simulate a number of plots in each stand and use them as support points for the rest of the plots in the stand. The other plots could then be given their value from a Kriging predictor and a spatially correlated random error according to a parametric or nonparametric family of probability distributions.

The spectral values were simulated pixelwise as a function of wood volume based on a regression function. The dependency between neighboring pixels of the sensor was not taken into account when the spectral reflectances were simulated. It is reasonable to assume that the results will change if a dependency between pixels is used for the spectral model. It is quite likely that the accuracy of the classification algorithm would increase and the noise level of the spectral signals would be lower. With such a construction the spatial dependency parameter, ρ, for the classifications would differ from zero and the classification algorithm would then have more usable information.

Systematic sampling is a sample design that is efficient, under some conditions, when closely placed units in the population are rather homogeneous, i.e. adjacent units tend to have similar values, and/or there exists a linear trend in the data. It has been shown in Ranneby *et al.* (1987) that systematic sampling is preferable to simple random sampling for the Swedish NFI for the above reasons. Therefore it would be of interest to compare the stratified sampling, based on remotely sensed data, with the systematic sampling. However, to make these comparisons fair, more care has to be taken in the modeling of the data, e.g. in the current study there are no trends in the data (as could be expected when going from coast to mountain).

In the case of rare events, for example where 1-5% of the area is covered with the event, there are also problems in the precise creation of a design and estimators. An example of a rare event in forestry applications is a clearcut area. To solve this rare event problem a design created with more variables than only wood volume could be of importance. Designs for rare events and multidimensional inventories are areas in which more research is necessary.

The simulations were coded in Fortran90 on a PC. They were also implemented on a parallel computer using a message passing system called MPI to send information between different processors.

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10 Andersson, H. Taper curve functions and quality estimation for Common Oak (Quercus Robur L.) in Sweden. Examensarbete i ämnet skogsuppskattning och skogsuppskattning och skogsindelning. ISRN SLU-SRG-AR--10--SE.

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41 Eriksson, F. Markbaserade sensorer för insamling av skogliga data - en förstudie. Examensarbete. ISRN SLU-SRG-AR--41--SE.

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47 Holmgren, J. Estimating Wood Volume and Basal Area in Forest Compartments by Combining Satellite Image Data with Field Data. Examensarbete i ämnet Fjärranalys. ISRN SLU-SRG-AR--47--SE.

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